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HYDRAULIC FLOCCULATION WITH UP-FLOW ROUGHING FILTERS FOR PRE-TREATMENT OF SURFACE WATER PRIOR TO CONVENTIONAL RAPID SAND FILTRATION

Hydraulisk flockning med uppströmsförfilter för förbehandling av ytvatten före konventionell snabbsandfiltrering

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Abstract

Hydraulic flocculation has been used in many different ways in drinking water treatment for many years. In this paper, the results of experimental work using an up-flow roughing filter for hydraulic flocculation prior to treatment with conventional rapid sand filtration are presented. The objective was to evaluate optimum flocculation conditions with up-flow roughing filtration and the quality of formed suspensions with respect to their filterability. River water was used for the experiments. Turbidity removal, head losses development and velocity gradients in the roughing filter were the parameters used to evaluate the effectiveness of pilot plant processes. Overall turbidity removal in the pilot plant was between 84 % and 97 %. Removal efficiencies in the up-flow filter were between 18 % and 73 % and at the rapid sand filter between 77 % and 92 %. Both units operated under positive pressure. Irrespective of operational conditions established, G-values between 45–190 s^{-1} were attained in the up-flow filter. Best performances were attained when the up-flow filter was operated at the lowest filtrations velocities and alum doses. Overall, the up-flow filter performed both as particle aggregation and separation unit and the quality of formed suspensions was suitable for removal by rapid sand filtration. The method can therefore provide a rather versatile technique for pre-treatment of turbid water prior to conventional rapid sand filtration.

Key words – water treatment; conventional treatment, roughing filtration; contact-flocculation-filtration

Sammanfattning

Hydraulisk flockning har använts på många olika sätt för beredning av dricksvatten under många år. I denna artikel redovisas effekterna av ett uppströmsförfilter med hydraulisk flockning före konventionell sandfiltrering. Syftet var att utvärdera de optimala flockningsförhållandena med uppströmsförfiltrering och hur filtrerbara flockarna, som bildades i den hydrauliska flockningen, var i nedströms sandfilter. Ytvatten från en flod användes för experimenten. För att bedöma nyttan av uppströmsförfiltret mättes reduktion i turbiditet och tryckfallsförlusterna över förfiltret, och hastighetsgradienterna i det. Turbiditeten minskade totalt mellan 84 % och 97 % över förfilter och sandfilter. Själva förfiltret reducerade turbiditeten mellan 18 % och 73 % beroende på flödeshastighet och dos aluminiumsulfat. Snabbfiltret avskiljde ytterligare turbiditet från vattnet. Både förfilter och snabbfilter drivs vid övertryck. Skjuvhastigheten (G-värdet) varierade mellan 45 till 190 s^{-1} i förfiltret, oberoende av aluminiumdos. Bäst turbiditetsreduktion och stabilast drift uppnåddes när uppströmsförfiltret belastades med låg hastighet och låga doser aluminiumsulfat. Sammantaget fungerade uppströmsförfiltret som en god reaktor för hydraulisk flockning med efterföljande partikelaggregering. Det bidrog också till en viss reduktion av flockar från vattnet och framför allt till att bilda suspensioner vilka kunde filtreras i snabbfilter nedströms. Metoden kan därför passa som en billig, enkel och snabb förbehandlingsmetod av grumligt vatten före konventionell sandfiltrering i vattenverk, inte minst i utvecklingsländer.

Nomenclature

d_0 filter medium grain size (m)
Eff. efficiency (%)
G average shear rate or velocity gradient (s^{-1})
Gt Camp number [–]
g gravitational constant ($m\ s^{-2}$)
K_m filter medium constant [–]
L effective length of filtration (m)
L_f depth (height) of filtration layer (m)
NTU Nephelometric turbidity units
P power dissipated (watts)
Q volumetric flow rate ($m^3\ s^{-1}$)
t time (s)
T_f mean residence time of fluid flow in filtration layer (s)
T_{res} residual turbidity (NTU)
T_{rw} turbidity raw water (NTU)
V volume (m^3)
v_f filtration velocity ($m\ h^{-1}$)
ΔH head loss (m)
ΔH_t head loss at time t through filtration layer length L_f (m)
ρ density ($kg\ m^{-3}$)
η porosity filter bed [–]
η_t porosity filter bet at time t [–]
μ absolute viscosity of water ($kg\ m^{-1}\ s^{-1}$)
ν kinematic viscosity of water ($m^2\ s^{-1}$)
θ_s filter media grain sphericity factor [–]

Introduction

The conventional methods of removing turbidity and solids from raw water generally consist of coagulation-flocculation followed by sedimentation and rapid sand filtration. In these methods chemical coagulation is used to reduce the repulsive forces responsible for the stability of colloidal dispersions while flocculation is used to enhance particle transport and aggregation, and the eventual formation of settleable/filterable suspensions. Filtration (deep bed filtration) is used as a polishing step (Chuang and Li, 1997).

Following destabilization with chemical coagulation, the rate of particle aggregation (flocculation) is governed by the possibility and frequency of collisions between destabilized particles, the efficiency of such contacts and the existence of transport mechanisms (mixing) to get particles close to each other, collide and eventually become attached (Stumn and Morgan, 1996; Wang et al., 2007).

Fluid motion for flocculation can be induced either by mechanical stirring or by the energy derived from hydraulic head loss. Mechanical flocculation provides high efficiency and flexibility of operation but is relatively costly in operation and maintenance along with its dependence on the availability of supplies and skilled labour. Hydraulic mixing on the other hand is less costly, can be operated by relatively unskilled personnel but has the restriction of being less flexible to mixing intensity and to flow and water quality variations (McConnachie et al., 1999; Polasek, 2007).

Hydraulic flocculation has been used in water treatment since many years and is particularly well suited for situations of limited financial capacity and skilled labour such as those prevailing in most developing countries. Methods of providing hydraulic flocculation include the use of baffled flocculation channels (Mishra and Breemen 1987; McConnachie et al., 1999), filtration through fixed granular media (McConnachie et al., 1999), and filtration through buoyant media (Vigneswaran and Ngo, 1995).

The methods relying on filtration through fixed granular media are the basis of the so-called flocculation supported filtration processes whereby, coagulant is introduced directly to the raw water inflow immediately prior to the filter inlet (Huisman, 1984; Hansen, 1988; McConnachie et al., 1999). The induced fluid shear resulting from the sinuous flow of the water through the interstices of the filter medium promotes the transport of destabilized particles from the suspension to the grain surface of the filter medium where they eventually become attached by mechanisms of sedimentation, adsorptions and interception (Mishra and Breemen, 1987; Hansen, 1988; Chuang and Li, 1997).

A common design of treatment plants using this concept is the so-called up-flow-down flow filtration. In this method, an up-flow roughing filter (also known as contact filter) is used for hydraulic flocculation prior to filtration with conventional gravity rapid sand filters (Mishra and Breemen, 1987). The primary potential advantage of up-flow/down-flow process is the reduction of capital and operational costs of water treatment which results from the elimination of settling basins and the elimination or significant reduction of dimensions of flocculation tanks (Mishra and Breemen, 1987; Vigneswaran and Ngo, 1995; Chuang and Li, 1997). Other advantages include the reduction in coagulant dosages, decreased sludge production, reduced operation and maintenance needs, and the possibility of maintaining flocculation efficiency regardless of flow and turbidity variations in the raw water.

Previous studies (McConnachie et al., 1999; Ingallinella et al., 1998; Mahvi et al., 2004) concerning the use of roughing filters for hydraulic flocculation, which emphasized the understanding of their performance as compared to conventional paddle flocculation, have demonstrated that the method can provide a rather versatile pre-treatment process capable of handling wide fluctuations in raw water turbidity and operating conditions such as coagulant doses, and filtration rates. McConnachie et al. (1999) reporting results from pilot studies conducted with an up-flow roughing filter operated with *M. oleifera* seed solutions as coagulant, concluded that the unit could treat effectively raw with turbidity as high as 50 NTU with minimum head losses generated in the filter. Ingallinella et al. (1998) reporting results of similar studies but using roughing filters operated with aluminium salts as coagulant, concluded that removal efficiencies as high as 90 % could be achieved even for raw water with initial turbidity as high as 340 NTU.

The work presented here follows a similar approach. Experimental work was conducted to assess the performance of a pilot plant consisting of an up-flow roughing filter used for hydraulic flocculation and a rapid sand filter used for final treatment in the removal of turbidity from river water. Turbidity removal, head losses development, and velocity gradients in the up-flow filter were the parameters used to assess the pilot plant performance. River water taken from the same source used for drinking water production at a full scale treatment plant servicing the city of Maputo was used to run the pilot plant experiments. Experimental results are therefore compared to those obtained at the full scale treatment plant.

The aim of this paper is to present the main results of the pilot plant experiments. The term 'contact filter' is used in this paper to describe the up-flow roughing filter operated as a hydraulic flocculator.

Background

In conventional treatment, mechanical or hydraulic flocculation is used to promote the formation of ideal suspensions in respect to their settling properties or filterability. Suspensions of four different properties can be formed (Polasek and Mult, 2002):

(i) Suspensions that are completely retained in the filter bed at the expense of high head loss during filtration;
(ii) Suspension which generates low head losses but which are poorly retained in the filter bed;
(iii) Suspensions which are poorly retained and generates high head losses and,
(iv) Suspensions which are completely retained in the filter bed and generates a minimum head loss. Suspensions of this type represent the ideal suspensions, the formation of which should be aimed at.

Whether settleable of filterable suspensions are envisaged, the key principle is to induce fluid motion to cause velocity gradients enough to promote particle contacts and aggregation. Two major factors govern the efficiency of flocculation processes (Wang et al., 2007; Polasek and Mult, 2005); the intensity and duration of agitation. The mixing intensity is expressed in terms of mean velocity gradient $G(s^{-1})$, which expresses the energy input into the system. The standard expression for G is

$$G = (P/\mu * V) \tag{1}$$

Where P is the power input into the system, μ is the absolute viscosity of the water and V, the volume of liquid in the reactor. For the work done by the water flowing through a system where hydraulic head loss is involved, the energy input P is given by

$$P = \rho * g * Q * \Delta H \tag{2}$$

with ρ, the water density, g the gravitational constant, Q the flow rate and ΔH the head loss across the system. Combining Eq. 1 and 2 results in:

$$G = \sqrt{\frac{\Delta H * g}{v * t}} \tag{3}$$

Were ν is the kinematic viscosity of the water.

The relationship for G in a porous media is derived from the following equation (Polasek, and Mult, 2002; Wang et al., 2007):

$$G = \sqrt{\frac{\Delta H_t * g}{v * T_f * \eta_t}} = \sqrt{\frac{\Delta H_t * g * v_f}{v * L_f * \eta_t}} \tag{4}$$

The mean residence time through the filter media is based on the model of length over velocity. Since the approach to fluid flow in a packed bed is based on an idealized capillary model based on which the packed media is regarded as a bundle of capillary tubes, to account for the tortuous path of the flow through the filter bed, the effective length of the idealized capillary tubes is related to the porosity of the filter bed and can be calculated as (Huisman, 1984; Chuang and Li, 1997):

$$L = L_f * \eta \tag{5}$$

The symbols in the right side of Eq. 5 have the same meaning as described in Eq. 4. The mean residence time can therefore be calculated according to the following expression (Chuang and Li, 1997):

$$T_f = L/v_f = L_f * \eta_t/v_f \tag{6}$$

The porosity of the clogged filtration layer η_t is obtained from Carman-Kozeney equation based on the head loss at specific time *t.* With K_m taken as 5.0, the expression for the porosity of the clogged filter layer is, according to Polasek and Mult (2002):

$$\Delta H_t = \frac{36 * K_m * v_f * v * L_f * (1 - \eta_t)^2}{g * \theta_s^2 * d_0^2 * \eta_t^3} \tag{7}$$

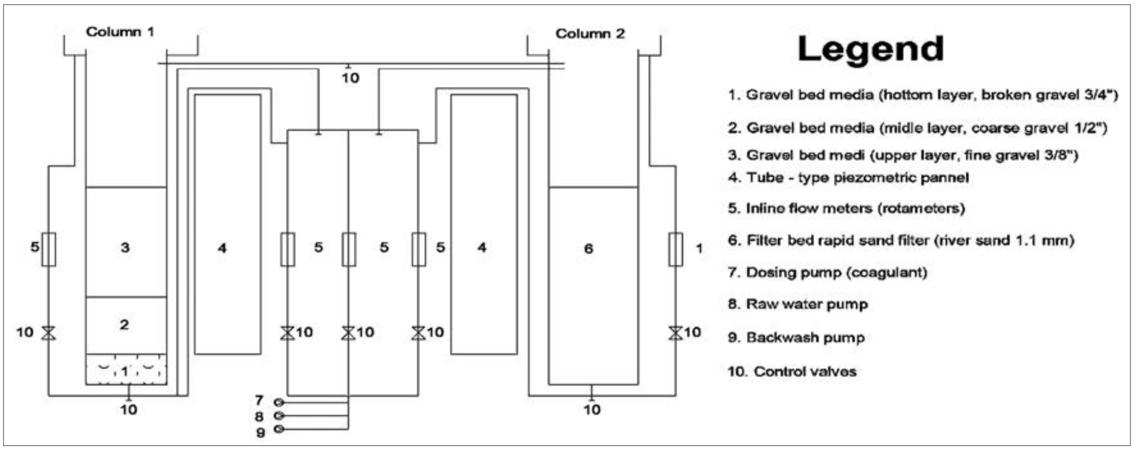

Figure 1. *Schematic diagram of the pilot plant arrangement. Column 1: multi-layer up flow roughing filter; column 2: single media gravity rapid sand filter.*

Materials and methods

Pilot plant description

The experiments were carried out at the laboratory of Hydraulics of the Department of Civil engineer of Eduardo Mondlane University in Maputo, Mozambique. The pilot plant consists of two Perspex columns, 2.75 m high with an internal diameter of 90 mm. One column was used as a contact filter and the other as a rapid gravity filter. The plant arrangement is depicted in Figure 1.

The contact filter was provided with a 1.25 m filter bed, consisting of three layers of gravel placed in the following manner: bottom layer: broken gravel, 0.25 m high 19.05 mm effective size and porosity of about 55.2 %; middle layer, coarse gravel, 0.55 m high, 12.5 mm effective size and porosity of about 54.6 % and upper layer, 0.45 m high, fine gravel with 2.78 mm effective and porosity of about 52 %. The depth of water above the gravel bed was set at 0.75 m. The column was further provided with a false floor consisting of a metal plate provided with evenly spaced 5 mm diameter holes onto which the gavel bed rested.

The gravity rapid sand filter was provided with a 1.05 m filter bed consisting of river sand with an effective diameter of 1.10 mm, and a porosity of about 44 %. The depth of water above the filter bed was of about 0.95 m. The filtration column was also provided with a false floor consisting of a metal plate drilled with evenly spaced 1 mm diameter holes onto which the filter bed rested.

Both columns were provided with diametrically opposed connections located 100 mm apart over the height of the column used for water sampling and piezometric head losses readings. The sampling ports consisted of stainless steel tubes extended some 5 mm into the filter bed onto which flexible draw-off tubes where fixed which allowed continuous head loss measurements (via a tube-type pressure gauging) and periodic collection of water samples for turbidity measurements. Roller type clamps were provided on the flexible tubes to allow interruption of flow during periods of no measurement.

Alum prepared as 10 % solution of $Al_2(SO_4)_3.18H_2O$ was used for coagulation purposes. The chemical was dosed from a reagent tank to the inlet pipe of the contact filter with the help of a positive displacement pump. Homogenization of the added chemical was achieved by turbulence generated by means of a throttled inlet valve.

All experiments were run at constant filtration velocities maintained through manual flow control attained via inline flow meters (rotameters). The contact filter was however run at filtration rates higher than those used in rapid sand filter therefore; excess water was wasted through overflow pipes located at the top of the columns.

Filtration experiments

A total of thirty four experiments were performed during a period of approximately 6 months from April to October 2007. The raw water inlet to the plant was arranged via a 600 l raw water reservoir connected to a positive displacement gear type pump and a manually operated inline flow controller. The feed water to the contact filter was prepared from two scenarios of coagulant addition (1.8 mg/l and 2.5 mg/l) and raw water turbidity. The effluent from the contact filter constituted therefore the feed water to the rapid sand filter.

During the period of experiments, the river water turbidity was generally low (less than 10 NTU). In order to test the pilot plant also for higher values of raw water turbidity some experiments were conducted with synthetic turbidity water prepared by adding clay to the raw water until levels of turbidity larger than 15 NTU were attained. The pilot plant was further run at filtration velocities of 6.3 m h^{-1}, 9.4 m h^{-1} and 12.7 m h^{-1} in the contact filter and of 3.2 m h^{-1}, 6.3 m h^{-1} and 9.4 m h^{-1} in the rapid sand filter.

Jar test experiments

Standard jar tests using a Janke and Kunkel jar test apparatus were used to determine the optimum alum doses for the raw water which showed a dosage rate of 2.5 mg Al^{3+}/l as the optimum dosage for maximum turbidity removal if conventional flocculation sedimentation were to be used. The pilot plant was tested also at a dosage rate of about ¾ the optimum dosage.

Sampling and analytical methods

Turbidity and head losses were the main parameters used to assess the performance of the plant. Samples of water for turbidity analysis were taken at different depths of the filter columns at regular time intervals of 45 minutes. The termination criterion was defined as turbidity breakthrough or maximum utilization of the permissible head loss, but because of logistic restrictions all experiments were interrupted after 9 to 10 hours of filtration.

Besides turbidity and head losses, temperature, pH and alkalinity were also used to analyse the raw water quality. These parameters were measured through analytical methods. Temperature, pH and alkalinity were measured prior to the initiation of the experiments. Temperature readings were taken with a standard mercury thermometer (accuracy of ± 1°C), pH was measured with a handheld digital meter from Wagtech International Ltd., and turbidity via a Hach turbidity meter DR 2500. Alkalinity was determined using a simplified titration method described in the *Standard Methods*, (APHA, 1998).

Head loss readings

Head loss readings were taken from both columns using a tube-type differential pressure gauge. Head loss readings were also taken at regular time intervals of 45 minutes.

Results and discussion

Raw water physicochemical characteristics

During the experiments the river water turbidity (T_{rw}) was between 4.0 and 9.7 NTU, the pH between 8.0 and 8.4, the total alkalinity between 115.6 and 122 mg $CaCO_3$/l and the temperature between 19 and 31.5 °C. The quality of the feed water to the filter columns was slightly different, first because some experiments were run with synthetic turbidity water and secondly because the source water was stored for about a day in a closed room before experiments took place. This slightly lowered the water temperature. The main characteristics of the raw and tested water are resumed in Table 1.

Overall performance of the pilot plant

A summary of the results for turbidity removal in the pilot plant is presented in Table 2. For each filtration run, mean values of influent and effluent turbidity are presented. As can be seen from Table 2, turbidity removal in the pilot plant was generally high and reached figures between 84 % and 96 %. This was independent of the quality of feed water or operational conditions (coagulant dose and filtration rates) established during individual runs.

The rapid sand filter had shown also very good performances. The filtrate quality was in general below the desirable limit of 1.0 NTU of the guidelines for treated water (WHO, 2004) and terminal head losses were, in general below the maximum permissible head loss defined on the basis of the depth of supernatant water (0.95 m) above the filter bed. The rapid sand filter could therefore have been run for longer periods without running into problems of negative pressures in the filter bed.

Table 1. *The range and average (N > 25) values of raw water quality used in this study.*

Parameter	Range	Average raw water quality	Average test water quality
Turbidity (NTU)	4.0–22.9[1]	4.7	13.7
Temperature (°C)	19.0–31.5	23.4	21.2
pH	8.2–8.6	8.1	8.4
Alkalinity (mg $CaCO_3$/l)	115.6–122.0	118.0	122.2

[1] synthetic turbidity

Table 2. *Summary results of turbidity removal in the pilot plant, contact filter and rapid sand filter.*

Run test	Raw water turbidity (NTU)	Filtration velocity[2] (m h^{-1})	Alum dose (mg/l)	Average turbidity (NTU) contact filter			Average turbidity (NTU) rapid sand filter			Run duration (hr.)	Maximum terminal head loss rapid sand filter (mm)	Overall removal efficiency pilot plant (%)
				Feed water	Filtrate	Removal efficiency (%)	Feed water	Filtrate	Removal efficiency (%)			
33 ÷ 34	16.6–22.9	6.3/3.2	1.8	16.6–17.4	6.1–7.0	57.7–73.4	5.3–6.2	0.7–0.8	87	9	269	96
28 ÷ 32	13.0–20.9	6.3/3.2	2.5	9.8–17.3	3.7–6.3	63.7–73.2	3.0–4.8	0.7–0.8	78–85	9	204	94–97
1 ÷ 4	5.7–9.7[1]	9.4/6.3	1.8	8.8–10.7	4.6–5.5	21.4–36.1	3.9–5.4	0.6–0.8	78–87	9–15[4]	937	88–92
15 ÷ 18	15.1–16.6	9.4/6.3	1.8	14.3–19.5	5.5–13.5	18.7–65.4	4.0–6.0	0.5–0.7	84–87	6.75–9	272	95–97
6 ÷ 9	4.0–4.2[1]	9.4/6.3	2.5	9.0–12.8	5.0–9.7	–[3]	3.7–5.8	0.5–0.7	86–91	9	320	84–89
10 ÷ 13	15.4–20.4	9.4/6.3	2.5	19.7–24.8	12.1–20.6	–[3]	6.3–7.0	0.5–0.7	91–92	8.25–9	308	96–97
14, 23 ÷ 27	14.7–18.9	12.7/9.4	1.8	12.2–17.3	4.1–9.6	34.6–73.2	4.0–5.9	0.6–1.0	82–87	7.5–9	583	95–96
19 ÷ 21	15.0–17.1	12.7/9.4	2.5	14.2–19.8	8.1–12.1	29.4–41.6	7.0–10.4	1.1–1.9	77–84	8.25–9	670	88–93

[1] Tests run with natural turbidity
[2] 6.3/3.2; filtration velocity in the contact filter and rapid sand filter respectively
[3] turbidity breakthrough in the contact filter
[4] filtration experiments 1 and 2 run continuously without filter cleaning totalling 15 h of continuous operation

From Table 2, it is also seen that the filtrate from the rapid sand filter had little variations during individual runs but increased slightly to a mean value of 1.9 NTU when the unit was operated at the highest filtration velocity (9.4 m h^{-1}) and alum doses in the pre-treatment of 2.5 mg/l (runs 19, 21, 22). However, the absolute limit of 5.0 NTU of the guidelines (WHO, 2004), was never exceeded.

The contact filter behaved slightly different. Turbidity removal in this unit was generally lower than in the rapid sand filter (18.7–73.4 %) and the filtrate turbidity experienced large variations during individual runs (see Table 2). This occurred particularly when the unit was run at a filtration rate of 9.4 m h^{-1} and alum doses in the feed water of 2.5 mg/l (runs 6–12). During these runs, turbidity breakthrough could be observed frequently. Because the sampling port used to tap effluent water from the contact filter was placed some 10 cm above the top of the filter bed, the frequent increases in effluent turbidity were attributed to the effect of gravitational sedimentation that occurred in the supernatant water above the gravel bed. This had a straining effect on the surface above the gravel bed that caused the concentration of flocs to reach its highest values.

This phenomenon, which is similar to the processes taking place in sludge-blanket type clarifiers started to develop right from the beginning of the filtration runs and gradually develop into a thicker and concentrated cloud of particles positioned few centimetres above the gravel bed. In subsequent experiments, the sampling port was lowered to ±1–2 cm above the top of the gravel bed. This allowed the collection of samples not affected by differential settling, hence of lower turbidity values.

The quality of feed water to subsequent rapid sand filtration was in general better than that leaving the gravel bed of the contact filter (Figure 2). This suggests that apart from a partial removal of particles in the gravel bed, additional removal of particles took place in the supernatant water above the gravel bed.

Proportion wise the gravel bed performed better than the supernatant layer in the removal of aggregates formed during flocculation. However, for low values of raw water turbidity the effect of gravitational settling had a higher impact in the removal of aggregates particularly when alum dosages of 2.5 mg/l, were applied. This resulted probably from the presence of a large amount of aluminium hydroxide aggregates which were thin enough to flow through the relatively coarse media of the gravel bed, but large and in concentration enough to rapidly develop a sludge blanket in the supernatant above the gravel bed.

The influence of the contact filter to the quality of suspensions transferred to the rapid sand filter appears therefore to have been that of particle aggregation and

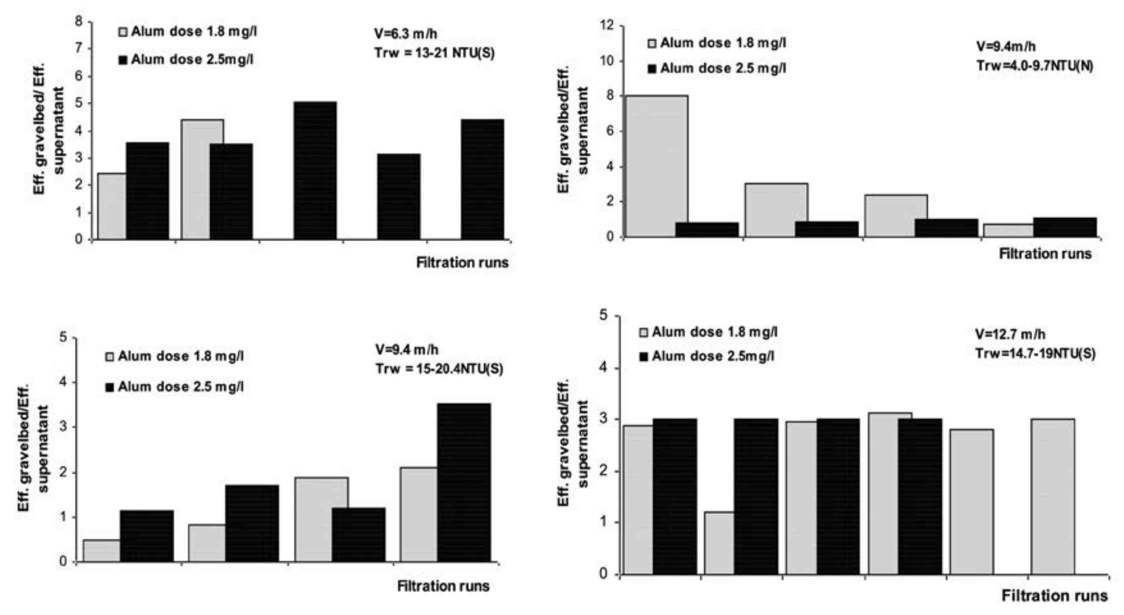

Figure 2. *Relative contribution of gravel bed and supernatant layer in turbidity removal in the contact filter: (N) = natural turbidity; (S) = synthetic turbidity; Eff. = efficiency (%). Information about filtration velocities and alum dosages applied is also shown.*

separation whereby, the gravel bed contributed mostly with particle aggregation and partial separation through mechanisms of particle bridging, and the supernatant water with partial separation through mechanisms of gravitational settling.

The performance of the pilot plant was also compared to treatment results obtained at the full scale treatment plant of Maputo water supply (Figure 3). In this plant, conventional coagulation/flocculation sedimentation is used for pre-treatment and rapid sand filtration is used for final treatment. The plant is operated with two parallel production lines. Sludge-blanket clarifiers operated at surface hydraulic loads of 1.6 m h^{-1} (line 1) and 2.4 m h^{-1} (line 2) are used for flocculation/sedimentation purposes. The rapid sand filters are operated at filtration rates of 5.2 m h^{-1} and 7.1 m h^{-1} respectively. The data used for the comparison was taken from the operator's database and comprehend results of filtrate turbidity when the pilot plant was operated under similar conditions of raw water turbidity and alum doses used for pre-treatment. As seen in Figure 3, the pilot plant had removal efficiencies comparable to that obtained at the full scale plant and produced a filtrate of better quality.

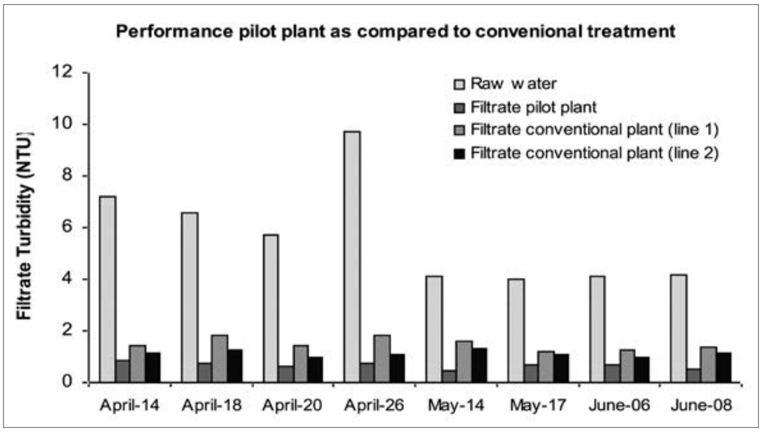

Figure 3. *Performance pilot plant as compared to conventional treatment with coagulation flocculation, sedimentation and rapid sand filtration.*

Performance of the contact filter

Head losses and filtration runs

In Figure 4, the development of pressure drop in the gravel bed of the contact filter is illustrated. The pressure drop increased linearly along with filtration rates and alum dosages which clearly indicate a time-dependent reduction of the gravel bed porosity and an increase in the inter-pore shear stress due to accumulation of particles.

The pressure drop in the contact filter was in all cases of a few centimetres and well below the maximum allowed head loss calculated from the available depth of supernatant water.

In up-flow filters, maximum head loss is limited by the danger of uplifting the filtering material which occurs when the soil pressure equals the water pressure (Huisman, 1984). The filtering material properties such as porosity, specific gravity and thickness of the filter bed set the limits. Because the contact filter was provided with a top layer made up of the finest gravel the maximum head loss was limited by the properties of this layer and was calculated as 0.35 m based on the following properties of the filtering material: porosity 52 %; specific density 2.6 kg m^{-3}; and thickness of about 0.45 m. Accordingly, the contact filter operated under positive pressure during all experiments which means that it could have been run for longer periods and also with a much lower (almost 50 %) depth of supernatant water.

Analysis of head losses developed when the unit was run at a filtration velocity of 12.7 m h^{-1} indicates that much higher values were observed and also that the head losses developed more rapidly. This resulted from high fluid shear stress established when the unit was run at such high filtration velocities which may also have promoted high rates of particle aggregation within the gravel bed, eventually associated with high rates of solids retention. This observation coincides with findings from other researchers (Chuang and Li 1997; Ingallinella et al., 1998 and McConnachie et al., 1998) who concluded, that shear stress affects flocculation processes and head loss development. As noted by the same authors, associated with increases in the rate of particle aggregation within porous media, an increase in head losses is expected. The magnitude depends on the induced shear stress but also on the rate of solids deposition/detachment.

The head losses at a filtration velocity of 12.7 m h^{-1} developed much faster than at 6.3 m h^{-1} or 9.4 m h^{-1} but, in contrast, the head losses at 9.4 m h^{-1} developed slightly lower than at 6.3 m h^{-1}. This unexpected behaviour was attributed to a possible predominance of thin aggregates that could flow easily through the relatively coarse media of the filter bed, thus limiting the rate of solids deposition and consequently the increase in head losses. This also explains the high filtrate turbidity observed with the plant operated at 9.4 m h^{-1} as compared to operation of the plant at 6.3 m h^{-1}, and similar conditions of raw water turbidity and alum doses. In fact, since flocculation in porous media is predominantly under ortokinetic conditions (Mishra and Breemen, 1987; Chuang and Li, 1997), the conditions with lower filtration velocities and longer retention times resulted in better conditions for the formation of larger aggregates and for increased rate of solids deposition that explains the relatively large head losses in the gravel media.

The quality of feed water with respect to its turbidity

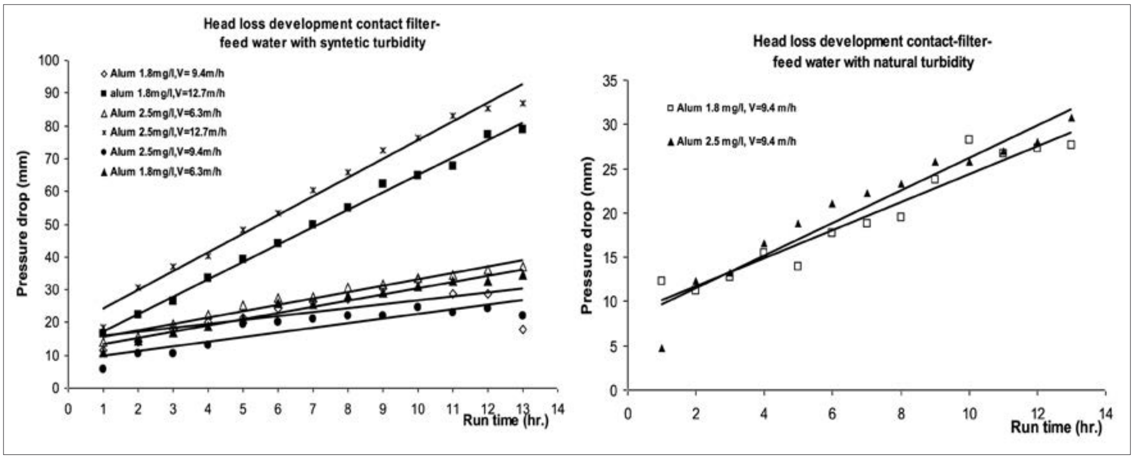

Figure 4. *Time dependent behaviour of head losses (mm) in the contact-filter for experimentsrun with syntetic turbidity (left) and natural turbidity (right). Average raw water turbidity wasin the range 4.0–9.5 NTU. Syntetic feed water had a turbidity of about 20 NTU.*

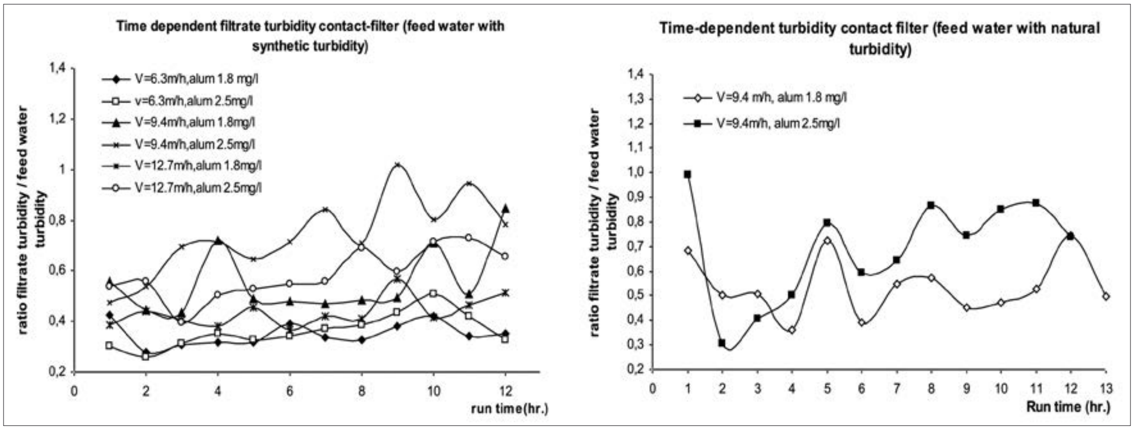

Figure 5. *Time dependent behaviour of filtrate turbidity (NTU) in the contact-filter, for experiments run with synthetic turbidity (left) and natural turbidity (right). Average raw water turbidity was in the range 4.0–9.5 NTU. Synthetic feed water had a turbidity of about 20 NTU. Information about filtration velocities and alum dosages applied is also shown.*

seems to have had little influence on head loss development in the contact filter. The differences shown in Figure 4 seem to have resulted from differences in filtration velocities and coagulant dosages applied rather than from differences in the feed water quality. This suggests that irrespective of the feed water quality, the flocculation conditions created within the gravel media resulted in suspensions of relatively similar properties with respect to their filterability. In fact, as noted by Chuang and Li (1997) and Declan et al. (2008) the value of turbidity in suspensions formed during flocculation in porous media is qualitatively proportional to the solids content but inverse of the particle size which means that the filterability of corresponding suspensions is independent of the raw water turbidity.

Turbidity removal

Figure 5 illustrates time-dependent values of filtrate turbidity from the contact filter. To account for variations in raw water turbidity, readings are plotted on the basis of the ratio between the filtrate turbidity and that of the feed water. As shown in Figure 5, the filtrate turbidity decreased slightly during the initial stages of filtration, but soon after that it started deteriorate and to show variations occasionally associated to turbidity breakthrough with filtration time.

The initial decrease in filtrate turbidity was probably due the high solid retention capacity of the clean gravel bed which led to a rapid accumulation of particles during the initial stages of filtration. During subsequent stages, the increase in solids being retained in the gravel bed accompanied by reduction in gravel bed porosity, led to an eventual increase in the inter-pore shear stress which may have promoted particle detachment and turbidity breakthrough with the filtrate. As shown in Figure 5, the highest variations in filtrate turbidity occurred more frequently when the unit was operated at 9.4 and 12.7 m h^{-1}, suggesting that shear stress affects not only flocculation processes as noted previously, but also particle retention and detachment in porous media.

As noted from Figure 5, most efficient treatment was obtained when the unit was operated at a filtration velocity of 6.3 m h^{-1} and alum doses of 1.8 mg/l. The low performances observed when the contact filter was run at 9.4 m h^{-1} were associated to poor flocculation conditions resulting from the combined effect of moderate to low agitation intensities and short residence times which, eventually resulted in the formation of aggregates that could flow easily through the relatively coarse media of the contact filter and where not strong enough to withstand the induced fluid shear stresses. Changing the filtration velocity to 12.7 m h^{-1} resulted in much higher agitation intensities and inter-pore shear stress. This eventually resulted in the formation of thin but much stronger aggregates (despite the short residence times) which, because of their smaller size were mostly retained through mechanism of particle bridging and attachment on the surface of the gravel media but were strong enough to withstand high induced shear stresses.

According to results shown in Figure 5, changing the alum dose from 1.8 mg/l to 2.5 mg/l seems to have had impacted the performance of the contact filter particularly when high filtration velocities were used. As shown in Figure 5, the poorest performances were mostly observed when using alum doses of 2.5 mg/l. Possible reasons for this could be that the aggregates formed when

Table 3. *Initial and terminal values of G (s^{-1}) and Gt generated at the two uppermost layers of the contact filter.*

Filtration velocity ($m\ h^{-1}$)	Reference layer	Initial G values		Initial G*t* values		Terminal G values		Terminal G*t* values	
		Alum dose ($mg\ l^{-1}$)							
		1.8	2.5	1.8	2.5	1.8	2.5	1.8	2.5
6.3	Middle	25	27	967	1006	45	56	1482	1706
	Upper	46	44	1819	1779	88	87	2971	2951
9.4	Middle	41	34	991	906	60	56	1352	1245
	Upper	40	31	1198	997	96	88	2353	1312
12.7	Middle	55	58	1015	1042	110	123	1659	1784
	Upper	64	79	1407	1631	168	192	2867	3128

using high alum doses are generally large in size but weak in strength, suggesting that they removal in porous media is largely affected by mechanisms of particle breakage and detachment from the filter grains. Chuang and Li (1997) and Ingallinella et al. (1998) have also reported that flocs formed with high alum doses are generally large in size but weak in strength, thus unable to withstand high inter-pore shear stresses.

Velocity gradients

Velocity gradients (G) and Gt-values calculated from to Eqs. 4 and 7 and the head losses generated across the two upper layers of the contact filter are presented in Table 3. As can be seen, velocity gradients (G s^{-1}) were between 45–120 s^{-1} in the middle layer of the contact filter and between 88–190 s^{-1} in the upper layer. The head loss across the bottom layer of the contact filter was in all cases negligible therefore, corresponding G and Gt-values are not presented.

References from text books (Stumn and Morgan 1996; Wang et al., 2007) recommend that mixing for optimum flocculation should generally be of low intensity, with G-values preferably between 20 and 70 s^{-1} and Gt-values between 2 x 10^4 and 2 x 10^5. Below these limits no proper flocculation occurs while, increasing G and *t* values beyond these limits results generally in floc breakage and turbidity breakthrough in subsequent treatment processes. The principle behind these limits is associated to the belief that low agitation intensity favours the formation of large and readily setleable aggregates and that, beyond a certain limit of agitation, floc breakage occurs. However, recent studies from Polasek (2007), arguing the principles behind the so-called customary flocculation suggests that, while slow mixing promotes the formation of large and readily settleable flocs the end result is in fact the formation of flocs that are large in size, but of low density, very fragile and with a tendency to fragment. As noted by the same author, this type of flocs is suitable neither for sedimentation nor for rapid sand filtration. In contrast if the flocculation is performed under high agitation intensities over the entire process until optimum flocculation is reached, the formed flocs are generally more compact and dense. Accordingly, depending on the resultant size of aggregates required, flocculation can take place under high agitation intensities with *G*-values preferably above 50 s^{-1} or low agitation intensities with G-values *below* 50 s^{-1}.

The high and low agitation intensities involve the same transport mechanism and differ only by the agitation intensity (*G*-value). When micro-flocs are to be formed, high agitation intensities (*G*-values between 100 and 500 s^{-1} are usually preferred while, for large and readily settleable macro-flocs, low agitation (G-values between 5 and 20 s^{-1} is generally preferred. The agitation intensity together with the duration of the process determines the final result. Flocs formed under low agitation and long retention times are generally larger and denser than those formed with high agitation and short contact times (Polasek and Mult, 2005; Polasek, 2007).

From the results shown in Table 3, it is seen that G-values in the contact filter ranged from conditions of moderate to high agitation intensities. Our interpretation to this is that this has favoured the formation of aggregates of different characteristics concerning the size and density but which were removed by sedimentation and attachment onto the surface of the gravel grains. From the results of Table 3, it also appears that best flocculation conditions were attained when the contact filter was run at a filtration rate of 6.3 m h^{-1}. However, due to the small size of the filtering material used in the upper layer of the contact filter, relatively large G-values were established (G ≈ 87–96 s^{-1}) in this layer which, eventually contributed to particle breakage. This was independent of the alum dose or filtration velocity applied.

At a filtration velocity of 6.3 m h^{-1}, the combined effect of lower agitation intensities and longer retention times resulted eventually in the formation of large aggregates hence, the highest removal efficiencies attained when compared to other filtration velocities. When the contact filter was operated at 9.4 m h^{-1} relatively large aggregates were eventually formed but now, the effect of high induced inter-pore shear stress and short retention times may have caused formed aggregates to break and be detached from the grains, thus leading to the highest concentrations of particles in the filtrate. Increasing the filtration velocity to 12.7 m h^{-1} resulted in agitation intensities that favoured the formation of thin but dense aggregates (Polasek, 2007) which were poorly retained in the gravel media thus, the lowest performances observed at this filtration velocity. The effect of particle breakage and detachment from the gravel grains when the contact filter was run at 9.4 m h^{-1} and alum doses of 2.5 mg/l seems, however, to have impacted the filtrate quality more seriously.

Performance of the rapid sand filter

Time-dependent filtrate turbidity and head losses from the rapid sand filter are presented in Figure 6. As can be seen the filtrate from the rapid sand filter was always of acceptable quality (T_{res} > 1 NTU). The terminal head losses was , in all cases, below the maximum permissible head loss of 1.35 m, calculated from Carman-Kozeney equation (Huisman, 1984), based on the available depth of supernatant water (0.95 m) and a clogged layer of about 30 % the filter bed thickness.

Exception is made for the filtration runs done with feed water prepared from filtration velocity of 9.4 m h^{-1} and alum doses of 2.5 mg/l in the contact filter, during which the filtrate from the rapid sand filter started deteriorate 3 to 4 h, after the beginning of the experiments. This resulted eventually from the high load of fine particles being transferred from the contact filter which, at the corresponding scenario of operation, had the poorest performances as is can be seen from Figure 6.

From analysis of results of head loss development in the rapid sand filter it is seen that the unit always operated under positive pressure which means that longer filtration runs could have been established without running into problems of negative pressures. This also indicates that turbidity breakthrough was the factor determining the duration of filtration runs particularly when filtration velocities higher than 6.3 m h^{-1} were chosen to run the plant.

From the results shown in Figure 6, it is also seen that head losses in the rapid sand filter developed more or less linearly. This indicates that impurities penetrated uniformly through the depth of the filter bed. This also indicates that irrespective of the performance of the contact filter, the quality of suspensions transferred to the rapid sand filter were generally of similar properties in respect to their filterability. As shown in Figure 6, irrespective of the conditions of operation of the contact filter, the resulting suspensions were in general completely retained in the rapid sand filter and generated minimum head losses. As noted by Polasek (2002) suspensions of this type represent the ideal suspensions, the formation of which should be aimed at during pre-treatment for filtration with conventional rapid sand filters. The optimum combination seems to have been that of operating the contact filter and the rapid sand filter at filtration velocities of about 6.3 m h^{-1} or lower and alum doses of 1.8 mg/l.

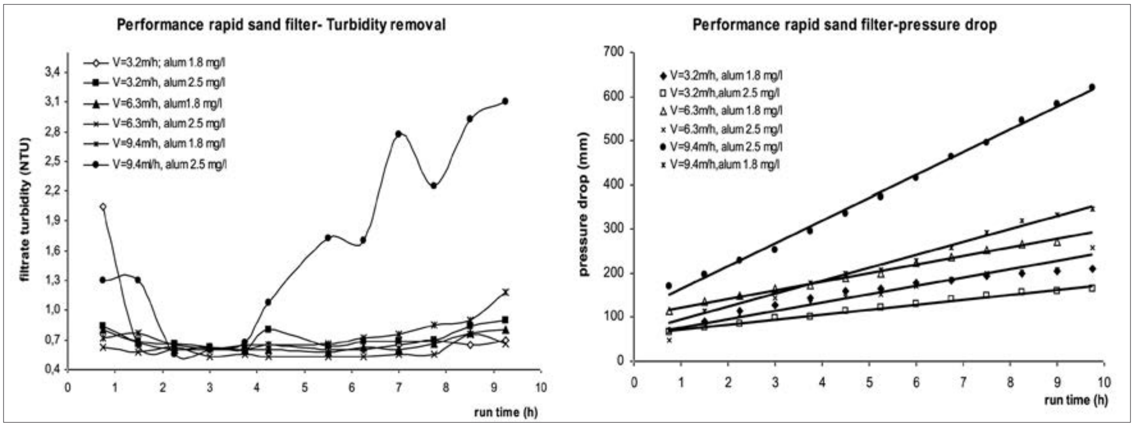

Figure 6. *Performance of the rapid sand filter. Time dependent values of filtrate turbidity (left) and head loss development (right) are presented. Also information on filtration velocities in the rapid sand filter and alum dosages applied in the contact filter is presented.*

Conclusions

Results of this study supports claims made by other researchers that the use of roughing filters for hydraulic flocculation provides a viable and flexible alternative for improved turbidity and solids removal by conventional rapid sand filtration.

In this study, the quality of suspensions produced at the contact filter was generally suitable for removal by subsequent rapid sand filtration independent of the operational conditions established (feed water turbidity, filtration velocities and alum doses) at individual filtration runs. Best performances were, however, attained when the contact filter was operated at a filtration velocity of 6.3 m h^{-1} and alum doses of about ¾ of the optimum dosage obtained from jar test experiments.

Overall performance of the pilot plant performance was in general above 84 %. The filtrate from the rapid sand filter was of acceptable quality and consistently below 1 NTU and the units operated under positive pressure during the entire duration of the experiments. Longer than the 9 to 10 h duration of filtration could therefore, have been established.

Velocity gradients in the contact filter were within limits of moderate to high agitation intensities and were, in general within limits recommended in literature for effective flocculation. Formed aggregates were suitable for removal by mechanisms of sedimentation and particle bridging in the gravel media of the contact filter and dense enough to be removed by mechanisms of sedimentation in the supernatant water above the gravel bed. The remaining flocs could be effectively removed through subsequent filtration.

The contact filter used in this study was designed with the filter bed arranged with the gravel size decreasing in the direction of the flow. This impacted significantly the unit's performance since floc breakage and detachment occurred mainly at the upper and finer layer of gravel bed. Further research is therefore required concerning the optimum composition and arrangement of the gravel media. The use of a relatively large supernatant layer above the gravel bed helped however; reduce significantly particle (turbidity) concentration in the filtrate.

Because filtration velocities used to run the contact filter, were much larger than those recommended for plain roughing filters (Smet and Visscher, 1990; Sánches et al., 2006) large investment and operational costs can be attained by using up-flow roughing filters as hydraulic flocculators. Saves can also be attained in relation to costs with chemical reagents. For optimum operation of up-flow roughing filters used for hydraulic flocculation, the units should however be designed for G-values between 40 and 90 S^{-1} and filtration velocities lower that 6.0 to 7.0 m h^{-1}.

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