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Household water purification system comprising cartridge filtration, UVC disinfection and chlorination to treat turbid raw water

Paulo Marcos Faria Maciel[a], Natália de Melo Nasser Fava[a], Antônio Wagner Lamon[a], Pilar Fernandez-Ibañez[b], John Anthony Byrne[b], Lyda Patricia Sabogal-Paz[a*]

[a]Department of Hydraulics and Sanitation, São Carlos School of Engineering, University of São Paulo, Avenida Trabalhador São-Carlense 400, São Carlos, São Paulo, 13566-590, Brazil.

[b]Nanotechnology and Integrated Bioengineering Centre, School of Engineering, Ulster University, Jordanstown, BT37 0QB, Northern Ireland, United Kingdom.

* Corresponding author: lysaboga@sc.usp.br

Abstract

A system composed of cartridge membrane filters (25 µm, 10 µm and 1 µm opening size), UVC-lamp and chlorinator was constructed and tested with high turbidity water (up to 236 NTU). The proposed system treated around 180 L day^{-1} of river water and the following parameters were analysed: pressure drop in filters, turbidity, apparent colour, true colour, *Escherichia coli*, total coliforms (TC), UV 254_{nm} transmittance, UV 254_{nm} absorbance and total organic carbon in both raw and treated water. The study was conducted in three phases. In Phase 1, the raw water was rested for 24 hours in a settling tank before filtration in a 10 µm cartridge filter followed by one cartridge of 1 µm, a UVC-lamp (17 W) and manual chlorination. In Phase 2, a 25 µm filter was added before the 10 µm filter. In Phase 3, a blanket filtration step was added before the raw water entered the rest tank. The filtration trials lasted 7, 21 and 69 days in Phases 1, 2 and 3, respectively. The turbidity reduction of the system ranged from 30% to 93%. Disinfection by UVC-lamp was able to inactivate *E. coli* up to 5.00log, however the TC reduction was lower (up to 4.24log). The final manual chlorination with a dose of 3 mg L^{-1} of sodium hypochlorite increased the reduction of TC (up to 5.94log), regardless of water turbidity. The system was effective in improving water quality aimed at implantation in rural communities for domestic use at household level.

Keywords: cartridge membrane filters, decentralized, drinking water, low-cost technologies, turbid raw water, rural communities.

Highlights

- Pre-filtration in non-woven synthetic fabric prolonged cartridge filters' lifespan.
- Surface on cartridge filter treating natural water formed microbiological community.
- UVC disinfection after cartridge filtration removed *E. coli* to non-detection level.
- Chlorination assured total coliform reduction to virtual absence.

1. Introduction

Worldwide, 785 million people still have no access to basic water services, consuming water from unprotected sources or depending on travel times to collect potable water [1]. It is estimated that globally 1.8 billion people use drinking water sources that have some type of faecal contamination [2,3]. Therefore, inadequate access to safe water contributes to nearly 1.7 billion episodes of diarrhoea per year [4]. As well as drinking and food preparation, it is important to have the availability of water for hygiene purposes such as handwashing, which is crucial against diarrheal episodes [5] and it is imperative to protect human health during all infectious disease outbreaks, including the COVID-19 outbreak [6]. In 2017, 18% of the global population still had no handwashing facilities at home [1].

While water on premises is not a reality for many populations, water treatment at a household level should be considered important as an interim and immediate solution [7]. Some interventions have provided point-of-use water treatment solutions based on ceramic pot filtration, household slow sand filtration, solar disinfection, among others [8–10]. However, many of these technologies are designed to produce limited amounts of water per day. Other solutions are developed to attend a small group of households [11] and are not suitable to serve an isolated single-family location.

There is a lack of information in the scientific literature on water treatment systems for serving family groups of up to 5 members based on materials that are easily available on the market. Technologies such as cartridge filtration and UV disinfection are solid, and their applications are widespread around the world. Notwithstanding, there is a lack of information on evaluating the efficiency of commercial products based on these technologies.

A previous study investigated commercial cartridge filters treating a daily volume of 250 L, considering turbidity removal and a pressure drop of the filter [12]. The evaluated system required less installation costs and shorter operation times when compared to other filtration systems, such as ceramic filtration or rapid sand filtration. However, there is still a gap in the literature regarding cartridge filtration technology considering turbid natural water treatment with bacterial contamination. It is generally mentioned that the filters clog quickly if the source water is cloudy [13], but a combination of filters with different porous and options of pre-treatment are still to be investigated.

Cartridge filtration systems are the most common worldwide point-of-use water treatment devices that use various types of filters in designated housing to produce potable water [14]. They are often needed for prefiltering before other filters or disinfection since they can reduce turbidity, are inexpensive, require small spaces and have a total reduced weight when compared to sand or other media filtration [13,15].

The ease of operation and maintenance of cartridge filters makes them very attractive for small water systems [16]. Particles can be retained on the membrane surface and form a cake layer that progressively grows as the filtration cycle continues and it acts as another physical barrier or sieve to pathogenic organisms [17,18].

UV-lamps are easy to install, they need little operator attention, no on-site storage or use of potentially harmful chemicals, they are cost-effective and they have a high efficiency for inactivation of various microorganisms [19,20]. There has been renewed interest in UV irradiation with lamps in recent years because of its well-documented ability to extensively inactivate two waterborne, chlorine-resistant protozoans, *Cryptosporidium parvum* oocysts and *Giardia lamblia* cysts, at relatively low irradiation doses [21].

However, surface water can be cloudy or contain sediment that will limit UV light penetration, and for that reason, the UV disinfection system is typically combined with other treatment devices such as cartridge filters [22]. Although UV disinfection is effective and promising in places with small distribution networks, it does not provide residual protection; therefore, the water stored after its treatment may be subject to new contamination [20,23]. Moreover, some microorganisms can be reactivated after inactivation by UV [24]. In order to achieve extended protection, chlorination can be performed to assure the residual protection of the water post UV-treatment.

Chlorine is an attractive solution because of its availability, ease of use and maintenance of residual in storage treated water. However, its effectiveness depends on the water pH, concentration and contact time, temperature and chlorine demand of the water. Moreover, natural water containing an elevated concentration of dissolved organic carbon and bromide may represent a potential of carcinogenic disinfection byproduct (DBP) formation [25]. Nevertheless, the correct chlorine dose and proper water pre-treatment reduce the occurrence of DBP precursors [26].

Considering this context, a water treatment prototype (WTPt) was constructed associating solid technologies that are applied in the context of isolated communities. The WTPt was designed to treat 180 L of raw river water per batch, considering one batch per day, with stressing conditions caused by elevated water turbidity. Sedimentation during 24 h followed by cartridge filtration was included for sediment removal, UVC-lamp for disinfection and chlorine for residual protection and safe storage. The purpose was to analyse the efficiency of the WTPt in terms of bacteria reduction (*Escherichia coli* and total coliforms – TC) and physical and chemical parameters (turbidity, apparent and true colour, absorbance at 254_{nm} and total organic carbon). In addition, microscopic analyses were performed to observe which microorganisms were retained in the cartridge filters. This study also aimed to improve the sediment removal step including an additional cartridge filter and introducing a fabric filtration with a non-woven blanket.

2. Material and Methods

2.1. Prototype characteristics and operation

The constructed prototype (Figure 1 and Figure S1 – Supplemental Material) comprised two 310 L water tanks; one centrifugal pump (1/2 hp 40 L min^{-1}, 40 m maximum height, *Amanco*); pressure gauges; a sequence of filter housings containing cartridge polypropylene pleated filters of 25 µm, 10 µm and 1 µm opening size; a 17 W UVC-lamp (Polaris™ UV-4C, *Polaris Scientific*, USA); and a manual chlorinator. The filter housing measured 30 cm (height) x 12 cm (diameter). The UV dose commercial information of the UVC-lamp is presented in Figure S2 (Supplemental material).

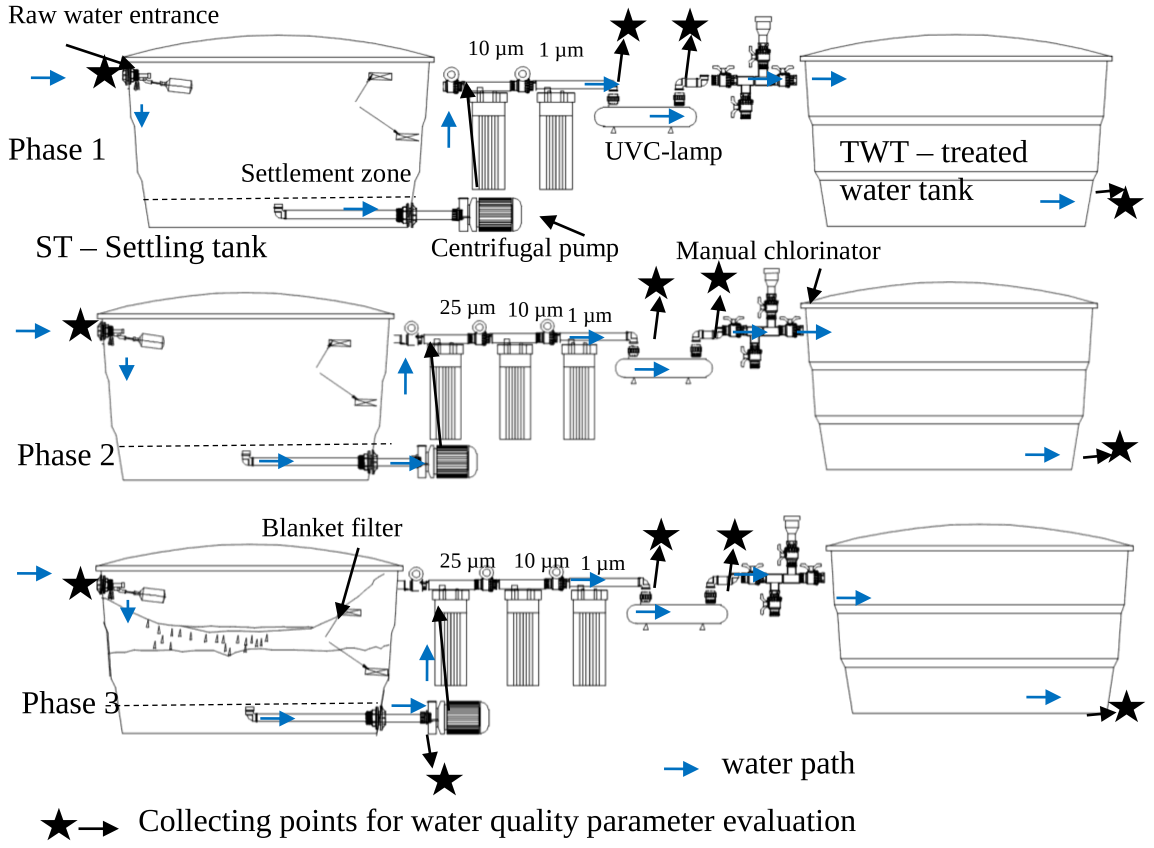

Figure 1 – Configuration of the Water Treatment Prototype in the three phases of the study and water collecting points indicated

The components of the prototype were assembled in a metal structure. The pump pumped water from the Settling Tank - ST to the elevated Treated Water Tank - TWT, passing through the filtration units and the disinfection units. The system inlet piping was positioned 15 cm above the base of the ST to provide a sedimentation zone for 24 hours between the raw water entrance and the pump start (Figure 1). One semi-automatic tap float was installed in each water tank to control the minimum and maximum level of water and the pump operation. The pump operation was related to one batch, which corresponded to the treatment of 180 L of raw water and the filtration rate during the batches ranged from 825 to 180 L m^{-2} h^{-1}, according to the filter clogging. One batch was performed per day of operation. The pump operation pressure was kept between 0.6 bar, at the first operation batch and 3.0 bar.

The study was conducted in three phases, with differences in the sediment removal step. Table 1 summarizes the phases of the study and Figure 2 shows a decision flowchart regarding the experimental procedure. In Phase 1, a sequence of two pleated filters was adopted (10 µm and 1 µm opening porous size) after the sedimentation time. In Phase 2, a 25 µm opening porous size pleated filter was added before the 10 µm filter. In Phase 3, two layers of a non-woven blanket were installed (specific gravity: ±0.2 g cm^3, composition: 100% polyester and thickness = 2.8 mm with 25 µm fibres) on the top of the ST to filter the raw water before the sedimentation time and a sequence of filters was used in Phase 2. The configuration of each phase is illustrated in Figure 1. The disinfection step performed by the UVC-lamp and manual chlorinator was used in the three phases.

Table 1– Experimental phases of the study

Phase	sediment removal step	disinfection step	water collection points
1	Sedimentation (24h) + cartridge filtration 10 µ and 1 µm	UV disinfection and chlorination	raw water entrance, after cartridge filters, after UVC-lamp, treated water tank
2	Sedimentation (24h) + cartridge filtration **25 µm**, 10 µm and 1 µm	UV disinfection and chlorination	raw water entrance, after cartridge filters, after UVC-lamp, treated water tank
3	**Blanket filtration** + Sedimentation (24h) + cartridge filtration 25 µm, 10 µm and 1 µm	UV disinfection and chlorination	raw water entrance, **before cartridge filters**, after cartridge filters, after UVC-lamp, treated water tank

Bold: Modification from the previous phase.

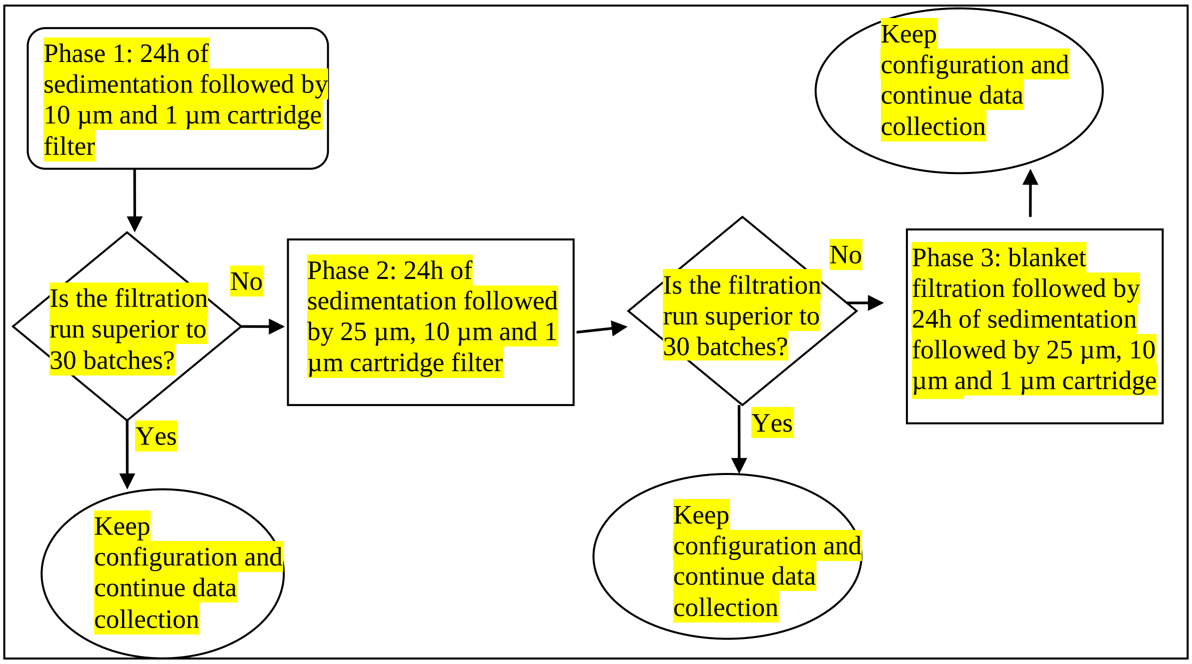

Figure 2 – Decision Flowchart of the experimental procedure

A semi-automatic control system was designed for the prototype operation. A block diagram of the design of the electrical control of the system is shown in Figure S3 and a model of the operation protocol is represented in Figure S4, both in the supplemental material of this manuscript.

2.2. Source water

The raw water was daily collected from the Monjolinho River (21.9869S; 47.8760W) in the city of São Carlos, state of São Paulo, Brazil, from August 2019 to February 2020. The water was moved directly to the ST, without storage time interval. This water is used as a source for the water treatment plant in the city of São Carlos. Characteristics of the raw water are presented in Table 2.

Table 2: Raw water characteristics

Characteristic	Mean ± standard deviation (median) [range]
Turbidity (NTU)	28.83 ± 29.83 (17.30) [7.34 – 236]

Apparent colour (Hu)	86.72 ± 61.74 (57.90) [25.9 – 316]
True colour (Hu)	38.60 ± 20.07 (30.70) [18.9 – 98.2]
UV$_{254}$ Absorbance	0.131 ± 0.057 (0.109) [0.057 – 0.2812]
UV$_{254}$ Transmittance (%)	55.23 ± 16.59 (59.80) [29.30 – 74.6]
Average Particle Size (nm)	414.93 ± 198.83 (347.25) [194 - 1068]
Total organic carbon (mg L^{-1})	3.55 ± 1.20 (3.23) [1.10 – 7.81]
Escherichia coli (CFU 100 mL^{-1})	14,911 ± 51,793 (1,400) [750 – 300,000]
Total coliforms (CFU 100 mL^{-1})	69,535 ± 205,691 (16,200) [4,900 – 1,000,000]

2.3. Sample collection and analyses

Performance analyses of the following parameters were considered for the evaluation of the WTPt: turbidity (2100N Turbidimeter – *Hach Company*, USA); apparent colour and true colour (DM-COR Colorimeter – *Digimed*, Brazil); absorbance at λ=254 $_{nm}$ and transmittance at λ=254 $_{nm}$ (Nanocolor® UV VIS II, *Macherey-Nagel*, Germany); average particle size (Zeta Sizer Nano Z90, *Malvern Company*, UK); total organic carbon – TOC (TOC-L, *Shimazu*, Japan); *Escherichia coli* and TC (Chromocult® coliform, *Merck*, Germany). Standard Methods (APHA et al., 2012) were followed to evaluate the above-mentioned parameters.

In Phases 1 and 2, samples were taken from the raw water and from treated water (after filters, after UVC disinfection and after chlorination in the TWT). In Phase 3, one extra collecting point was added before the membrane filtration system to evaluate the blanket filtration step. These water collecting points in the three phases are shown in Figure 1.

The three pressure gauges positioned before each cartridge filtration unit were read in each batch operation to evaluate the pressure drop. A ball valve after the pump regulated the flow rate of the system, which was measured daily. The initial flow rate was kept under 4.5 L

min^{-1}. The ball valve was completely open at the end of the filter run. In the last 17 batches of Phase 3, the flow rate was deliberately reduced to near 3 L min^{-1} to investigate the effect of increasing the UVC irradiation in the treatment.

The filter run was defined here as the number of batches, in which one batch is equal to one day of operation, between starting the operation and stopping it to clean or replace the first membrane filtration unit. The path taken by the water after the centrifugal pump defined the order of the filters.

2.4. Non-woven blanket cleaning

The blanket used in Phase 3 was cleaned when clogging was observed. Maintenance consisted of removing the blanket from the tank, placing it on the floor and scraping the solids using a broom for this procedure only. While the blanket was scraped, it was washed with the water produced by the WTPt. Pictures of the dirty blanket and its cleaning are presented in Figure S5 of the Supplemental Material of this manuscript.

2.5. Microscopic analysis

At the end of Phase 3, microorganisms housed on the surfaces of the non-woven blanket and the three pleated filters (25 µm, 10 µm and 1 µm) were microscopically identified. To visualise and identify organisms, one drop of the pellet of centrifuged material of each sample was placed in a glass slide, covered with a coverslip and observed in an optic microscopic (BX51, *Olympus*®, Japan), in the bright field under the 40x objective (400x magnification).

2.6. Statistical Analyses

The effect of the WTPt on water quality parameters was evaluated by statistical tests performed using the PAST software – PAlaeontological STatistics, published by Hammer et al. [27]. Shapiro-Wilk's test was used to assess data normality ($p > 0.05$). The two-tailed Mann-Whitney U test was used to test the medians of the influent water and the treated water ($p < 0.05$ means different medians). The Kruskal-Wallis test compared the medians of three or more groups (i.e., influent water, water after blanket filtration and filtered water).

3. Results and Discussion

3.1. Source Water

The collected river water represented a scenario where the surface water is the only available alternative to a household. In Brazil, surface water is the main source of supply for 56% of the cities [28]. This sort of source is susceptible to surface runoff and contamination. The studied raw water was intended for the stressed challenge phase of testing of the WTPt, as well as being one real source of supply.

3.2. Pressure drop in cartridge filters

The pressure drop in filter 1 in the three phases is presented in Figure 3, as well as the pump operation pressure. In Phase 1, Filter 1 (10 µm) started to clog on the fourth day; after this, the pressure drop raised abruptly for the next three days. The operation in this phase was interrupted on the seventh day because the flow rate was too low even though the ball valve after the pump was completely open. The pressure drop in the second filter is shown in Figure S6 of the Supplemental Material of this manuscript.

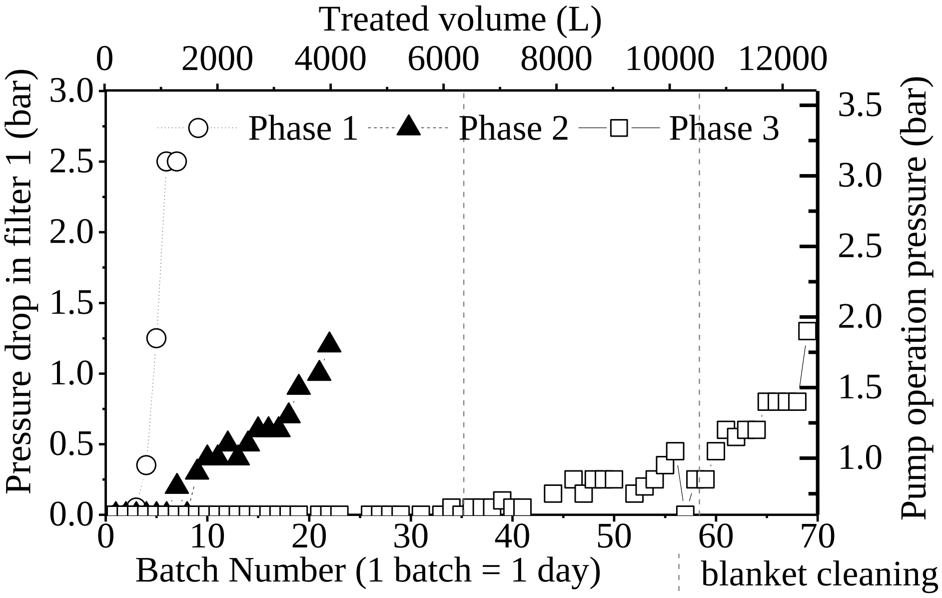

Figure 3. Pressure-drop in filter 1 in Phase 1 (2 filters – filter 1: 10 µm), Phase 2 (3 filters – filter 1: 25 µm) and Phase 3 (blanket + 3 filters – filter 1: 25 µm); and the pump operation pressure.

The cartridge filters in this study are generally used to protect a water purifier from damage and extend its life [29]. These filters remove suspended solids and should be chosen according to characteristics such as the particle size and flow rate requirements. It is expected that head losses increase significantly with prolonged use over time, due to the clogging particles retained on the outer surface of the cartridge, with a consequent reduction in the filtration capacity which indicates the need to replace the cartridge itself [30]. The 10 µm filter was inadequate to be the first filter of the system, despite succeeding the water decantation for 24 hours in the ST.

In Phase 2, the filter 1 (25 µm) started to clog on the eighth day and the filter run lasted for 22 days. In general, the largest rating size that will remove the intended contaminants will require the least maintenance [31]. Although more extended than Phase 1, the 22-day filter run was still insufficient for household drinking water treatment purposes.

The pressure drop on the second filter in Phase 2 is shown in Figure S7 of the Supplemental material of this manuscript.

Accordingly, in Phase 3 the pre-filtration was adopted in a non-woven blanket before the water decantation in the ST. The blanket filtration stage preserved the membrane filter's lifespan. Nonetheless, as the blanket accumulated suspended solids, it needed to be cleaned, as shown by the dashed line in Figure 4. The cleaning procedure took 20 min of one person's work. Phase 3 lasted 69 days and the first membrane filter started to clog around the 40th day. In this phase, the flow rate was maintained in the desired value for a long period and the need to increase the opening of the ball valve until the 50th day was not observed (Figure 4). The pressure drop in filter 2 in Phase 3 is presented in Figure S8 of the Supplemental material of this manuscript.

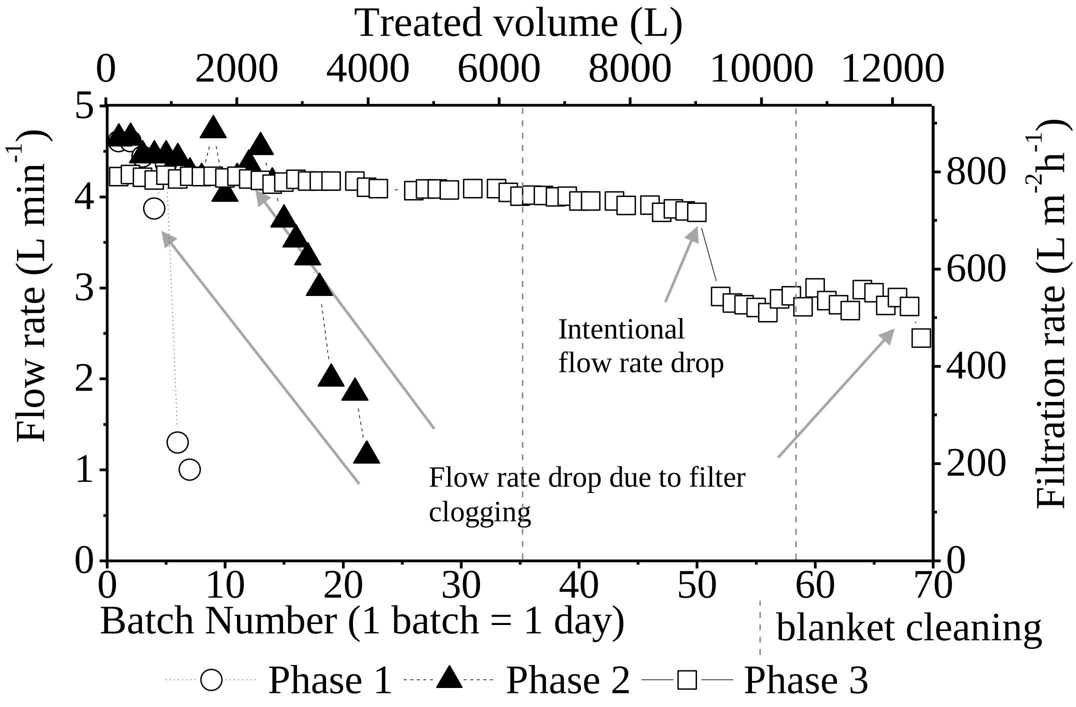

Figure 4 – Flow rate and filtration rate behaviour of the WTPt in Phase 1 (2 filters), Phase 2 (3 filters) and Phase 3 (blanket + 3 filters).

The pleated cartridge filters are surface filters, therefore the filter layer restrains particles higher than the mean pore size. The filter relies on the mechanism of straining. This mechanism is still dominant when the cake layer is formed above the surface [32]. Previous research hypothesized that other deposition mechanisms, such as inertial impact, interception and Brownian diffusion, also occurs on pleated filters as they observed a removal of particles smaller than the filter pores [12]. As particles were retained, the interstitial water velocity increased. This phenomenon can lead to particle breakthrough and Afkhami [12] observed turbidity removal decline with an increase of pressure and consequent increase of interstitial water velocity. Particle breakthrough was not investigated in the present study since there was considerable variation in the turbidity of the natural study water.

3.2. Water quality parameter evaluation

The value of the water quality parameters after the cartridge filters and after UVC disinfection in Phase 1 and Phase 2 are shown in Table 3, as well as the p-value for statistical comparisons between the medians of the raw water parameters and treated.

In both Phase 1 and Phase 2, significant differences were observed for the reduction of turbidity, apparent colour and average particle size. The treatment did not significantly change the true colour, absorbance at λ=254 nm and TOC, in both phases. Indeed, TOC is reported to not be removed at perceptible levels by cartridge filtration and UVC irradiation [31,33].

The cartridge filtration was reported to remove nearly 54% of turbidity elsewhere [34]. In Phase 1, turbidity removal ranged from 36%, on the first day to 98% on the last day, when the filter was almost completely clogged. In Phase 2, the turbidity removal ranged from 48% to 90%. Data from routine measurements are presented in the figures of the Supplemental Material (Figure S9 to S19).

The reductions and variations of water quality parameters from Phase 1 and Phase 2 were similar. Nevertheless, the p-values of Phase 2 indicate a statistically stronger difference from this phase compared to the p-values of Phase 1 (Table 3). This was due to the greater filtration run of Phase 2, which enabled greater data collection than the previous phase.

Water after cartridge filters presented elevated values of *E. coli* and TC. A significant reduction of these two groups was observed before disinfection only in the last measurement of Phase 1 (2.87 log for *E. coli* and 2.34 log for TC) when the filters were almost clogged and the flow rate was too low (0.86 L min^{-1}). More details can be seen from Figure S14 to Figure S18 (Supplemental Material).

The evaluated WTPt was challenged to treat 180 L day^{-1}. Achieving such a daily volume in a household treatment unit can be a difficult task considering the use of compact devices. In the present study, there was still an aggravating factor such as the treatment of water with high peaks of turbidity.

The treatment of high turbidity water is usually carried out by decanting the water. However, this operation depends on product dosing, which can be complicated, and mixing units, that take up a lot of space. As the cartridge filters showed to be sensitive to turbidity stress and ineffective, a non-woven blanket was proposed to pre-filter the raw water, which increased the sustainability of the WTPt.

In Phase 3, the difference between the three groups of samples was evaluated, therefore, in Table 4, the average value of physical and chemical parameters of the raw water, the water after blanket filtration and settling, and the water after cartridge filtration are presented. The microbiological parameters in these three groups of samples and after the UVC disinfection stage are also presented. Similar to what was observed in Phase 1 and Phase 2, the treatment in Phase 3 presented a statistical effect on turbidity, apparent colour and average particle size (Table 4).

Table 3 – Treated water characteristics in Phase 1 and Phase 2, after cartridge filtration and after UVC disinfection.

Parameter	Phase 1						Phase 2					
	After cartridge filtration			After UVC disinfection			After cartridge filtration			After UVC disinfection		
	Value (M± SD)	Reduction or variation	p-value	Value (M± SD)	Reduction or variation	p-value	Value (M± SD)	Reduction or variation	p-value	Value (M± SD)	Reduction or variation	p-value
Turbidity (NTU)	7.92 ± 6.59	68 ± 23%	0.0215	N.E.	N.E.	N.E.	4.96 ± 1.42	65 ± 11%	<0.0001	N.E.	N.E.	N.E.
Apparent colour (Hu)	30.60 ± 21.07	57 ± 27%	0.0215	N.E.	N.E.	N.E.	25.83 ± 6.22	47 ± 16%	<0.0001	N.E.	N.E.	N.E.
True colour (Hu)	21.53 ± 6.91	18 ± 15%	0.3837	N.E.	N.E.	N.E.	26.42 ± 4.69	34 ± 11%	0.0606	N.E.	N.E.	N.E.
UV$_{254}$ Absorbance	0.074 ± 0.017	16 ± 13%	0.3827	N.E.	N.E.	N.E.	0.068 ± 0.012	27 ± 6%	0.1124	N.E.	N.E.	N.E.
Average Particle Size (nm)	306 ± 25	31 ± 14%	0.0369	N.E.	N.E.	N.E.	292 ± 74	27 ± 18%	0.0312	N.E.	N.E.	N.E.
Total organic carbon (mg L^{-1})	2.84 ± 0.12	1 ± 2%	1.0000	N.E.	N.E.	N.E.	2.78 ± 0.26	6 ± 25%	0.8852	N.E.	N.E.	N.E.
Escherichia coli (CFU 100 mL^{-1})	1,423 ± 1,253	0.55 log median (0.02 – 2.87 log)	Not applica-ble*	<1	3.61 log median (2.87 – 4.06 log)	Not applicable*	371 ± 321	0.58 median (0.20 – 1.26 log)	0.0515	<1	2.92 log median (2.41 -4.08 log)	<0.0001
Total coliforms (CFU 100 mL^{-1})	5,835 ± 8,152	1.22 log median (0.10 – 2.33 log)	Not applica-ble*	79 ± 46	2.50 log median (2.08 – 3.10 log)	Not applicable*	6,720 ± 4,276	0.40 log median (0.15 – 0.85 log)	0.03671	50 ± 24	2.47 log median (2.35 -2.94 log)	0.0051

*Insufficient data to perform statistical comparison of median. N.E.: parameters not evaluated after UVC-disinfection, as they were not expected to change. M ± SD: mean ± standard deviation. The p-value < 0.05 indicates that there is a difference between the median of parameter of the treated water compared to the raw water.

Table 4 – Water characteristics in different stages in Phase 3

Parameter	Raw water (M ± SD)	After Blanket filtration and settling (M ± SD)	After Cartridge filtration (M ± SD)	p-value (equality of medians)	After UVC disinfection	Total reduction or variation
Turbidity (NTU)	37.28 ± 42.63	14.73 ± 16.79	11.55 ± 13.44	<0.0001	N.E.	67% ± 17%
Apparent colour (Hu)	103.66 ± 71.11	62.81 ± 54.44	30.60 ± 21,71	<0.0001	N.E.	51% ± 17%
True colour (Hu)	53.94 ± 21.24	47.48 ± 23.94	40.67 ± 20.36	0.2448	N.E.	26% ± 13%
UV_{254} Absorbance	0.183 ± 0.060	0.164 ± 0.065	0.143 ± 0.059	0.3306	N.E.	22% ± 15%
Average Particle Size (nm)	377 ± 183	270 ± 34	256 ± 25	<0.0001	N.E.	24% ± 20%
Total organic carbon (mg L^{-1})	4.29 ± 1.29	3.86 ± 0.98	3.87 ± 0.92	0.4397	N.E.	8% ± 16%
Escherichia coli (CFU 100 mL^{-1})	20,206 ± 62,201	8,958 ± 28,887	8,286 ± 29,110	<0.0001	<1	3.23 log median (2.47 – 5.17 log)
Total coliforms (CFU 100 mL^{-1})	95,662 ± 249,306	24,078 ± 57,869	20,076 ± 51,022	<0.0001	47 ± 38	2.91 log (median) (1.62 – 4.24 log)

N.E.: parameters not evaluated after UV disinfection. The p-value < 0.05 indicates that at least one of the three compared groups has a different median; it means a statistical effect of the treatment. M ± SD: mean ± standard deviation.

In Phase 3, when comparing the water samples after blanket filtration and settling, and after cartridge filtration, no statistically significant differences were observed for turbidity (p=0.0955), apparent colour (p=0.0593), true colour (p=0.4306), average particle size (p=0.0634), total organic carbon (p=0.9215), *E. coli* (p=0.5633) and TC (p=0.6798). Turbidity explains the effect of the blanket filtration in Figure 5, in which removal in this phase ranged from 30% to 93% (mean 67% ± 16%).

The cartridge filtration step showed little additional removal of turbidity after the previous stage (Figure 5). This result was expected since the average particle size influent to the cartridge filtration (270 ± 34 nm) was inferior to the minimum opening size porous (1 µm) of the filters used.

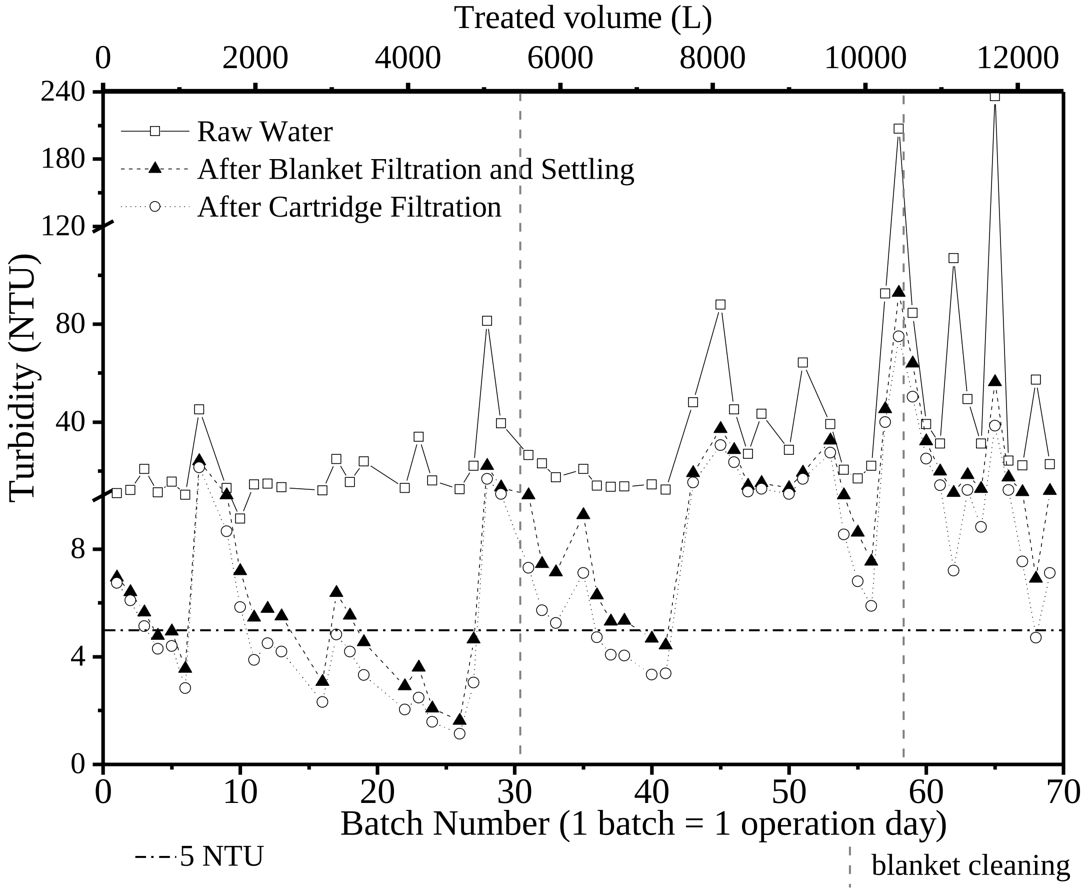

Figure 5 – Turbidity in raw water, water after blanket filtration and settling and after cartridge filtration in Phase 3.

Occasionally, water may contain fine suspended material, which may be too small to be removed by typical cartridge filtration [31]. Thus, the WTPt was not able to produce water with turbidity below the acceptance level of 5.00 NTU [35] when the water after blanket filtration and sedimentation was above 6.50 NTU.

On the other hand, in Phase 3 the system proved to be efficient when the raw water showed turbidity values near 10 NTU. On day 26, when the turbidity of the raw water was 12.5 NTU, the water after cartridge filtration presented 1.13 NTU of turbidity. Pontius [34] showed effective turbidity removal with filters which had smaller size openings, such as 0.45 µm and 0.10 µm. Afkhami et al. [12] showed high removal of turbidity with pleated cartridge filters, however they adopted a pressure drop in the system limited to 1 bar and water treatment with artificial turbidity, caused by the addition of kaolinite.

The mean turbidity removal by blanket filtration combined with the settlement was 59 ± 18%, varying from 17% to 90%. As the ST possessed a sedimentation zone (Figure 1), the remaining water from the previous day was mixed with the water that was recently filtered by the blanket. Therefore, the wide range of turbidity removal in the blanket filtration stage is explained by the raw water quality variation (Figure 5).

This removal variation can also be explained by the ripening period that may have improved the performance of the filtration by the blanket [36]. A substantial reduction in the turbidity is expected to occur when the solids are retained on the surface of the fabric [37].

The filtration by fabric is shown to have a better performance in removing contaminants as the number of layers increases. In our research, only two layers of non-woven blanket were considered, mainly because of the large area of the upside of the 310 L tank. Nonetheless, Siwila and Brink [38] reported improvements of more than 40 percentage points from one to eight layers of non-woven geotextile, in a bench-scale experiment. Therefore, the optimization of fabric filtration for producing a large volume has yet to be evaluated. The turbidity of the treated water met the minimum acceptable value of 5 NTU in some moments of Phase 3, however the TC values were not below the detection limit (1 CFU 100 mL^{-1}) after UVC disinfection (Figure 6).

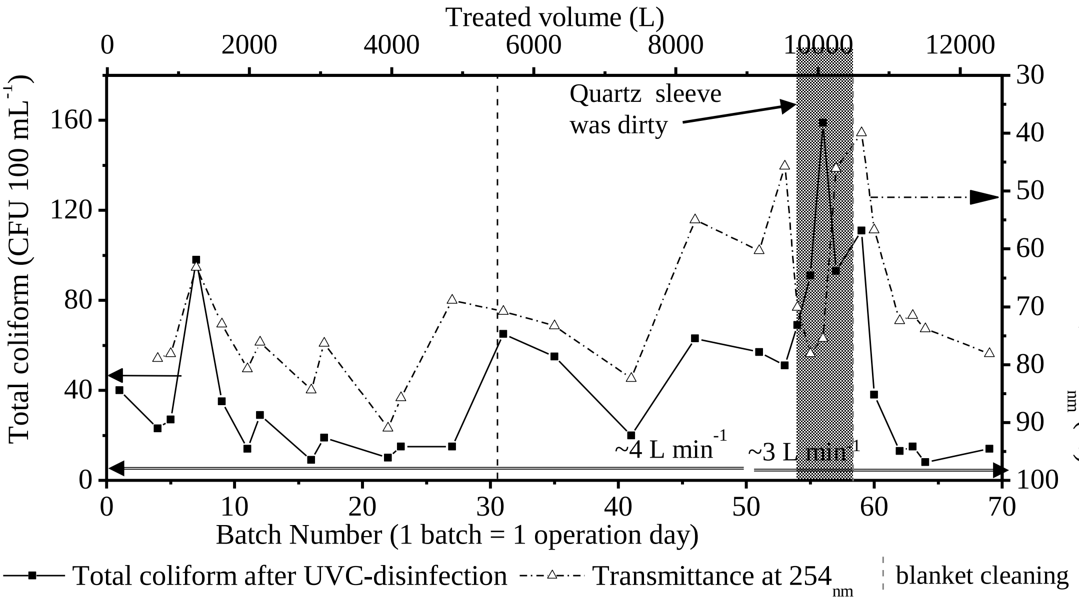

Figure 6 – Total coliform remaining after UVC disinfection and Transmittance at λ=254 nm in Phase 3 related to batch number

The efficiency of the UV radiation depends on the transmittance at λ=254 nm of the medium and the flow rate. The best results for TC inactivation with the flow rate of 4 L min^{-1} were attained when the transmittance was near 90%. This agrees with the recommended values of transmittance-254 for water to use UVC disinfection by the experts in the area, which is recommended to be > 75-80 % [39]. After the 50th day of the study, the flow rate was changed to 3 L min^{-1}, aiming to achieve better TC inactivation.

Between days 54 and 57, relatively high values of transmittance were noticed, however less inactivation of TC was obtained, which indicated that the quartz sleeve that involved the UVC bulb was dirty (Figure 6). Fouling on the quartz-water interface is a linear process caused by a broad spectrum of inorganic metals and anionic ligands [20,40]. After cleaning the quartz sleeve, the distance between the lines of "Transmittance UV at 254 nm" and "Total coliform after UVC disinfection" in Figure 6 increased in the part of the experiment of flow rate 3 L min^{-1} compared to the one of 4 L min^{-1}. The difference in distance between these lines indicates the effect of the flow rate on the total coliform removal.

The recommended UV dose for routine drinking water disinfection is set by most regulatory bodies at 40 mJ cm^{-2} for a 4-log inactivation, which is sufficient for all bacteria, protozoans and viruses except adenovirus [41,42]. The flow rates applied here promoted doses greater than 40 mJ cm^{-2} of UV radiation (Figure 2). However, increasing levels of turbidity, particulate matter and natural organic matter absorb more UV light and make it less available for disinfection [22]. A turbidity value greater than 1 NTU is appointed to shield microorganisms from UV radiation [29].

The *E. coli* count after UVC-disinfection was almost always below the detection limit of 1 CFU 100 mL^{-1}. The exception to this was observed in batch numbers 53, 54 and 56, when the quartz sleeve was dirty (Figure S16, Supplemental Material). This group of bacteria is sensitive to UV irradiation, even when the water presented low transmittance at λ= 254 nm. As an example, in the 57th batch, the water transmittance was 46% and the *E. coli* count was below the limit detection after UVC disinfection. This disinfection step showed to be protective for drinking water household interventions, i.e. above 2 *E. coli* log reduction [43], in all the analyses performed. When the influent water presented *E. coli* contamination as 10^5 CFU 100 mL^{-1}, the UVC-disinfection reached above the 4-log reduction, which is considered highly protective [43].

The chlorine dose of 3 mg L^{-1} was applied daily by the manual chlorinator in all tests, regardless of the water turbidity. This simple device was used to insert the chlorine at a point before the TWT (Figure 1). The flow through the pipe promoted the successful mixing of chlorine. The treated water rested for 30 minutes in the TWT after the end of the filtration to ensure sufficient contact time for the indicator bacteria to be inactivated by the chlorine action.

After the chlorination stage, the TC count was below the detection limit of 1 CFU 100 mL^{-1}, as was expected. Even when the turbidity of 40 NTU was measured in the filtered water (Phase 3, 57th batch), the inactivation of up to 6 log of TC was attained by chlorination. As an effect of high turbidity of the filtered water, low residual chlorine values were observed, for instance, the value of 0.4 mg L^{-1} in the 57th batch of Phase 3. Hence, the final chlorination step ensured that the treated water presented bacterial contamination indicators (*E. coli* and TC) below the detection limit, even when the raw water presented total coliforms at concentrations of 10^6 CFU 100 mL^{-1}.

It was not necessary to increase the chlorine dose according to the increase in turbidity, contrary to what was previously recommended by the literature [44]. As householders cannot measure the water turbidity before chlorination [44], the present study aimed to ensure that the dose of 3 mg L^{-1} would be sufficient to inactivate bacteria, regardless of turbidity. On the other hand, if the householder realizes that the chlorinated water is turbid, it is recommended to be consumed within 8 h post-chlorination [45], because the residual chlorine might not be maintained.

Although there is a concern regarding the formation of potentially carcinogenic by-products when chlorine is dosed in turbid water, Lantagne et al. [46] did not observe a concentration of trihalomethanes (THM) that exceeded the WHO guidelines when adding chlorine to turbid waters with TOC concentrations ranging between 0 and 9.8 mg L^{-1}. Besides, Abdullah et al. [47] did not find a correlation between water turbidity and THM formation.

3.3. Microbiological community on the surface of filters and blanket

According to the microscopic analysis of filter’s surfaces, algae was the most predominant group, both in the variety of genera and number, with some genera such as *Melosira*, *Navicula*, *Pleurosigma* and *Trachelomonas* occurring in all samples. However, cyanobacteria, helminths and protozoa were also identified. Protozoa was the second most prevalent group founded herein. Among them, we highlight *Corythion* spp. and *Giardia* spp. found in all samples. The visualized genera retained in each filter of the Phase 3 experiment are presented in Table 5.

The methodology used observed the pre and post content of the blanket, the 25 µm filter and the 10 µm, since the sediments retained on the surface of one barrier represented what passed through the previous one. Hence, it was not possible to observe the microorganisms post the 1 µm filter.

Table 5 – Microorganisms in the sediments from blanket and cartridge filters identified by bright field microscopy

Biological class	Microorganisms	Blanket	Pleated filters		
			25 µm	10 µm	1 µm
Algae	*Acanthosphaera* spp.		x		
	Achnanthidium spp.	x		x	x
	Ankistrodesmus spp.	x	x		
	Aulacoseira spp.	x	x		
	Asterocystis spp.				x
	Chilomonas spp.		x		
	Chlorella spp.	x	x	x	x
	Chlamydomonas spp.		x		
	Closterium spp.				x
	Coelastrum spp.	x	x		
	Cyathomonas spp.		x		
	Cyclotella spp.			x	
	Desmodesmus spp.		x		x
	Diatoma spp.				x
	Euastrum spp.		x		
	Euglena spp.	x	x		
	Kirchneriella spp.	x			
	Melosira spp.	x	x	x	x
	Micrasterias spp.		x		
	Navícula spp.	x	x	x	x
	Nitzchia spp.	x	x		
	Oocystis spp.	x			

	Palmella spp.	x			
	Phacus spp.		x		
	Pleurosigma spp.	x	x	x	x
	Rhodomonas spp.		x	x	
	Scenedesmus spp.	x	x	x	
	Sphaerocystis spp.	x	x		
	Staurodesmus spp.		x		
	Synedra spp.	x	x	x	x
	Tetrastrum spp.	x			
	Trachelomonas spp.	x	x	x	x
Helminths	*Tabellaria* spp.	x			
	Hymenolepsi spp. (egg)		x		
	Nematode (larvae)	x		x	
Protozoa	*Blastocystis*				
	Coleps spp.	x			
	Corythion spp.	x	x	x	x
	Entamoeba spp. (cyst)			x	x
	Euplotes spp.		x		
	Giardia spp. (cyst)	x	x	x	x
	Paramecium spp.	x			
	Vorticella spp.		x		
Others	*Anabaena* spp. (cyanobateria)	x	x	x	x
	Rotifera (animalia)	x			

(x): surface above where the microorganisms were identified.

One study has demonstrated infective-stage larvae being able to traverse polypropylene cartridge filters of 20 µm, 10 µm and 1 µm filtration ratings [48]. Even though filtration rating as 1 µm is expected to completely retain larger organisms such as nematodes, nominal pore size ratings are the average pore size rather than the largest; particles larger than the nominal pore size may pass through the filter [16]. Many filter manufacturers attest that filter micron sizing is based on nominal particulate ratings of >85% of a given size as determined from single-pass particle counting results [48]. This characteristic partially explains the presence of some organisms such as nematode larvae in the surface of 10 µm filter and *Corythion* spp. in the surface of 1 µm filter, even though they are organisms larger (≅ 1mm and ≅ 45µm, respectively) than the porosity of the filters used in the system. As shown in Table 5, nematode was identified on the surface of the 10 µm filter, which was not identified after the 10 µm filter.

While some organisms require inactivation doses within the spectrum offered by the UVC system used, such as *Cryptosporidium* [42] and nematode larvae [49], some nematode eggs are hardly susceptible to this type of water treatment [49].Thus, it is essential to establish periodic cleaning of the quartz sleeve to inactivate a wide variety of microorganisms, because clogging reduces UV light transmittance [42] and it is essential to retain the egg form of helminths by physical barriers.

Despite the evasion of some microorganisms through physical barriers (25 µm and 10 µm) the use of these blanket and three filters in sequence, among other things, increases their lifespan since the accumulation of microorganisms is partitioned, according to the size, which postpones the clogging of the filters, which last longer. The partitioned grouping of microorganisms also results in more than one biofilm. The gelatinous aspect of biofilm favours the retention of microorganisms which are removed from the water, helping to improve its quality.

3.4. Operation and cost evaluation

The potential user of the WTPt can have autonomy to operate the system with specific training and periodic follow-ups. Attention should be paid to the functioning of the UVC-lamp, indicator lights monitor the lamp operation and the user can easily interpret if it is or not working properly. The commercial UVC-lamp is made of a stainless-steel cylinder that protects the user from any UV radiation. The mercury bulb is kept inside a quartz-sleeve. Instructions should be provided to the household user on how to periodically clean the quartz sleeve and how to change and dispose of the bulb after the end of its lifespan. In the case of interventions, it would be better to be accompanied by specialized personnel for periodic maintenance. Maintenance by households would be required to ensure efficient and correct application of the system.

The WTPt cost US$ 1,114 (February, 2021). The most expensive item of the system was the UVC-lamp, acquired in Brazil for US$ 415. Each cartridge filter cost US$ 5.90 and the replacement UV bulb was budgeted at US$ 99.00. Considering the system working 1h per day, it would expend monthly 11.20 KWh and 0.51 KWh of power consumption of the pump and UVC-lamp, respectively. The power consumption of this system could be reduced by 75% by replacing the centrifugal pump by one 80W diaphragm pump, which fits in the configuration of the WTPt.

The operation and maintenance costs of the system are presented in Table 6. The major expense would be the replacement of the three cartridge filters after 59 days of operation. By comparison, the flocculant-disinfectant sachet from Protec & Gumble®, which can treat turbid water, would cost US$ 10 per 1,000 L of water treated [50].

The proposed system can treat daily larger volumes than presented here. Perhaps a household could not afford the initial price of the WTPt, nevertheless the cost per litre of treated water is compatible with the Brazilian minimum income. It could also be a solution in for small schools, farms, or any isolated facility.

Table 6 – Operation and maintenance costs of the water treatment prototype

Expense item	1,000 L (US$)	1 month (US$)
UVC bulb (9,000 h per bulb)	0.06	0.32
Cartridge filters (12,000 L)	1.42	7.67
Chlorine	0.07	0.38
UVC-lamp: expenses on power consumption*	0.01	0.05
Pump: expenses on power consumption*	0.23	1.23
Total	1.79	9.66

*considering US$ 0.11 KWh^{-1} (average price of electricity in rural areas in Brazil)

4. Conclusions

This work has experimentally assessed the capacity and effectiveness of a treatment prototype based on cartridge filtration, UVC disinfection and chlorination to provide the potable water daily needs for a household of 5 members sourcing from a local river.

It was observed that commercial cartridge filters were severely impacted by stressing conditions of turbidity, as direct filtration through 10 and 1 µm cartridge filters resulted in only 7 batches treating 180 L each. Nevertheless, pre-treatment with fabric filtration and 25 µm filter increased the sustainability of the evaluated system, resulting in 69 batches (days of operation). From microscopic observation, an active biological layer was observed on the surface of filters and the blanket, which could have contributed to both the filter clogging and retaining of particles.

The proposed system can be an attractive solution considering source water with turbidity below 10 NTU. When considering sources with higher values of turbidity, more studies should be conducted to optimize the water clarification since the UVC disinfection was not carried out properly in case of filtered water turbidity higher than 1 NTU and transmittance at UV 254 nm higher than 75%. The chlorine disinfection step was one barrier of safety in the case of the present study as the final water presented *E. coli* and the total coliform count was below the detection limit (virtually absence) in all tests performed.

5. Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

6. Acknowledgments

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7. Supplementary Material

The scheme of the water treatment prototype evaluated the UVC-lamp dose information, the semi-automatic operation protocol for the WTPt, the block diagram of the WTPt electrical control, the steps for the blanket cleaning procedure, the pressure drop per filter, turbidity and colour and coliform removals per operation phases are provided as supplementary material.

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Supplemental material

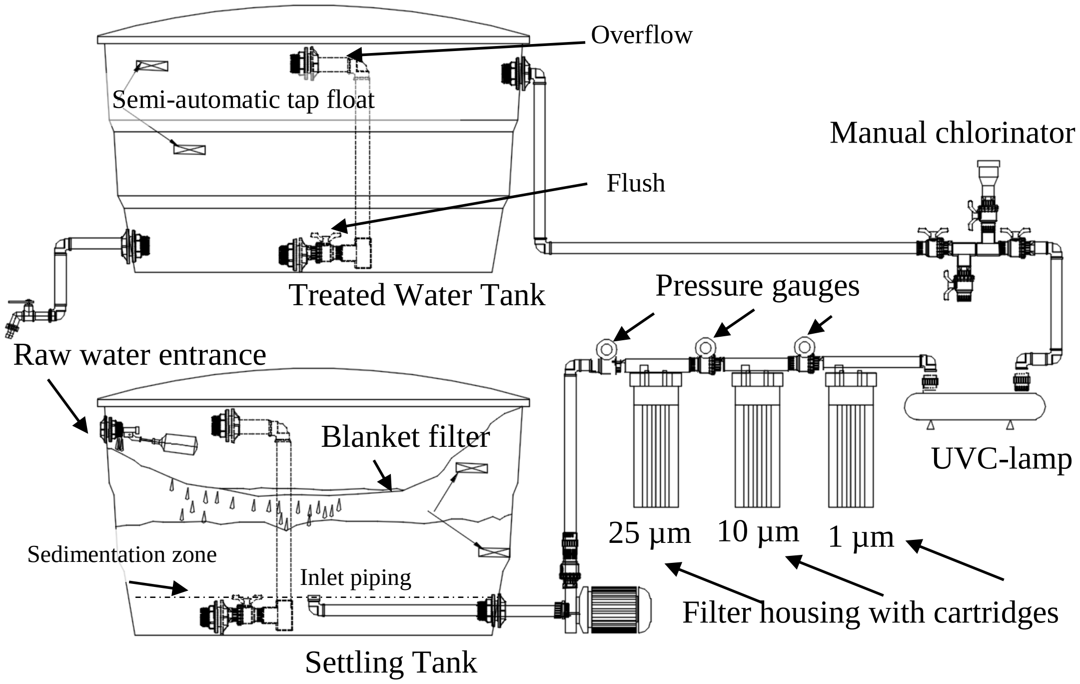


Figure S1 – Scheme of the Water Treatment Prototype evaluated

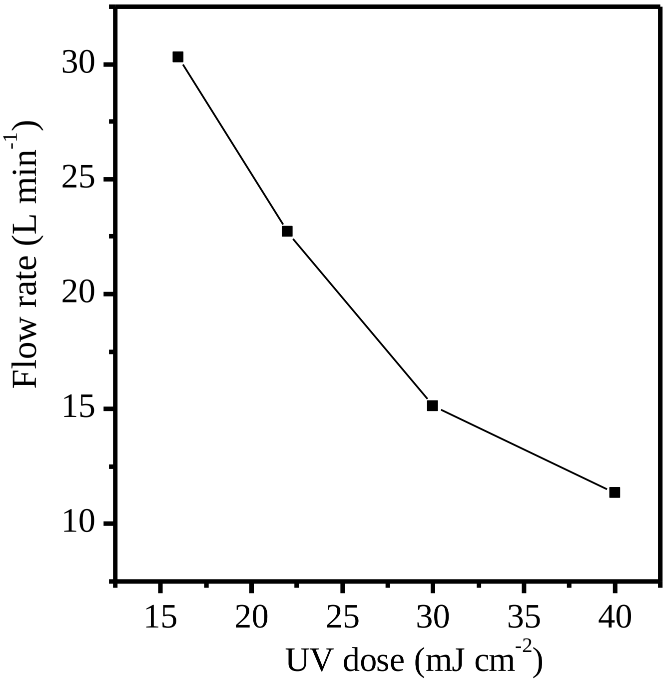


Figure S2: UVC-lamp Polaris™ UV-4C information dose according to the flow rate, adapted from HYDRONIX (2018)

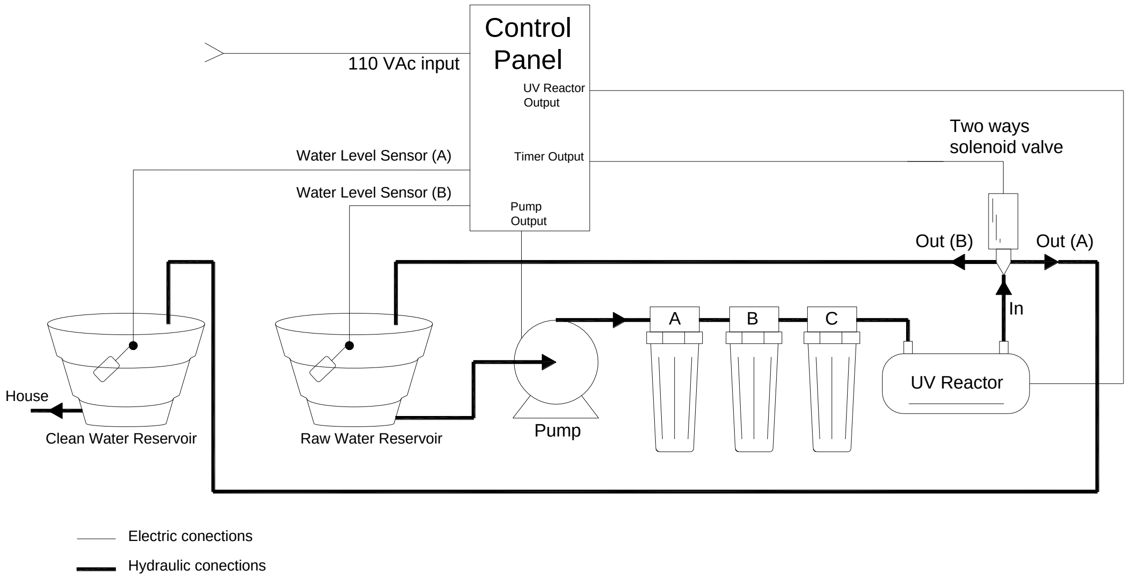
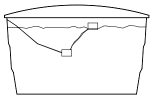


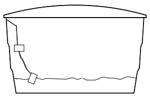
Figure S3 – Block diagram of the electrical control of the Water Treatment Prototype

- 8:00 am: The pump and the UVC-lamp are turned on (manual action).



*ST: highest level

AND



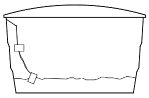
TWT: lowest level

The system is energized, and the pump and the UVC-lamp can be started

- 8:00-8:05 am**: The water flows through the filters, the UVC-lamp, the two-way solenoid valve, and returns to the ST. The UVC-bulb warms up.
- The operator adds chlorine (sodium hypochlorite or calcium hypochlorite) to the manual chlorinator (manual action).

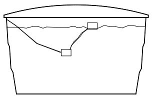
- 8:05 am: A timer sends a signal to the solenoid valve to close the returning way and open the way to the TWT. The water flows through the filters, the UVC-system, the manual chlorinator and to the TWT (automatic action).

- ~8:50 am: The ST goes to the lowest level, and the pump and the UVC-lamp are turn-off (automatic action).



ST: lowest level

OR



TWT: highest level

The system is de-energized, and the pump and the UVC-lamp are turned off

- After 8:50 am: The operator opens the raw water entering gauge and the water decants in the ST until the next operation day.
- The treated water is collected from the TWT, which is then empty.

* ST: Settling Tank; TWT: Treated Water Tank

**During the first 5 minutes of the pump operation, the water passed through the UVC-lamp and returned to the ST in the control of a two-way solenoid valve. This action was performed to remove any air bubble and debris and to allow the warming of the UVC-lamp, as a manufacturer UVC-lamp recommendation.

Figure S4 – Model of the semi-automatic operation protocol for the Water Treatment Prototype.

Figure S5- Steps for the blanket cleaning procedure

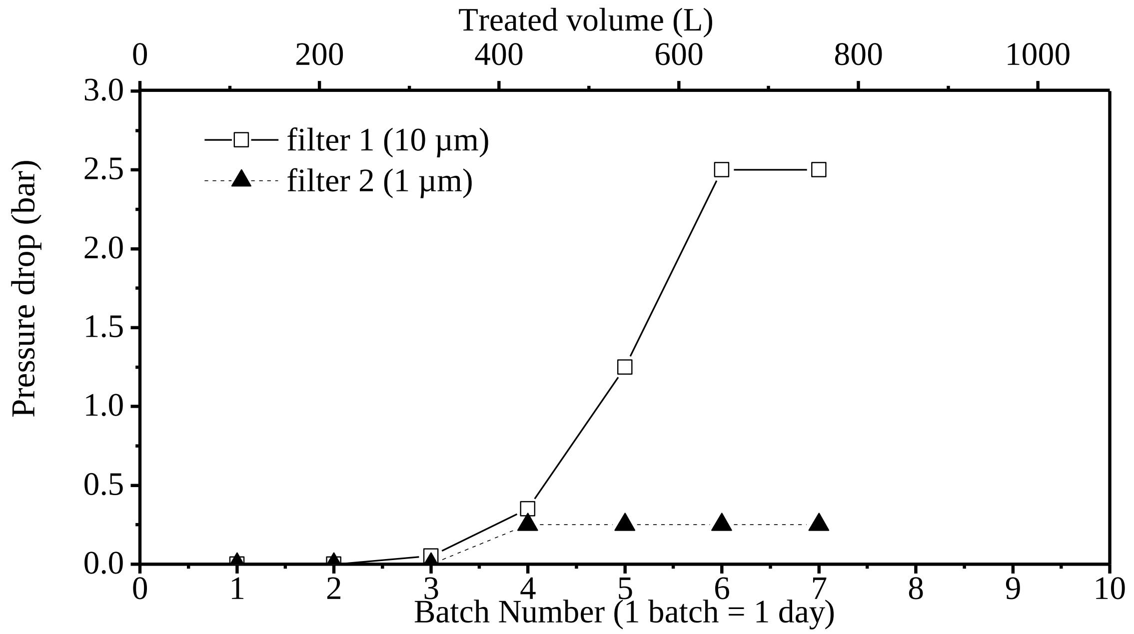


Figure S6 – Pressure drop in filter 1 (10 µm) and filter 2 (10 µm) during Phase 1 operation

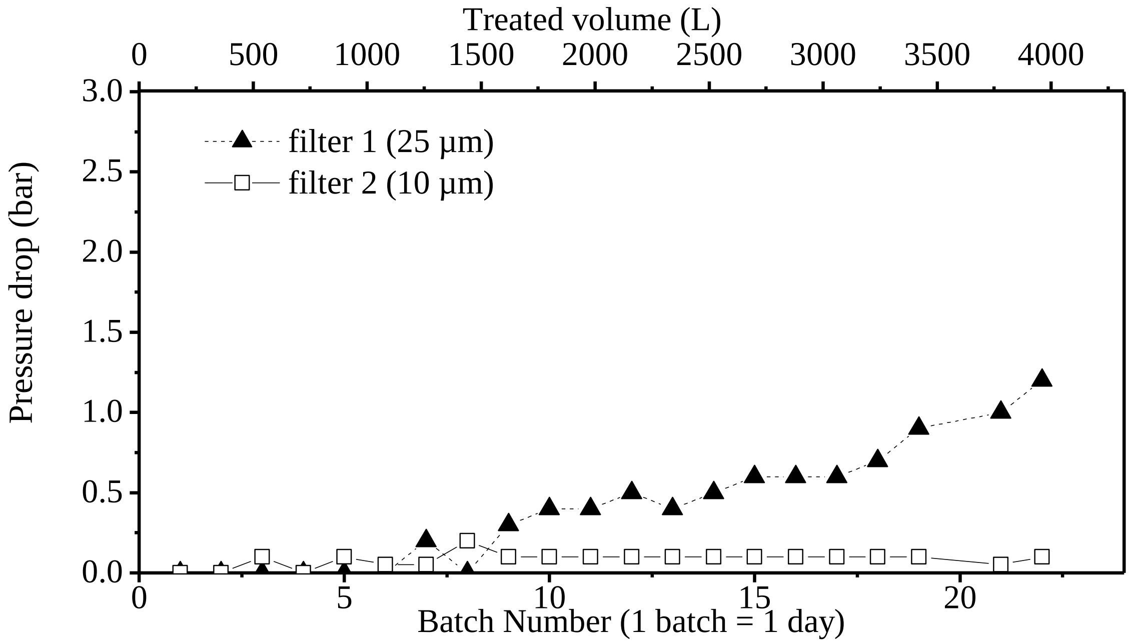


Figure S7 – Pressure drop in filter 1 (25 µm) and filter 2 (10 µm) during Phase 2 operation

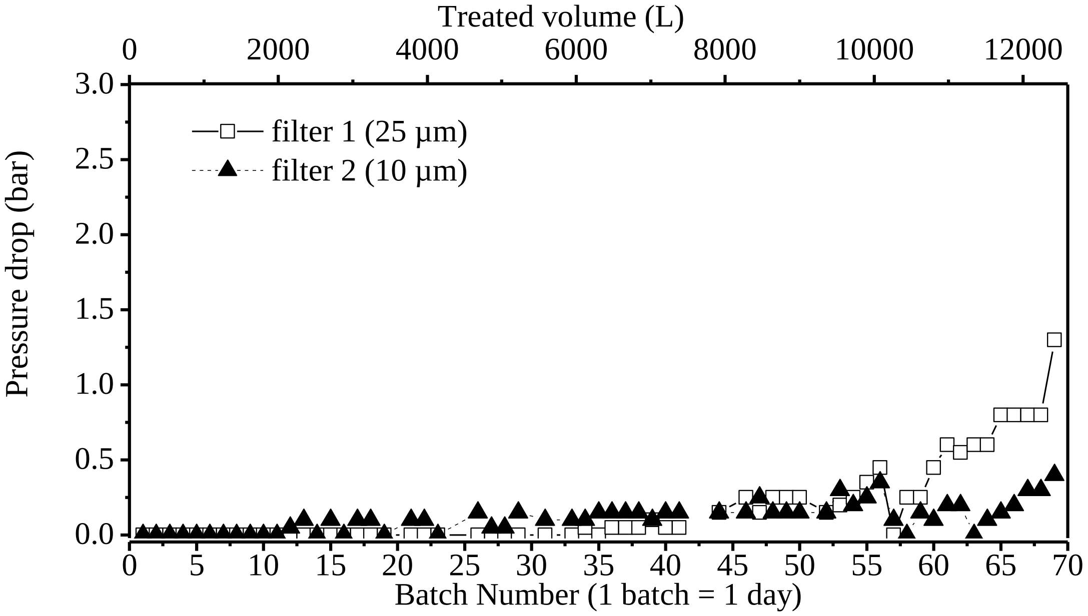


Figure S8 – Pressure drop in filter 1 (25 µm) and filter 2 (10 µm) during Phase 3 operation

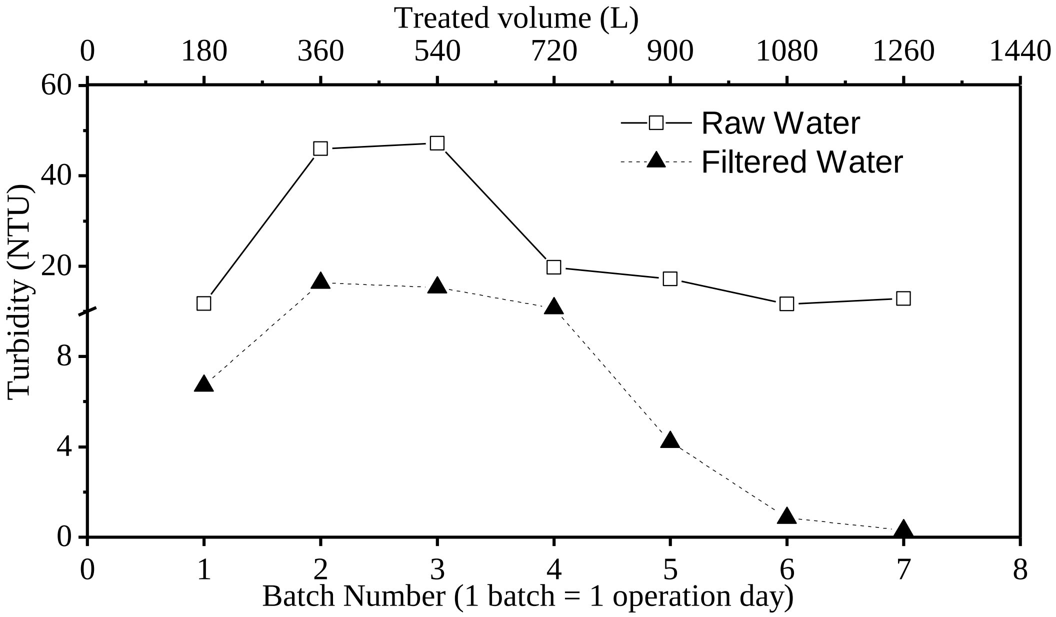


Figure S9 – Turbidity of raw and filtered water during Phase 1 operation

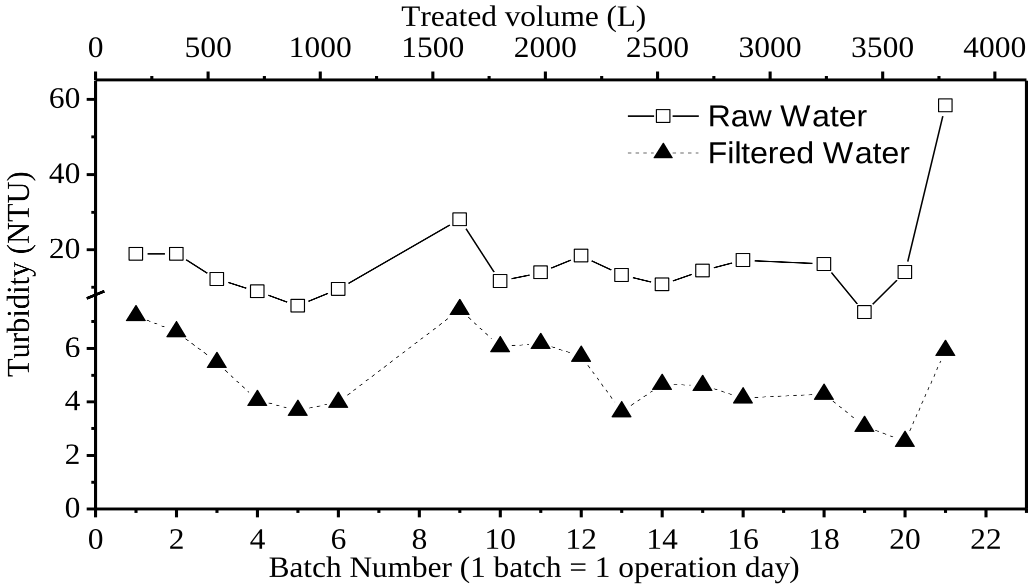


Figure S10 – Turbidity of raw and filtered water during Phase 2 operation

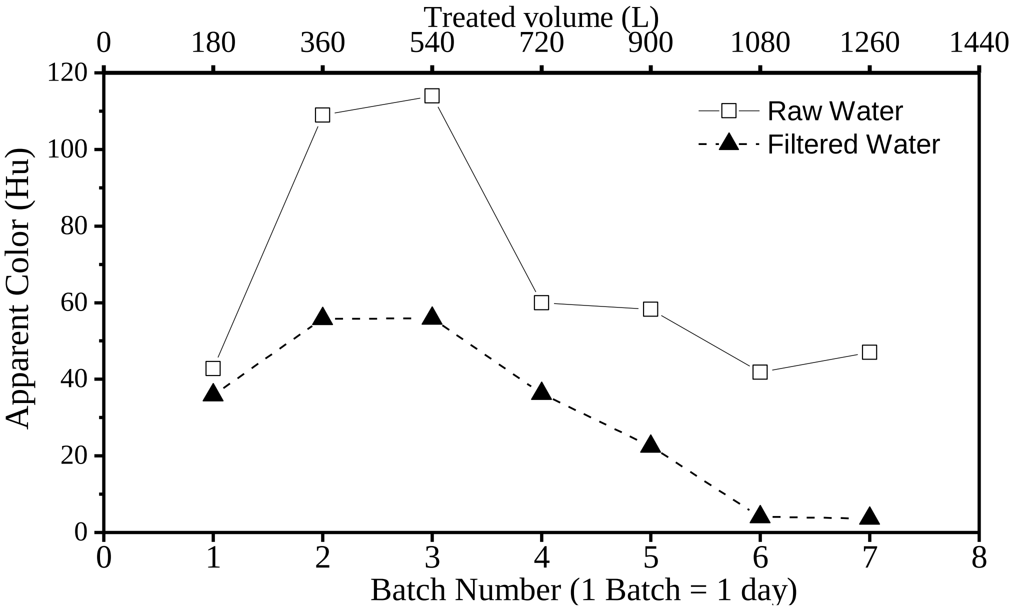


Figure S11 – Apparent colour of raw and filtered Water during Phase 1 operation

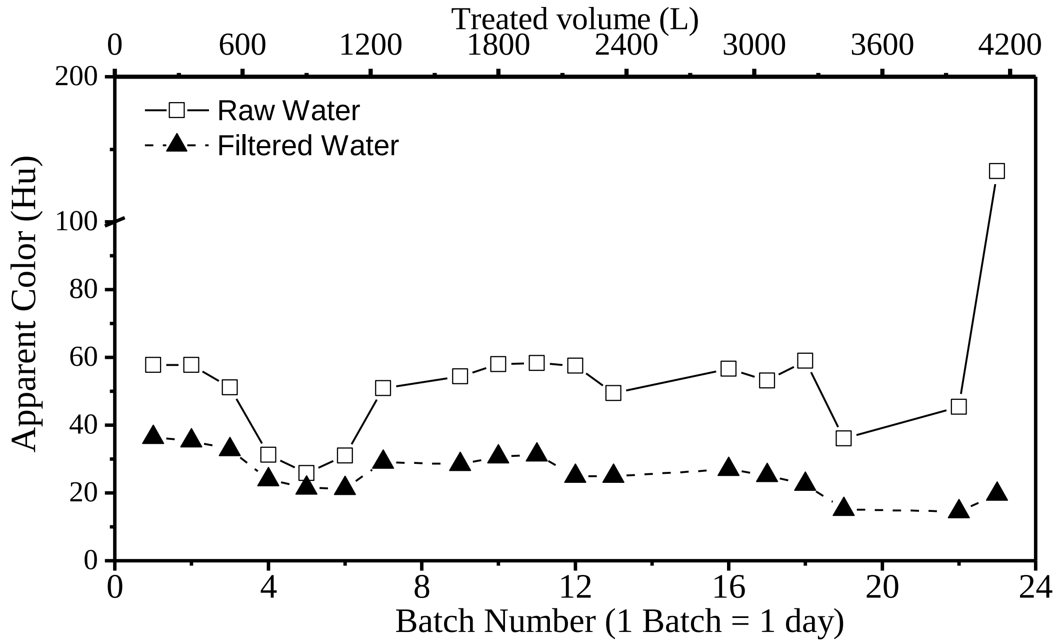


Figure S12 – Apparent colour of raw and treated water during Phase 2 operation

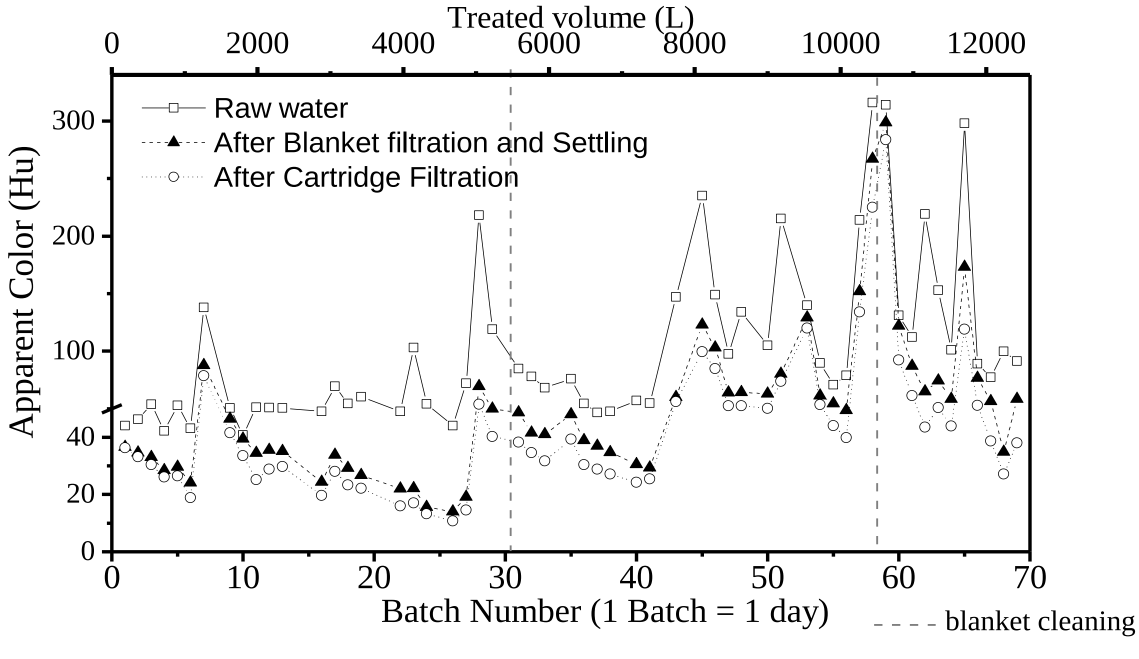


Figure S13 – Apparent colour in raw water, water after blanket filtration and settling, and water after cartridge filtration, during Phase 3 operation

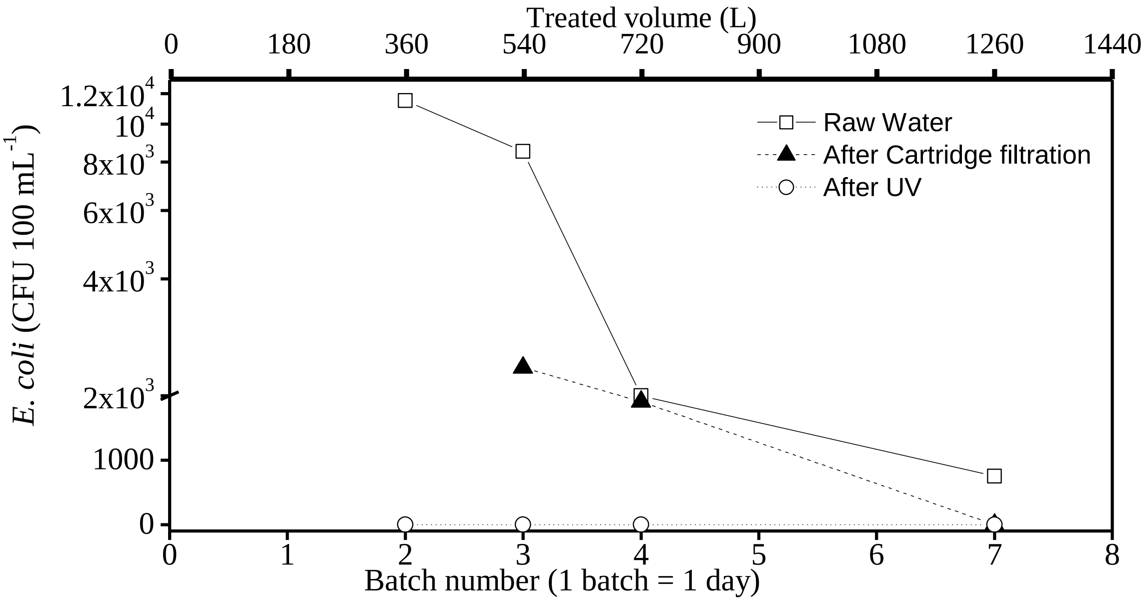


Figure S14 – *Escherichia coli* in raw water, after cartridge filtration, and after UV irradiation during Phase 1 operation

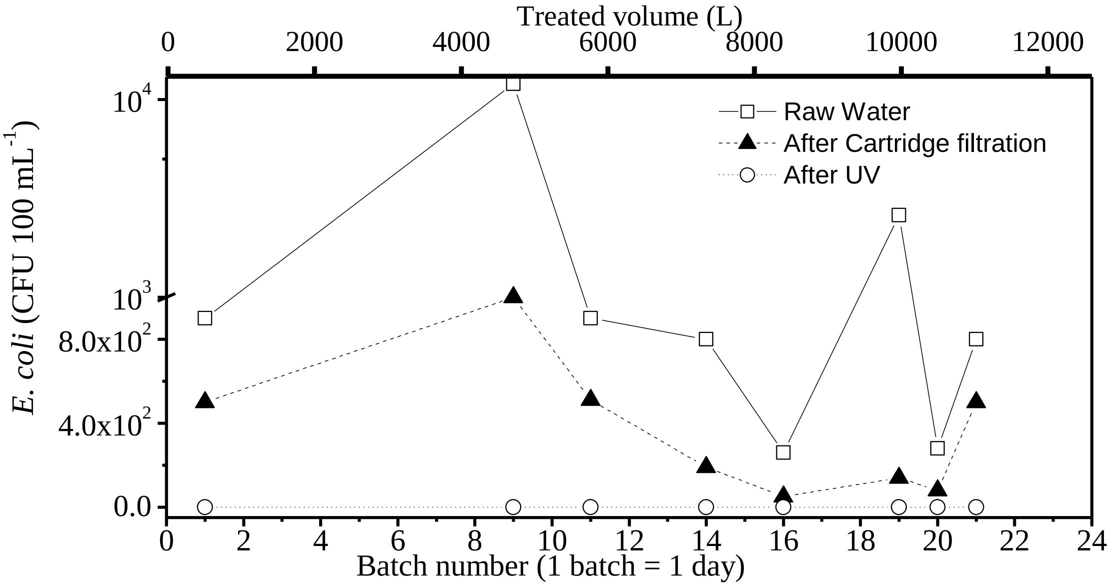


Figure S15 - *Escherichia coli* in raw water, after cartridge filtration, and after UV irradiation during Phase 2 operation

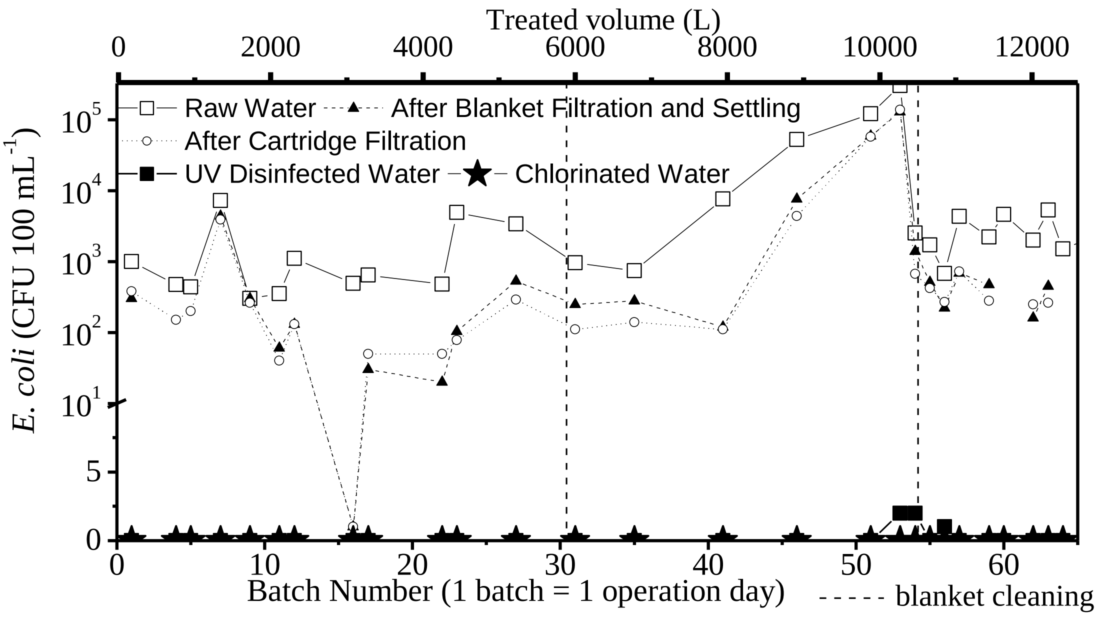


Figure S16- *Escherichia coli* in raw water, after blanket filtration and settling, after cartridge filtration, and after UV irradiation during Phase 3 operation

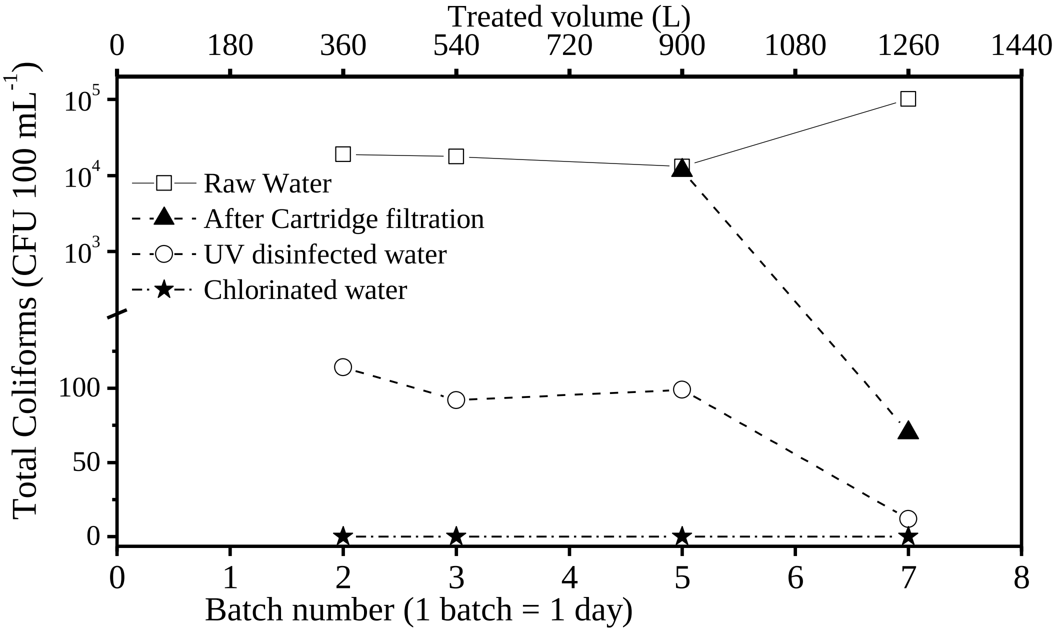


Figure S17 – Total coliforms in raw water, after cartridge filtration, after UV irradiation, and after chlorination, during Phase 1 operation

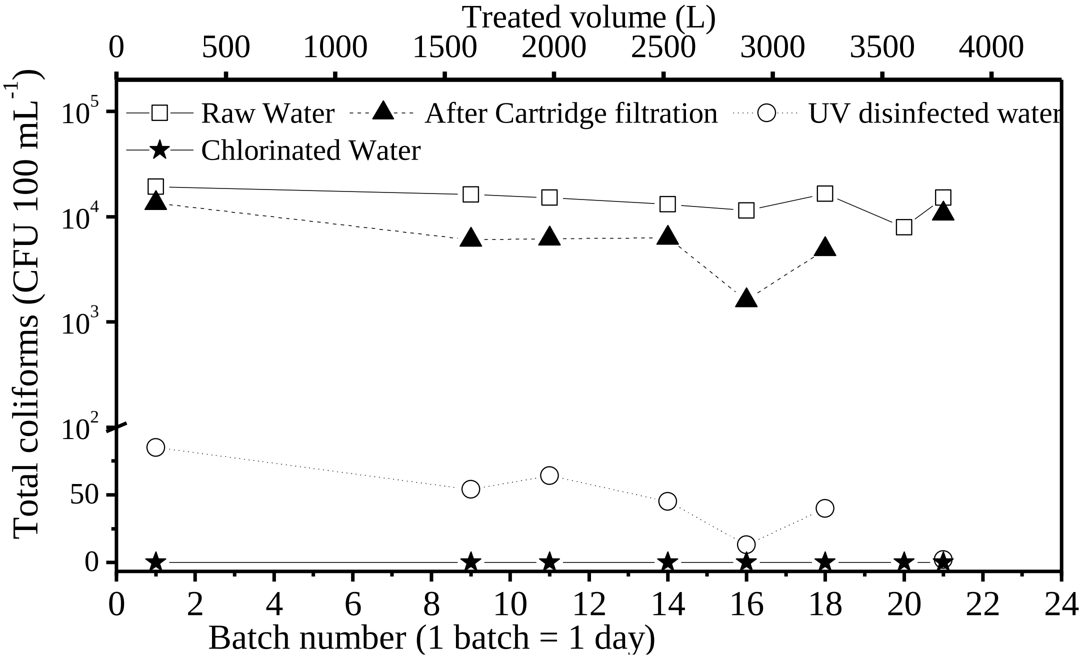


Figure S18 - Total coliforms in raw water, after cartridge filtration, after UV irradiation, and after chlorination during Phase 2 operation

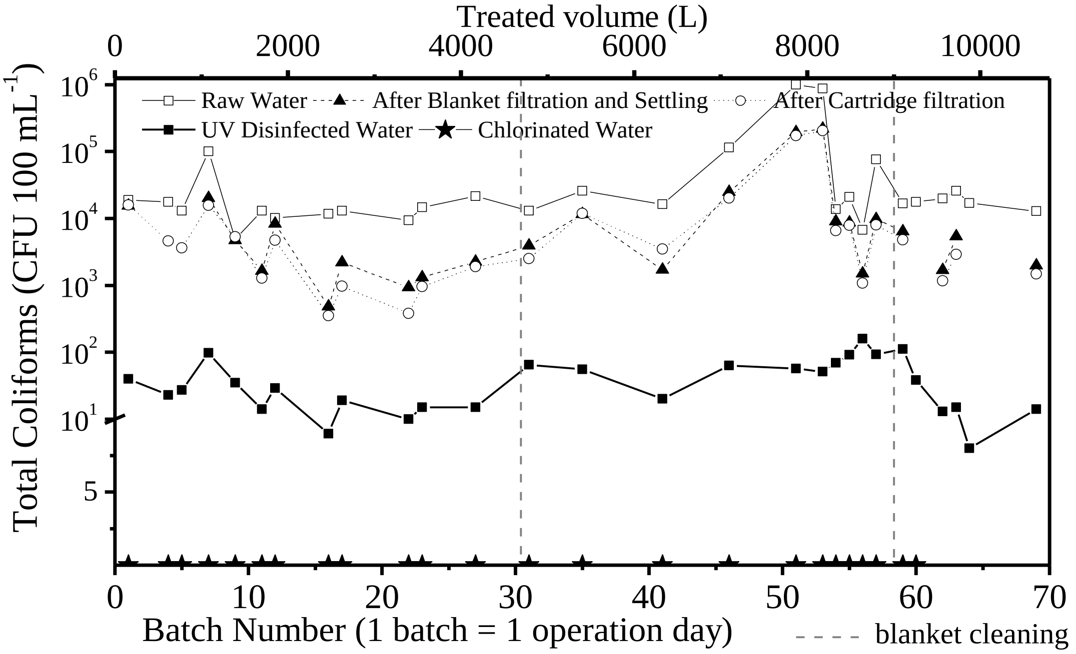


Figure S19 - Total coliforms in raw water, after blanket filtration and settling, after cartridge filtration, after UV irradiation, and after chlorination during Phase 3 operation

References

HYDRONIX, 2018. The Polaris Scientific UV^{TM} System [WWW Document]. URL https://hydronixwater.com/wp-content/uploads/2018/10/PSUV_Catalog.pdf (accessed 5.12.20).