Chemically enhanced gravel pre-filtration for slow sand filters: advantages and pitfalls

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Abstract The chemical enhancement of gravel (or roughing) filtration with coagulants, *i.e.* direct (gravel) filtration, has been proposed as a pre-treatment alternative for slow sand filters. However, studies have frequently focused on the *efficiencies* of the pre-filters in terms of reduction percentages. The *effectiveness* of the pre-treatment on the subsequent slow sand filtration is not usually cited or even evaluated.
By incorporating a pilot-scale slow sand filter in our trials, both aspects of the pre-treatment process were assessed: *efficiency* and *effectiveness*. In terms of turbidity reductions, our results demonstrated that chemically enhanced pre-filtration was substantially more efficient (93.2 to 99.5%) than conventional pre-filtration (50.6 to 79.3); this was also observed in terms of reductions in the level of other parameters (*i.e.* thermotolerant faecal coliforms and dissolved organics). Yet, the use of a coagulant can have a negative impact on the slow sand filtration run.

Keywords Coagulation; gravel filtration; pre-treatment; roughing filtration; slow sand filtration

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Introduction

Slow sand filtration (SSF) offers advantages in terms of its simple operation and maintenance requirements, making it an attractive technology for small to medium communities. However, the application of SSF is limited by raw water characteristics. That is, different aspects of water quality (e.g. solids/turbidity, algae, iron, dissolved oxygen) can influence the efficiency and/or duration of the filtration run. The frequent citing (e.g. Wegelin, 1986; Hendricks *et al.*, 1991; Lloyd *et al.*, 1991) of maximum influent turbidities less than 10 Nephelometric Turbidity Units (NTU) has led many designers to adopt this value as the simple "rule-of-thumb" for the application of SSF, although limits vary in the published literature.

The limitations of SSF can be overcome with appropriate combinations of pre-treatment stages. Gravel pre-filters in combination with SSF provide a multiple-barrier system (Galvis *et al.*, 1994, 1998). Gravel, or roughing, filters can be classified based on the direction of flow, i.e. horizontal or vertical (up-flow or down-flow), and according to the filter configuration, i.e. in series or in layers.

Poor performance of pre-filters is not frequently reported. In two documented cases, one possible reason for the underperformance was attributed to the raw water's particle size distribution (Lloyd *et al.*, 1991; Ingallinella *et al.*, 1998), which contained significant fractions of colloidal particles. Filtration theory, based on impaction probability calculations, suggests that colloidal particles (i.e. $< 1\ \mu m$) would be less efficiently removed than other particles (Boller, 1993).

One possibility to overcome water quality constraints could be through the use of coagulants in the pre-treatment stage. Alum was used in an *ad hoc* manner for slow sand filter pre-treatment during a flooding event in Salem (USA) (Logsdon *et al.*, 2002). The application of coagulants prior to gravel pre-filtration, *i.e.* direct (gravel) filtration, has also been investigated as a pre-treatment alternative for SSF. Ingallinella *et al.* (1998)

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and Mwinga *et al.* (2004) studied the process on up-flow gravel pre-filters; despite having slow sand filters incorporated to their pilot-systems, reported results emphasised only the pre-treatment efficiencies. By only testing an alum-dosed horizontal pre-filter, Ahsan (1995) also did not evaluate the pre-treatment's impact, *i.e.* effectiveness, on the SSF run. Others have tested the process on waters that perhaps according to literature would not warrant any turbidity reduction measures other than conventional gravel filtration (Carvalho *et al.*, 2001).

Objective

The objective of this study was to assess the *efficiency* as well as the *effectiveness* of chemically enhanced up-flow gravel filters in series (UGFS) as pre-treatment for slow sand filters.

Materials and methods

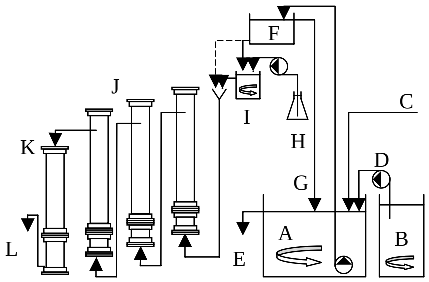
Experimental setup

Experimental work was conducted at the Shalford Water Treatment Works (Thames Water Utilities), using the River Tillingbourne water. Turbidity levels of this River can remain below 20 NTU for prolonged periods, peaking (>20 NTU) mainly during rain events. As such, kaolin (WhitChem Ltd., UK) was added to simulate particulate loadings and to challenge the system.

Figure 1 illustrates the layout for the experimental setup. River water is piped to a mixing tank, where the kaolin stock slurry was added via a peristaltic pump. A submersible pump raised the model water to the constant head feed tank that operated on an overflow, which was sufficient to mix the kaolin slurry with the river water. A constant flow device, similar in principle to a constant head chlorine doser (WRC, 1989), was used for flow control. A submersible fountain pump kept the kaolin slurry under constant agitation.

The test rig consisted of two parallel three-stage UGFS were made from 200 mm PVC-U pipes (Capper Plastics, UK). Each column was 1.20 m high with a 0.10 m high raised floor to support gravel. The first, second, and third columns were filled with 0.60 m of 40 (initially, then 20), 20, and 10 mm graded gravel, respectively. A sampling tap was located 20 mm below the level of the 0.30 m supernatant. Pre-filters were also fitted with piezometric taps throughout the column. The difference in level between each column was of 0.15 m, determining the maximum headloss.

Pre-treatment lines fed two influent flow controlled slow sand filters built with same materials as the pre-filters. SSF columns had a sand bed of 0.35 m and a supernatant of 0.80 m. Piezometric taps were located at the supernatant/sand interface and every 100 mm down the sand bed. Filters were covered to prevent the penetration of light. Outlets were located above the sand bed level; ensuring that media would not dry in the event of a



A = Mixing tank
B = Kaolin slurry
C = River water
D = Peristaltic pump
E = Overflow (to waste)
F = Constant head tank
G = Overflow
H = Alum stock solution
I = Rapid mix device

Figure 1 Schematic diagram of experimental system (not to scale) flow interruption. Sand had an effective size of 0.3 mm, uniformity coefficient of 1.8, and porosity of 37%.

Aluminium sulfate (BDH, UK) stock solutions were prepared daily using deionised water. Dosing was done by a peristaltic pump (504U, Watson Marlow, UK) into a 1 L plastic beaker that also received water from the constant head tank. Mixing occurred in the beaker mounted on a water-driven magnetic stirrer (Camlab, UK) connected to the constant head tank. The non-dosed filter series received water straight from the constant head tank. Considering that the slow sand filters are known to provide biological treatment and that there were no pH adjustment facilities, doses to be tested where selected provided that they would not bring the pH below 7.0.

Analytical methods

Turbidity was measured hourly using a 2100 P (HACH, USA) turbidimeter as specified by the manufacturer. Other parameters were sampled once daily. Thermotolerant faecal coliform (FC) counts were determined using the International Standards Organisation (1990) membrane filtration method. Duplicate tests were performed with sterile 0.45 μm membrane filters (Gelman Sciences) and membrane lauryl sulphate broth (OXOID, UK). pH was measured according to APHA *et al.* (1995). Total and dissolved (*i.e.* passing a 0.45 μm membrane filter) aluminium residuals from the alum-dosed series were determined using the extraction technique described by Van Benschoten and Edzwald (1990). Ultraviolet absorption at 254 nm wavelength (UVA-254) was used as a surrogate for dissolved organics and analysed according to Eaton (1995). Al and UVA-254 analyses utilised a Helios Alpha UV-vis spectrophotometer (Unicam, UK) and a 10 mm lightpath far UV quartz cuvette (Hellma, UK).

Plan of experiments

The experimental site could only be accessed during working hours, as it was in a treatment works. This limited the duration for a gravel filtration run to 5 days. During which typical activities such as sampling, kaolin addition, and alum dosing were carried out, culminating in the filter cleaning on the last day by drainage and hosing down the gravel beds. On weekends, the system was left to run unattended with river water only. Hence, slow sand filters could function continuously.

In total 25 gravel pre-filter runs were conducted. Table 1 summarises the operational conditions during the study for the dosed filters (series A). The control series (B) undertook the same turbidity loadings with no alum dosing. Slow sand filters were incorporated at run 12, running at a rate f of 0.150 m^3/m^2 h. Two slow sand filter runs were carried out, the first under the pre-treatment regimes of runs 12 to 19 ($f = 0.5\,m^3/m^2$ h) and the second during runs 20 to 25 ($f = 1.0\,m^3/m^2$ h).

Table 1 Summarised operational conditions of pre-filtration runs

Run no.	*F*	*Dose*	Other comments:
1 to 9	0.5 and 1.0	2.6	Calibrations, run 5 at 1.0 m^3/m^2 h, at moderate turbidities (approx. 100 to 150 NTU).
10 to 12	0.5	2.0 and 4.0	Low turbidities (30 to 40 NTU), varied dosing, SSF incorporated to test rig.
13 and 14	0.5	4.0	Moderate turbidities (approx. 75 and 150 NTU).
15	0.5	0.0	Changing of media in gravel filters, no dosing.
16 to 19	0.5	2.0 to 6.0	Moderate-high turbidities (approx. 100 to 300 NTU), varied dosing.
20 to 25	1.0	4.0 to 8.0	Higher *f* and moderate-high turbidities (approx. 150 to 300 NTU).

f = filtration rate (m^3/m^2 h); *Dose* = alum dose (mg/L as Al) for coagulated series

Results

Gravel pre-filtration

Table 2 summarises the turbidity reduction efficiencies for the pre-treatment stages. Pre-treatment data are for the runs 12 to 19 and 20 to 25 during the first and second slow sand filter trials, respectively. The previous runs followed the same general trends, but their effectiveness as a pre-treatment could not be judged as no SSF run was conducted; hence those results are not presented.

The series A was consistently more efficient ($>93\%$) in reducing the turbidity than the control series B ($<80\%$). Higher turbidities required more alum for an increase in performance. Under comparable turbidity and dosing conditions (run 25 compared to 19), at the higher filtration rate of $1.0\,\mathrm{m^3/m^2\,h}$ the effluent quality deteriorated.

The mean turbidity reduction efficiencies of the undosed series B did not drop when the filtration rate was increased. What can be observed for each filtration rate applied is that for increasing raw water turbidities, the pre-filters presented higher efficiencies. Effluents produced in most cases were well above recommended value (i.e. 10 NTU).

Throughout these trials no headloss was detected in the control filters. On the coagulated series A none of the filters reached the maximum 150 mm headloss. The highest recorded headlosses for each filter were between 9 and 14 mm. From the headloss readings it was apparent that the most of the headloss developed in the first half of the filters. Indicating that the bulk of the removed matter is accumulated in the lower portions of the gravel pre-filters. Some particulate accumulation upon the gravel surface was also noted upon visual inspection of the supernatant in both series.

UVA-254 and thermotolerant faecal coliform performance data are summarised in Table 3. FC removal efficiencies followed trends similar to that of turbidity reductions. UVA-254 reduction increased at higher alum doses and appeared to be independent of the filtration rates. Possibly, some of the UVA-254 reductions observed were due to adsorption of organics on to the clay particles.

Slow sand filtration

Performance data for the two slow sand filter runs are presented in Table 4. It is apparent that in both runs SSF-A produced an effluent with superior quality in terms of turbidity, UVA-254, and FC levels. The SSF-A presented lower reduction efficiencies for those

Table 2 Summary of results for runs 12 to 25 for series A and B (A = dosed; B = control)

Run no.	*f*	*Dose*	Average turbidity (NTU)			Reduction efficiency (%)		Duration (d)
			Raw water	Series A	Series B	Series A	Series B	
12	0.5	2.0	36.8	2.51	11.5	93.2	68.7	5
13	0.5	4.0	73.8	1.69	19.7	97.7	73.4	5
14	0.5	4.0	151	2.25	38.6	98.5	74.5	5
15	0.5	0.0	Media changed in 1st filters, both series on river water only (no kaolin)					
16	0.5	4.0	112	1.09	26.0	99.0	76.8	3
17	0.5	2.0 to 4.0	203	6.26	44.1	96.9	78.2	5
18	0.5	4.0 to 6.0	251	2.03	60.3	99.2	76.0	5
19	0.5	6.0	285	1.48	64.6	99.5	77.4	5
20	1.0	6.0	190	3.88	66.5	98.0	65.0	2
21	1.0	6.0	139	3.17	68.6	97.7	50.6	4
22	1.0	8.0	206	3.89	51.1	98.1	75.2	4
23	1.0	8.0	295	7.70	77.2	97.4	73.8	4
24	1.0	4.0	155	5.61	39.5	96.4	74.5	2
25	1.0	6.0	240	3.65	49.6	98.5	79.3	2

f = filtration rate ($\mathrm{m^3/m^2\,h}$); *Dose* = alum dose (mg/L as Al) for coagulated series

Table 3 Summary of performance ranges for UVA-254 and faecal coliforms (FC) for PF runs

	Pre-filter: series	Raw water		Pre-filter effluent		Reduction efficiency (%)	
		Min.	Max.	Min.	Max.	Min.	Max.
UVA-254	A (dosed)	0.060	0.149	0.032	0.065	31.5	57.8
(cm^{-1})	B (control)			0.066	0.135	3.9	25.0
FC	A (dosed)	510	3836	5	173	86.0	99.3
(cfu/100 mL)	B (control)			132	1240	20.5	82.3

Note: all values are pre-filter (PF) run averages

parameters than in SSF-B (except for UVA-254 in run 2). This was considered to be a result of the lower pre-treated loadings received by SSF-A.

It was apparent that, only three weeks into the run (Figure 2, SSF run 1), SSF-B had ripened sufficiently to produce an effluent of similar quality (in terms of turbidity) to that of SSF-A. This did not occur during the second slow sand filter run. Furthermore, SSF-B was more susceptible to variations in the incoming turbidities. Probably this was due to the higher turbidity loading and a less efficient pre-treatment level at a higher filtration rate (1.0 m^3/m^2 h).

Although SSF-A had a better effluent quality and had an influent that was apparently more "acceptable" (<10 NTU) than SSF-B in both runs, the duration of SSF-A's run was shorter than that of the control filter. In fact, incoming turbidities for SSF-A were on average an order of magnitude less than that of SSF-B (Table 4). During run 1, SSF-A had reached its terminal headloss (*i.e.* supernatant overflowed) at day 46 whilst SSF-B continued to run until day 53. The second run for SSF-A lasted only 23 days due to the development of excessive headloss. Yet, SSF-B operated until day 28 when its run was discontinued without having reached its maximum headloss.

The increments in SSF-A's headloss development (in both runs) were most evident in periods following an increase of influent turbidities. This development was limited and sometimes negative only when influent turbidities of less than 2 NTU were measured. The most likely cause of the higher headlosses experienced in the SSF-A would be revealed in a qualitative assessment of the influent particulates, as the particle loading was smaller on these filters.

Table 4 SSF runs 1 and 2 performance data summary (series: A = dosed; B = control)

	Series	Pre-filter effluent	SSF effluent	SSF reduction
Turbidity (NTU)				
Run 1	A	3.04 [1.09; 10.5]	0.61 [0.42; 0.95]	80.1%
	B	28.5 [2.48; 79.8]	0.85 [0.32; 1.25]	97.0%
Run 2	A	4.89 [2.74; 13.7]	0.57 [0.26; 0.99]	88.4%
	B	50.7 [3.44; 88.6]	6.84 [1.28; 45.0]	56.5%
UVA-254 (cm^{-1})				
Run 1	A	0.046 [0.031; 0.063]	0.044 [0.030; 0.061]	4.9%
	B	0.091 [0.066; 0.131]	0.080 [0.054; 0.126]	12.7%
Run 2	A	0.048 [0.030; 0.065]	0.047 [0.030; 0.063]	3.5%
	B	0.102 [0.070; 0.131]	0.100 [0.068; 0.127]	2.3%
FC (cfu/100 mL)				
Run 1	A	71 [3; 270]	9 [< 1; 61]	86.9%
	B	411 [124; 2775]	41 [4; 212]	90.0%
Run 2	A	17 [4; 33]	5 [2; 11]	71.4%
	B	326 [140; 497]	73 [21; 262]	77.6%

Note: values are SSF run averages; range: [min.; max.]

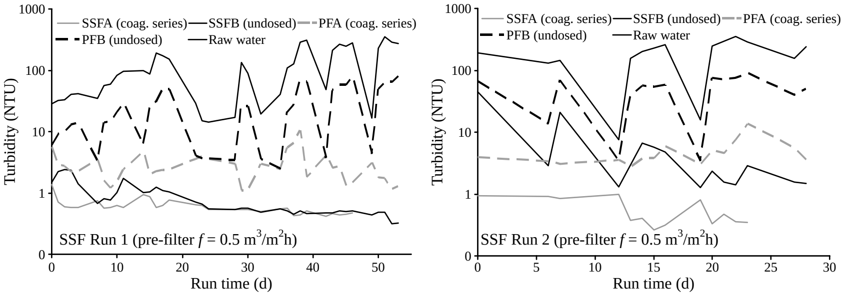


Figure 2 Turbidity profiles during SSF runs 1 and 2 (SSF = slow sand filter; PF = pre-filter series)

A strong positive correlation between the alum-dosed pre-filter turbidities and total aluminium residuals (Figure 3) indicated that insoluble hydroxide precipitates were likely to be the cause of the observed headlosses in SSF-A. Only a small fraction of the measured total residual was from the Al contained in the kaolin particles, as demonstrated by Figure 3. Hence, for turbidities ranging from about 50 to 350 NTU, total Al levels in the raw water (with kaolin only) were equivalent to Al levels in the coagulated pre-filtered effluent with a turbidity varying from 1 to 6 NTU.

Discussion

Making allowance for the different operational conditions (*e.g.* filtration rate, coagulant doses, media sizes, etc.) tested, the efficiency of the chemically enhanced pre-filters in this study are in broad agreement with other investigations. It is evident from these experiments that having a goal of less than 10 NTU can result in an efficient, but perhaps not effective pre-treatment when resorting to chemical enhancement of pre-filters. Using a similar process on 4 to 8 m long horizontal gravel filters, Ahsan (1995) considered an effluent with less than 3 NTU to be acceptable for a hypothetical slow or rapid sand filter application. An Al residual of 330 µg/L (assumed here to be the total fraction) of the pre-filter effluent was also reported with no associated turbidity. An estimate from Figure 3 would indicate a value between 5 to 6 NTU. It was suggested that a subsequent filtration stage would remove most of the aluminium. This is likely to be the case, but the difference is that unlike rapid sand filters, slow sand filters are not designed to do so and do not have backwash facilities to clean the media. Application of this process for rapid sand filtration has been reviewed by Di Bernardo and Isaac (2001). In the case of slow sand filters, it is apparent that the SSF process can have its run shortened due to excessive headloss caused by Al residuals from the coagulation process.

In order to limit the headloss on the slow sand filter due to aluminium hydroxide precipitates, this study would suggest a *maximum* limit of 2 NTU for an alum-dosed

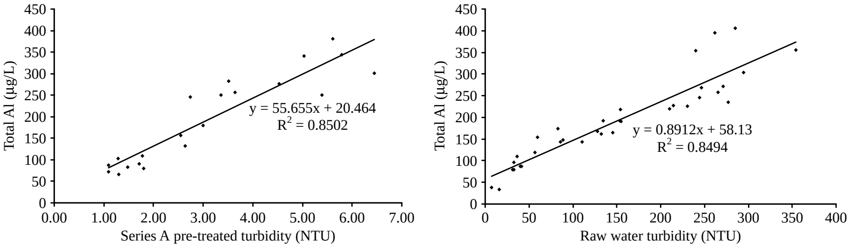


Figure 3 Correlations between turbidities (alum-dosed pre-filters and raw water) and total Al

pre-treatment. Such a limit would most likely require a target *average* turbidity below this value, possibly even less than 1 NTU. If it weren't for the risk posed by protozoan pathogens resistant to conventional chlorination, such a high quality pre-treatment effluent could perhaps render the slow sand filter obsolete.

Evidence from this study suggests that for a chemically enhanced pre-filtration system to be an efficient and effective pre-treatment, a stringent process control and monitoring is warranted. Such an operational requirement may not be available in places where gravel pre-filtration is typically utilised, *i.e.* small to medium rural communities.

No quantitative evaluation of the cleaning efficiency in the alum-dosed filters compared to the control filters was made; anyhow, this is an aspect worthy of mention. During the draining of the filters, it was visually observed that retained matter (flocs) on the gravel surface of the alum-dosed filters was more easily displaced, as did Ahsan (1995). Yet, simple draining was insufficient to clean the filters; both series required the hosing down of the gravel bed.

Conclusions

Chemically enhanced (with alum) pre-treatment can dramatically increase the performance of the treatment system as a whole in terms of turbidity and UVA-254 reduction, as well as thermotolerant faecal coliform removal. The use of a coagulant increases the efficiency of the pre-treatment barrier when compared to conventional gravel pre-filtration. Also, the coagulated matter retained in the filters is more readily cleaned by hydraulic flushing. However, in order for this process to be an effective pre-treatment measure for SSF it requires a strict process control (2 NTU maximum). Despite substantial improvements in water quality, the upstream coagulant based pre-treatment may actually shorten the slow sand filter run, rendering the pre-treatment process less effective. Considering the difficulties and constraints faced by small to medium communities, this process may be beyond their capacity to implement, operate, and maintain such a pre-treatment option.

Acknowledgements

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