Evaluation of two-stage filtration systems in drinking water treatment

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ABSTRACT

Two parallel pilot plants, PP_1 and PP_2, each consisting of a two-stage filtration system, were evaluated; the first stage of PP_1 consisted of an upflow coarse sand filter while that of PP_2 consisted of an upflow gravel filter. Both pilot plants had a rapid downflow sand filter as a second stage. System pretreatment performance was determined based on the efficiency of filtering surface raw water previously coagulated with aluminium sulphate. Filter run lengths were longer in PP_1 than in PP_2. Coagulant doses were determined and controlled by using a bench-scale sand filter, the dominant mechanism being adsorption-destabilization with partial charge neutralization. Results of turbidity, apparent colour, total iron and manganese concentrations in the final effluent in both pilot plants were shown to meet Brazilian standards. The quality of effluents from both systems showed no variation and thus the two filtration systems were equivalent. Conclusively, both systems were found to be technically feasible processes for water clarification and compare favourably with conventional clarification systems of flocculation, sedimentation and filtration when treating raw water with turbidity lower than 20 NTU and true colour below 50 HU.

Key words | two-stage filtration, upflow direct coarse sand filtration, upflow direct gravel filtration, water treatment

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INTRODUCTION

In developing countries, there is currently a growing demand for alternative technologies for water pretreatment processes to conventional water treatment plants (chemical coagulation, flocculation, sedimentation or flotation and filtration). This is due mainly to the higher construction, operational and maintenance costs of conventional plants, which have been shown to be more appropriate for highly economically developed regions. The upflow sand filtration of chemically coagulated water, highly investigated during the last three decades (Di Bernardo & Isaac 2001), is one such technological alternative. However, factors such as: more restrictive water source quality criteria; variations in water source quality; fluidization of finer grains at the top layer for high filtration rate; rupture of sand bed at some cross-sections due to high headloss caused by solids retention; high consumption of backwash water; and filtered and backwash water exiting the filter from the same side, still limit the application of upflow direct filtration. Earlier research works reported in Di Bernardo *et al*. (2004) were conducted using the upflow filter with gravel or coarse sand as a means of pretreating the water furnished to a downflow rapid filter.

The main objective of this study is to investigate the behaviour of a two-stage filtration system used for turbidity removal. Experimental research work was carried out in two pilot plants in order to compare the performance of an upflow coarse sand filter/rapid sand downflow filter system (UCSF system) with the upflow gravel filter/rapid sand downflow filter system (UGF system).

MATERIALS AND METHODS

Description of pilot plants

This study was carried out at the Sao Carlos School of Engineering (University of Sao Paulo, Brazil) using two parallel pilot plants, PP_1 and PP_2, each of which consisted of a two-stage filtration system. The first stage was an upflow coarse sand filter in the UCFS system and an upflow gravel filter in the UGF system. In both systems the second stage was a rapid downflow sand filter (RSF_1 and RSF_2, respectively).

The UCSF consisted of a 9.1 cm internal diameter and 4.1 m high transparent acrylic column. A perforated acrylic plate was fitted at the inlet of the filter to provide uniform flow distribution. Above this plate a support gravel bed, 0.6 m deep, was placed. The support gravel bed grain sizes ranged from 31.7 to 2.4 mm, arranged in seven layers. Above the support gravel bed a 1.6 m deep sand layer was placed. The sand grain sizes ranged from 1.00 to 2.38 mm, having effective size of 1.2 mm and a uniformity coefficient of 1.5. On the other hand, the UGF was composed of an 80 cm internal diameter and 2.95 m high metallic cylinder. The filter bed consisted of a support layer, 0.45 m deep and gravel grain size ranging from 50.0 to 38.0 mm above which were four 0.30 m high layers of successively decreasing gravel grain sizes: 31.7–19.0 mm (1st layer), 15.9–9.6 mm (2nd layer), 9.6–4.8 mm (3rd layer) and 4.8–2.4 mm (4th layer).

The RSF_1 and RSF_2 were identical, each consisting of a 9.1 cm internal diameter transparent acrylic column, 2.9 m high. The filter bed of either filter consisted of a 0.7 m deep sand layer supported on a perforated acrylic plate and a screen. The grain sizes ranged from 1.41 to 0.42 mm, having an effective size of 0.54 mm and a uniformity coefficient of 1.57.

Piezometers were installed to measure headloss across the filter beds: six in the UCSF, three in the UGF and five in each of the rapid downflow sand filters.

Pilot plant experiments

Surface water was continuously abstracted from a raw water pipeline of the Municipal Water Supply Service and pumped to a splitting box (SB) assembled above the upflow filters. The flow to be filtered was selected by the size of the orifices delivering flow to each system. The orifices were operated under a constant head created by an overflow weir, which delivered excess flow to waste. Flow from the splitting box to each pilot plant was collected in funnels (F_1 and F_2) and carried by hoses to the first-stage filters (Figure 1).

To evaluate system performance a series of ten experiments, organized in two groups (see Tables 1, 2, 3 and 4): Group A (experiments A1 to A5) and Group B (experiments B1 to B5), characterized respectively by raw water turbidities ranging from 12 to 19 NTU and 8 to 12 NTU were carried out. Each experiment consisted of filtration runs carried out in plants PP_1 and PP_2.

The main objective of the experimental study was to evaluate and compare the performance of the filters operating at filtration rates ranging: from 8.33 to 15 m h^{-1} (UCSF); from 5 to 20 m h^{-1} (RSF_1); from 3.33 to 7.9 m h^{-1} (UGF); and from 5 to 10 m h^{-1} (RSF_2). Due to difficulties controlling the flow rates to each filter, the measured filtration rates were different from the target filtration rates (Table 1).

In all the experiments (except B2, B4 and B5), the filter runs of the first stage and of the second stage filtration units ended simultaneously. In pilot plant PP_1, runs were finished when the maximum terminal available headloss to the UCSF was reached; and in pilot plant PP_2 they were finished when the maximum terminal available headloss to the RSF_2 was reached. Experiment B5 was carried out to evaluate the performance of pilot plant PP_1 when RSF_1 was maintained in operation until its maximum terminal headloss available was reached. Experiments B2 and B4 were carried out to evaluate the performance of UGF during long filtration periods. With this purpose in mind, this latter filter was maintained in operation even after the end of the filter runs of RSF_2. Experiment B4 had the additional objective of evaluating the performance of RSF_2 in two consecutive filter runs while receiving the effluent of UGF uninterruptedly and without intermediate down flushes.

Performance of both pilot plants was evaluated based on their filtering efficiency of surface raw water with turbidity, true and apparent colour values of less than 20 NTU, 50 HU and 175 HU, respectively. In this evaluation the following parameters were measured or

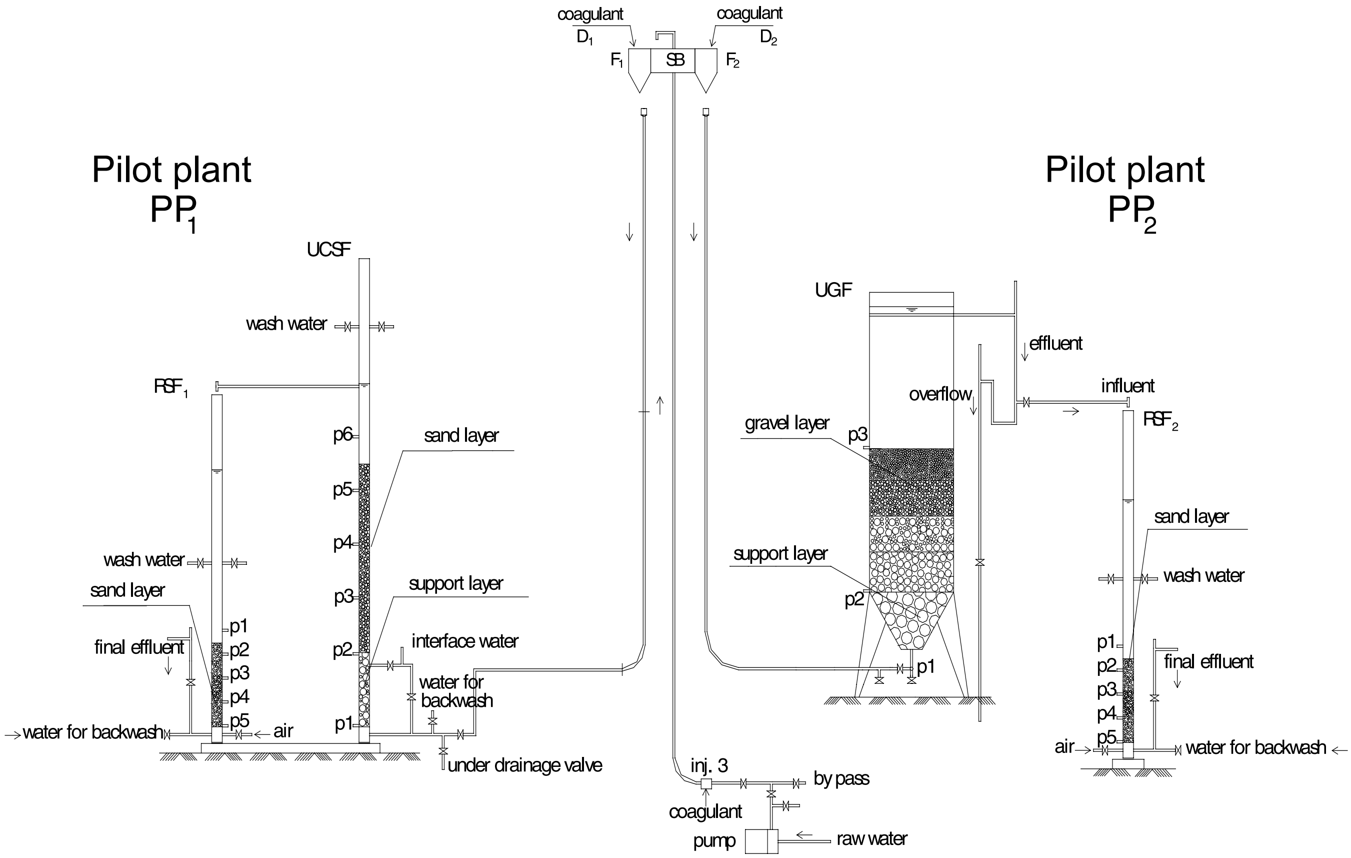

Figure 1 | Schematic of pilot plants PP_1 and PP_2.

controlled: filtration rate, headloss, turbidity, particle counts in the range of 2 to 48 μm (Hiac/Royco Counter, model 8000A), apparent and true colour, total iron and manganese, total coliforms, *E. coli*, total organic carbon, temperature, pH, alkalinity and zeta potential (Zetamaster Malvern Instruments Ltd). Water quality parameters were analysed by employing techniques described in the *Standard Methods for the Examination of Water and Wastewater* (1995). Besides the final effluent quality, performance of both systems was characterized by measuring water consumption and operation time required for cleaning of the filters.

Coagulation

The alum coagulant stock solution was prepared daily by dissolving 4 g (0.5 g in experiments A1 and A2) of iron-free commercial alum solution (≈620 g l^{-1} of $Al_2(SO_4)_3 \times 14.3\ H_2O$) in 1 litre of deep well water. In all experiments the coagulant was added by means of a diaphragm-type metering pump. In experiments A1 and A2 the coagulant was pumped to two identical devices (D_1 and D_2) assembled above funnels F_1 and F_2, respectively. Each device consisted of a 0.12 m high and 38 mm internal diameter PVC tube. The coagulant was fed through the upper side of the device, and allowed to drop at constant rate through an orifice perforated at its bottom.

To intensify the mixture of the coagulant with the raw water, D_1 and D_2 were positioned in such a way that the dripping occurred in the region of higher turbulence in the funnels F_1 and F_2. From experiment A3 onwards these devices were replaced by an in-line central jet injection blender (Inj.3) installed in the outlet tube of the raw water pump (Figure 1).

Table 1 | Filtration rates in experiments of groups A and B: pilot plants PP_1 and PP_2

		Filtration rates in PP_1 ($m\ h^{-1}$)				Filtration rates in PP_2 ($m\ h^{-1}$)			
		UCSF		RSF_1		UGF		RSF_2	
Group	Experiment	Target	Measured	Target	Measured	Target	Measured	Target	Measured
A	A1	15	14.9 to 15.5	10	9.9 to 10.4	3.33	3.4 to 3.5	10	10.4 to 10.7
	A2	15	14.8 to 15.6	10	9.8 to 10.6	3.33	3.3 to 3.5	10	10.1 to 10.5
	A3	—	—	—	—	4.6	4.5 to 4.7	10	10.1 to 10.4
	A4	—	—	—	—	4.6	4.5 to 4.7	10	10.4 to 10.7
	A5	15	14.2 to 14.4	10	9.8 to 10.4	7.9	7.8 to 7.9	10	9.9 to 10.1
B	B1	—	—	—	—	7.9	7.8 to 7.9	10	10.2 to 10.4
	B2	15	14.2 to 14.5	7.5	7.9 to 8.1	7.9	7.8 to 7.9	7.5	7.4 to 7.5
	B3	—	—	—	—	7.9	7.8 to 7.9	7.5	7.3 to 7.6
	B4	8.3	8.2 to 8.4	12.5	12.6 to 12.8	7.9	7.8 to 7.9	5.0	4.8 to 5.0
	B5	15	14.6 to 14.9	20	19.7 to 20.4	—	—	—	—

During the experiments the coagulant doses were determined by the use of a bench-scale filter consisting of a 19 mm internal diameter PVC tube, 0.25 m in height. Inside the tube there was a fine sand layer (grain sizes 0.30–0.42 mm), 0.15 m deep, supported directly on a metallic screen. This filter was fed directly with coagulated water from the pilot plants. The average filtration rate was 2.5 $m\ h^{-1}$ (5 $m\ h^{-1}$ in experiments A1 and A2). Coagulant doses were considered appropriate when the bench-scale filter effluent turbidity, after 30 min of filtration, had become equal to or less than 1 NTU. This method for determining the coagulant doses differs however from that employed in other upflow sand or gravel filtration experiments mentioned in the literature; here the selection of the coagulant doses was based on the effluent turbidities of the pilot plants (Ahsan 1995; Ingalinella *et al*. 1998).

Filter cleaning procedures

At the end of each experiment, filters were cleaned. The UCSF was cleaned by injecting treated water for 10 min at an upflow velocity of 100 $m\ h^{-1}$, to provide an expansion of approximately 30% in the sand bed.

Cleaning of the UGF was performed by downward flushes. The filter box was filled with raw water and drained by quickly opening the underdrainage valve. The downward drainage velocity reached 34 to 41 $m\ h^{-1}$, less than those suggested (60 to 90 $m\ h^{-1}$) by Wegelin (1996). This procedure was repeated 3 to 5 times (treated water being used in the last cycle) until clear washwater was obtained. At the end of each flush, the water level was kept 10 to 20 cm above the gravel bed surface thus preventing the penetration of air and formation of bubbles inside the filter bed. Rapid downflow sand filters were cleaned by air-scour alone (for 5 min) followed by backwashing for 10 min at an upflow velocity of 43 $m\ h^{-1}$ in order to produce an expansion of approximately 30% in the sand bed.

Intermediate down flush

Five intermediate down flushes (IDFs) were carried out during each filter run to increase run lengths of the UCSF

Table 2 | Coagulant doses, pH and zeta potential in experiments of groups A and B

		Doses		pH		Zeta potential (mV)	
Group	Experiment	(mg l^{-1})*	(mg l^{-1})**	Raw water	Coag. water	Raw water	Coag. water
A	A1	5.4 to 7.1	11.5 to 15.1	6.84 to 7.36	6.63 to 7.03	−17.5 to −18.0	−8.0 to −13.9
	A2	4.6 to 6.9	9.8 to 14.6	6.86 to 7.01	6.59 to 6.84	−18.2	−4.7 to −13.0
	A3	3.9 to 4.3	8.3 to 9.0	6.74 to 6.91	6.44 to 6.81	−18.3 to −18.9	−11.7 to −14.9
	A4	4.1	8.6	6.73 to 6.88	6.55 to 6.65	−19.6 to −23.2	−9.7 to −13.3
	A5	4.2 to 5.1	9.0 to 10.7	6.58 to 6.84	6.32 to 6.55	−20.8	+7.7
B	B1	3.7 to 4.0	7.9 to 8.5	6.76 to 6.88	6.59 to 6.75	−14.9 to −16.6	+0.5 to +4.4
	B2	3.3	7.0	6.79	6.64	−22.3 to −16.1	−3.8 to −4.7
	B3	3.3	7.0	6.65 to 6.76	6.54 to 6.66	−16.0 to −17.1	−0.3 to −0.4
	B4	3.3 to 3.9	7.0 to 8.3	6.66 to 7.03	6.39 to 6.87	−19.7 to −18.7	−1.3 to −8.3
	B5	4.2 to 4.7	9.5 to10.7	6.96 to 7.09	6.47 to 6.82	−19.2 to −20.7	−5.7 to −9.5

*mg l^{-1} of $Al_2(SO_4)_3 \times 14.3H_2O$; **mg l^{-1} of commercial alum solution.

(seven IDFs in experiment B2). Each IDF lasted around 30 seconds, leading to an average drainage velocity of 34 m h^{-1}. During this period, treated water was simultaneously injected at the interface between gravel and coarse sand layers of the UCSF to avoid the formation of any vacuum in this region (Di Bernardo & Fernandes 1987). To reduce the UGF effluent turbidity and consequently increase the length of RSF_2 filter runs, IDFs were carried out in the UGF during experiments A2, A4, A5 and B3. These IDFs lasted approximately 50 seconds, leading to drainage velocities ranging from 34 to 41 m h^{-1}.

RESULTS AND DISCUSSION

Coagulation

In the experiments of Group A, the coagulant doses ranged from 3.9 to 7.1 mg l^{-1} of $Al_2(SO_4)_3 \times 14.3H_2O$, resulting in coagulated water pH values of 6.3 to 7.0 and coagulated water zeta potential values of −14.9 to −4.7 mV, except in experiment A5 in which the zeta potential (Table 2) was positive. In the experiments of Group B, coagulant doses were found to be lower, ranging from 3.3 to 4.7 mg l^{-1} of $Al_2(SO_4)_3 \times 14.3H_2O$, associated with coagulated water pH values of 6.4 to 6.9 and coagulated water zeta potential values between −9.5 and −0.3 mV, except in experiment B1 (+0.5 to +4.4 mV). Due to the low total alkalinity presented by raw water during the experiments (between 10 and 15 mg l^{-1} as $CaCO_3$), no additional chemicals were required to adjust the coagulation pH. Water temperature varied from 19 to 26°C during the experimental work.

The coagulant doses did not cause charge neutralization to zero zeta potential; this fact may be attributed to the criteria adopted in selecting the coagulant dose (bench-scale filter effluent turbidity ≤1 NTU, after 30 min of filtration). These results suggest, therefore, that adsorption-destabilization with partial charge neutralization was the dominant coagulation mechanism. This mechanism is considered ideal for direct filtration of

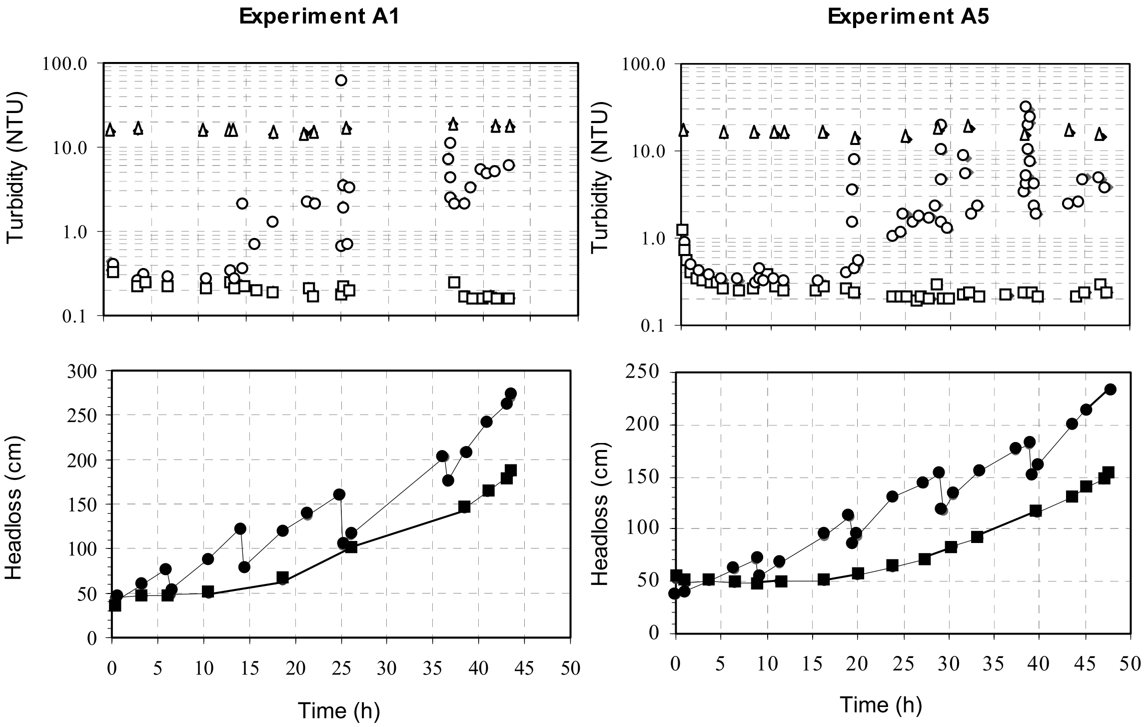

Figure 2 | Turbidity of raw water (△), UCSF effluent (○) and RSF$_1$ effluent (□) and headloss in granular media of UCSF (●) and of RSF$_1$ (■) in experiments A1 and A5.

chemically coagulated water (Amirtharajah & Mills 1982; American Water Works Association 1999).

Effluent quality

Turbidity, particle counts and colour in UCSF and UGF supernatants

About 10 to 16 h after the beginning of the UCSF operation in experiments A1, A2 and A5 of Group A, an increasing concentration of small flocs was observed, for experiments A1 and A5, in the supernatant of the UCSF as can be observed in Figure 2. This was probably due to the advance of a clogging front towards the top of the UCSF granular media. A continuous and intense deterioration of the UCSF supernatant quality could also be seen associated with this phenomenon. The UCSF supernatant turbidity increased from 0.28 to 6.0 NTU (A1), 0.31 to 3.6 NTU (A2), and 0.30 to 5 NTU (A5) while the apparent colour increased from 1 to 45 HU (A1), 1 to 7 HU (A2), and to 15 HU (A5). Moreover, the total number of particles (2–48 μm) increased from 316 ml^{-1} to 3,966 ml^{-1} (A1) and 63 ml^{-1} to 310 ml^{-1} (A5).

In experiments A1, A2 and A5, despite the simultaneous injection of treated water in the gravel/sand interface region, a large amount of flocs was visible in the supernatant of the UCSF right after the end of each IDF. This caused turbidity peaks in the UCSF supernatant, as pointed out in Di Bernardo & Isaac (2001), reaching high values (62 NTU) mainly after the second, third and fourth IDFs (Figure 2). This phenomenon must have been caused by the strong water jets inside the granular media due to inadequate operation (quick opening) of the valve installed in the pipe that feeds the gravel/sand interface.

During experiments B2, B4 and B5 of Group B, neither the presence of flocs in the supernatant of the UCSF nor the degradation of effluent quality was observed (Figure 3). In these experiments the removal of 2 to 48 μm particles by the UCSF was high (96.4 to 99.7%) and, as can

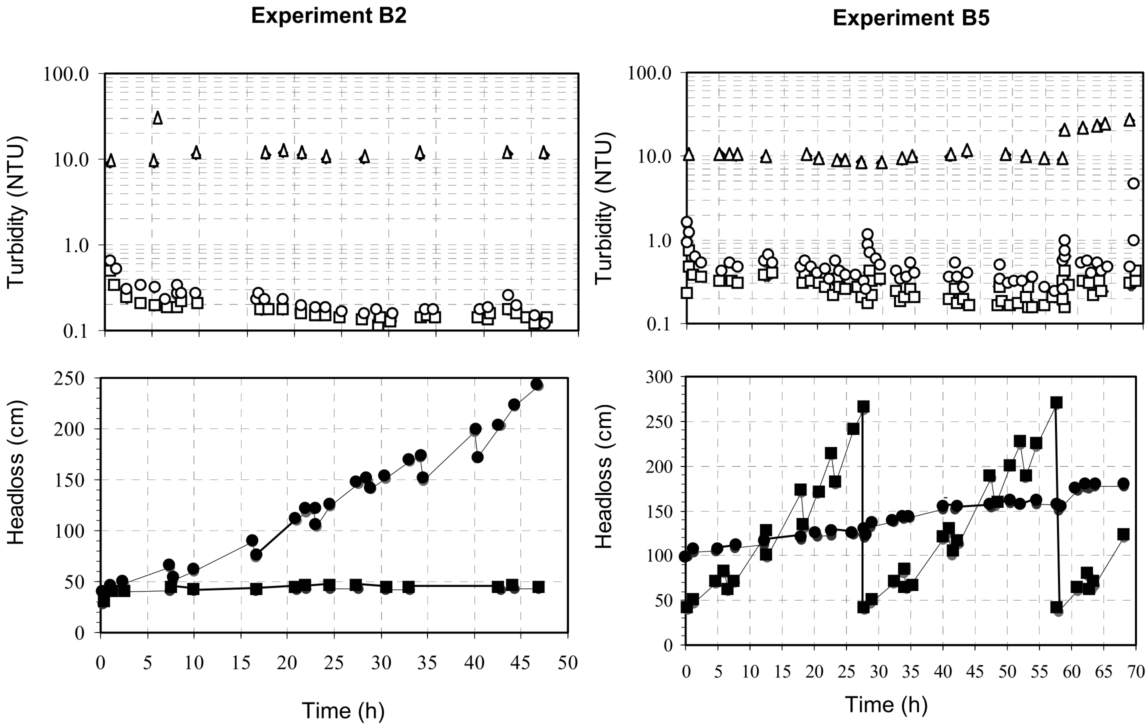

Figure 3 | Turbidity of raw water (△), UCSF effluent (○) and RSF_1 effluent (□) and headloss in granular media of UCSF (●) and of RSF_1 (■) in experiments B2 and B5.

be observed in Figure 3, its supernatant presented low values of turbidity (1.5 to 0.12 NTU), apparent colour (<5 HU) and true colour (<2 HU), meeting the requirements of Brazilian standards (Brazilian Health Ministry 2000). Since the filtration rates were the same in experiments A1, A2 and A5 of Group A and B2 and B5 of Group B, the better quality of raw water obtained in Group A experiments seemed to be the most important and determining factor for the good performance of the UCSF. In experiments B2, B4 and B5 high turbidity peaks right after each IDF in the UCSF were not observed in its supernatant. Besides the better quality of the raw water, a proper operation (slow opening) of the valve installed in the gravel/sand interface feed piping appears to have contributed to this.

On the other hand, the UGF supernatant presented a consistently poorer quality than that of the UCSF effluent, even in experiments A1, A2 and A5, in which a continuous and intense deterioration was observed in UCSF supernatant quality.

In experiments A1, A3, B1, B2 and B4 (without IDFs), UGF removal of 2–48 μm particles varied from 14 to 92% and its supernatant presented high turbidity (1.6 to 7.3 NTU) and apparent colour (15 and 55 HU) values; the true colour was, however, equal to or less than 3 HU. In these experiments the quality of the supernatant began to deteriorate after approximately 12 h of UGF operation as can be observed in Figure 4 for experiment B4 where the UGF supernatant turbidity, apparent and true colour attained values of about 7 NTU, 55 HU and 3 HU, respectively.

IDFs performed in experiments A2, A4, A5 and B3 seemed to have reduced the deterioration in quality of UGF supernatant. This is confirmed by the values of removal of 2–48 μm particles in the UGF which varied between 65 and 90% and the supernatant which presented turbidity ranging from 2.1 to 5.8 NTU, apparent colour between 15 and 30 HU and true colour equal to 1 HU. Nevertheless, turbidity peaks (up to 5 NTU) right after IDF were observed (Figure 5).

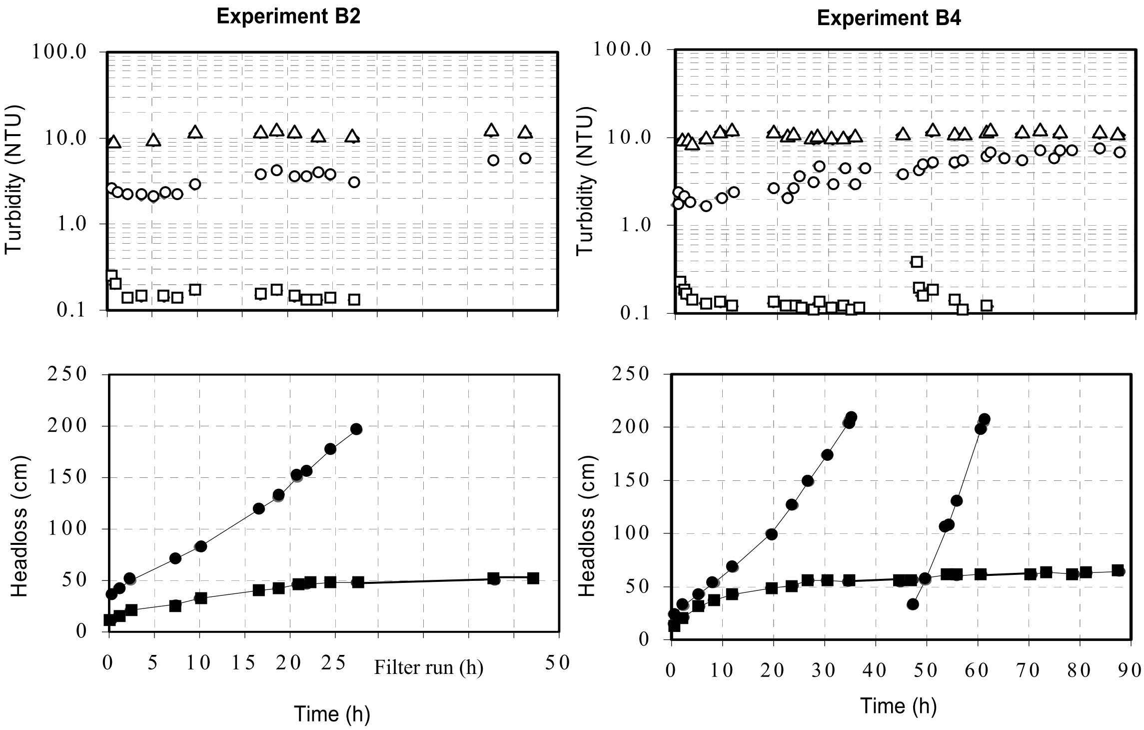

Figure 4 | Turbidity of raw water (△), UGF effluent (○) and RSF_2 effluent (□) and headloss in granular media of UGF (●) and of RSF_2 (■) in experiments B2 and B4.

A large amount of flocs in UGF supernatant after 20 h of operation at filtration rates of 3.33 to 4.58 m h^{-1} without IDFs (experiments A1 and A3) was also observed. However, no presence of flocs was observed in the UGF supernatant when operating at the same filtration rate range of 3.33 to 4.58 m h^{-1} with IDFs (experiments A2 and A4). When operating at higher filtration rates (≈7.8 m h^{-1}) with IDFs (experiments A2 and A4) or without IDFs (experiments A1 and A3), the presence of these flocs in UGF supernatant was observed after approximately 1.5 h of operation. These facts suggest that, when operating at approximately 7.8 m h^{-1}, the UGF acts mainly as a gravel bed flocculator.

Removal of total coliforms, *E. coli*, total iron and manganese in UCSF and UGF

The results obtained indicate that the removal of total coliforms (≥85.3% removal) and *E. coli* (≥76.7% removal) in the UCSF seemed to be lower than in the UGF (≥90% removal for both cases). As regards the total iron removal, the UCSF proved be more efficient than the UGF. This is confirmed by the reduced raw water values (0.6 to 1.7 mg l^{-1}), which, in most cases, were reduced to values under 0.005 mg l^{-1} in the UCSF supernatant (>99% removal) and between 0.05 and 0.45 mg l^{-1} in the UGF supernatant (47 to 96% removal). Total iron removal in the UGF was however higher in experiments with IDFs. Total manganese removal showed an efficiency of about 50% in UGF and values ranging from 33% to more than 85% in UCSF.

Quality of pilot plant (PP_1 and PP_2) effluents

Despite fluctuations in quality of the RSF_1 influent, the final effluent quality from PP_1 remained practically nearly the same in experiments A1, A2 and A5 of Group A. In these experiments the RSF_1 removal of 2–48 μm particles varied between 21 and 98%; its effluent turbidity remained between 1.2 and 0.1 NTU and its

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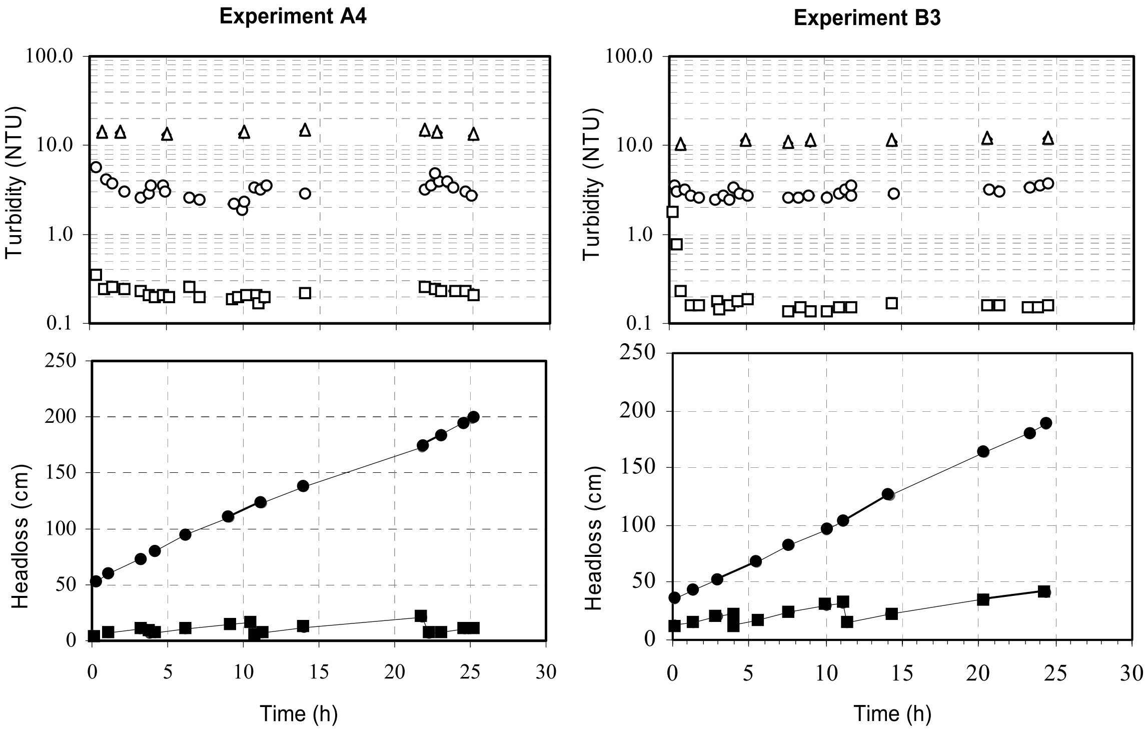

Figure 5 | Turbidity of raw water (△), UGF effluent (○) and RSF_2 effluent (□) and headloss in granular media of UGF (●) and of RSF_2 (■) in experiments A4 and B3.

apparent and true colours were less than 2 HU throughout the runs (Figure 2 and Table 3). Here RSF_1 played an important role in the performance of pilot plant PP_1, ensuring the quality of the final effluent according to Brazilian standards.

In experiments B2, B4 and B5 of Group B, RSF_1 also showed good effluent quality, which was nearly the same as that of UCSF (Table 4 and Figure 3). In fact, with the exception of the values of apparent colour which were higher in the UCSF effluent, there were no significant differences between the supernatant of UCSF and the effluent of RSF_1 as regards turbidity, particle counts (in the 2 to 48-μm range), true colour, total coliforms, *E. coli*, total iron and total manganese values. A close look at these values indicates that, for the above-mentioned experiments, the second-stage filtration unit (RSF_1) was not actually necessary in pilot plant PP_1. This is backed by the fact that the first-stage filtration unit (UCSF) supernatant quality met the Brazilian standards (Brazilian Health Ministry 2000). Not withstanding, the down flow filter is always highly recommended.

Regarding pilot plant PP_2, in all experiments water quality improved significantly after the rapid down flow sand filtration in RSF_2. In fact, the quality of RSF_2 effluent was equal to or significantly better than the quality of UGF supernatant with respect to turbidity, particle counts (in the 2 to 48-μm range), colour, total coliforms, *E. coli*, total iron and total manganese (Tables 3 and 4 and Figures 4 and 5). This proves the second-stage filtration unit to be necessary in pilot plant PP_2 for the same final effluent quality to be met according to Brazilian standards.

For total organic carbon (TOC) removal, the obtained data were erratic throughout the whole experimental study. TOC removal efficiency showed a wide variation: from 1 to 77% (UCSF), 2 to 82% (UGF), and 9 to 39% (RSF_1 and RSF_2), and in some cases, TOC concentration in filter effluents exceeded that of the influents.

Table 3 | Quality of raw water and filter effluents in pilot plants PP_1 and PP_2: experiments A1–A5 (group A)

		PP_1		PP_2	
Parameters	**Raw water**	**UCSF supernatant**	**RSF_1 effluent**	**UGF supernatant**	**RSF_2 effluent**
Turbidity (NTU)	11.8 to 18.7	0.27 to 6.0	0.16 to 1.2	1.6 to 6.4	0.18 to 0.56
Particles ($\#ml^{-1}$)	5,400 to 13,000	50 to 4,000	45 to 200	800 to 7,500	50 to 850
Apparent colour (HU)	110 to 175	1 to 45	≤2	15 to 40	≤1
True colour (HU)	30 to 45	≤1	≤1	≤2	≤1
Total iron ($mg\ l^{-1}$ Fe)	0.90 to 1.66	< 0.005 to 0.16	< 0.005 to 0.07	0.05 to 0.26	< 0.005 to 0.04
Total manganese ($mg\ l^{-1}$ Mn)	< 0.003 to 0.04	< 0.003 to 0.04	< 0.003 to 0.03	< 0.003 to 0.04	< 0.003 to 0.01
TOC ($mg\ l^{-1}$)	2.6 to 7.8	4.6 to 9.0	3.9 to 9.6	2.6 to 7.3	1.6 to 9.4
Total coliforms per 100 ml	10.0 to 8,164.0	< 1 to 1203.3	< 1 to 47.4	< 1 to 4.1	≤1.0
E. coli per 100 ml	10.0 to 1,012.0	< 1 to 235.9	< 1 to 2	< 1	< 1

Table 4 | Quality of raw water and filter effluents in pilot plants PP_1 and PP_2: experiments B1–B5 (group B)

		PP_1 effluents		PP_2 effluents	
Parameters	**Raw water**	**UCSF supernatant**	**RSF_1 effluent**	**UGF supernatant**	**RSF_2 effluent**
Turbidity (NTU)	8.4 to 11.9	0.12 to 1.5	0.11 to 0.78	1.7 to 7.2	0.11 to 1.8
Particles ($\#ml^{-1}$)	9,900 to 15,000	30 to 360	30 to 250	1,230 to 7,300	35 to 200
Apparent colour (HU)	50 to 95	≤5	≤2	15 to 40	≤1
True colour (HU)	9 to 35	≤2	≤1	≤3	≤1
Total iron ($mg\ l^{-1}$ Fe)	0.60 to 1.34	< 0.005	< 0.005 and 0.12	0.25 to 0.45	< 0.005 to 0.08
Total manganese ($mg\ l^{-1}$ Mn)	< 0.003 to 0.09	< 0.003 to 0.06	< 0.003 to 0.06	< 0.003 to 0.01	< 0.003 to 0.01
TOC ($mg\ l^{-1}$)	1.4 to 12.5	2.6 to 3.0	2.2 to 11.6	2.2 to 5.4	1.5 to 12.3
Total coliforms per 100 ml	2,723.0 to 19,862.8	39.3 to 364.5	56.5 to 185.0	131.3 to 78.2	8.6 to 68.9
E. coli per 100 ml	191.1 to 1,258.0	1 to 26.2	3.1 to 19.9	18.7 to 34.1	≤1.0

Headloss and filter run times

A comparative analysis of the two systems shows that, in all experiments, the headloss in granular media (corrected to 20°C by using Fair-Hatch's equation) was higher in the UCSF (2.3 to 2.7 m) than in the UGF: 0.28 to 0.64 m (in experiments with IDF) and 0.18 to 0.41 m (in experiments

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without IDF). It was also observed that most of the headloss occurred in the support gravel layer and in the lower portion of the sand bed of the UCSF, which is in agreement with observations by Di Bernardo & Isaac (2001) and Di Bernardo *et al*. (2004). The development of headloss with time in granular media of the UGF was shown to follow an exponential pattern (curved downwards) as shown in Figure 4.

In a similar fashion, in pilot plant PP_1, the headloss in the granular media (corrected to 20°C by using Fair-Hatch's equation) was higher in the UCSF (2.3 to 2.7 m) than in RSF_1 (0.4 to 1.9 m). An opposite tendency was, however, observed in pilot plant PP_2. Here the headloss was higher in RSF_2 (1.9 to 2.2 m) than in the UGF (0.18 to 0.64 m). Filter run lengths varied from 27 to 48 h in pilot plant PP_1 except in experiment B4, where the filter run length could be appreciably extended (88 h) by reducing the UCSF filtration rate down to 8.33 m h^{-1}. In experiment B5, RSF_1 was kept in operation until its maximum available terminal headloss was reached. During this period (68 h), three consecutive filter runs were carried out in the UCSF, the first and the second ranging from 27 to 30 h, but the third interrupted after approximately 11 h of operation (Figure 3).

Run lengths in pilot plant PP_2 varied from 14 to 35 h (in experiments without IDF) and from 16 to 25 h (in experiments with IDF). In experiments B2 and B4, which were carried out to evaluate the performance of the UCSF during long filtration periods without IDFs, this filter was kept in operation for 47 and 88 h respectively (Figure 4).

Removal of impurities from the granular media during each intermediate down flush resulted in significant headloss reductions in the UCSF (8 to 70%) and the UGF (≈90%).

Consumption of treated water for filter cleaning

The total consumption of treated water for IDF and for granular media cleaning after each filter run was higher in the UCSF (18.6 m^3 m^{-2}) than that observed during the UGF granular media cleaning (0.5 m^3 m^{-2}) after each filter run. The consumption of treated water, for granular media cleaning of rapid downflow sand filters, after each filter run was 7.2 m^3 m^{-2}.

Comparison of pilot plants PP_1 and PP_2

Except for total coliforms and *E. coli* counts, which were higher in the effluent of PP_1 in the experiments of Group A, there were no significant differences in the quality of effluents from the pilot plants. In the experiments of Group B, the quality of RSF_2 effluent (effluent from PP_2) was compared not only with that of RSF_1 effluent (effluent from PP_1), but also with the UCSF supernatant, since, as mentioned earlier, in Group B, RSF_1 could have been left out. Significant differences were not observed in the quality of these effluents based on values of turbidity, apparent colour, total iron and manganese. One the whole, the quality of these three final effluents were shown to meet Brazilian standards. Total coliforms and *E. coli* counts were higher in the supernatant of the UCSF and in the effluent of RSF_1, not meeting these standards and hence requiring further disinfection (Tables 3 and 4). Nonetheless, it should be emphasized that, although a good supernatant quality was achieved in the UCSF, the down flow filter is always recommended.

As regards the behaviour of the two systems, the arrangement of the UCSF system is safer than the UGF system owing to the better quality of supernatant.

CONCLUSIONS AND RECOMMENDATIONS

Based on the research study performed, the following conclusions are reached:

- Direct filtration assays in a bench-scale sand filter are adequate for estimating coagulant doses.
- Values of coagulant doses, pH and zeta potential of coagulated water suggest that coagulation may occur with partial charge neutralization.
- When operating at approximately 8 m h^{-1}, the upflow gravel filter acts mainly as a gravel bed flocculator.
- Headloss in granular media is higher in the upflow coarse sand filter than in the upflow gravel filter and its development with time follows an exponential behaviour (curved downwards).

- Headloss in the granular media in the UCSF system is higher in the upflow coarse sand filter than in the rapid downflow sand filter. In contrast, in the UGF system, the headloss is higher in the rapid downflow sand filter than in the upflow gravel filter.
- Filter run lengths are longer in the UCSF system (27 to 48 h) than in the UGF system (14 to 35 h). When the UFCS system is operated at filtration rates of 15 and 20 m h^{-1} in the upflow coarse sand filter and rapid downflow sand filter, respectively, and the rapid downflow sand filter is kept in operation until its maximum available terminal headloss is reached, a filter run length of approximately 68 h can be achieved in this filter.
- Removal of impurities from granular media during each intermediate down flush results in significant headloss reduction in granular media of upflow filters. Reductions in headloss are higher in the upflow gravel filter (≈90%) than in the upflow coarse sand filter (8 to 70%).
- The total consumption of treated water for granular media cleaning is higher in the upflow coarse sand filter (18.6 m^3 m^{-2}) than in the upflow gravel filter (0.5 m^3 m^{-2}).
- Regarding final effluent quality, the two-stage filtration systems studied are basically equivalent. Both systems are considered to be technically feasible processes for water clarification and compare favourably with conventional clarification systems of flocculation, sedimentation and filtration.

Further investigation of similar two-stage filtration systems are, however, recommended in order to evaluate their performance: (i) in treating raw water of poorer quality; (ii) in withstanding raw water quality deterioration peaks; (iii) at higher filtration rates; (iv) when the upflow gravel filter is operated for long periods (above one week) and cleansed only via intermediate down flushes.

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