Improving simultaneous removal of BDOC and turbidity in rapid filters by application of permeable synthetic collectors

Wolfgang Uhl, Andreas Palinski and Rolf Gimbel

ABSTRACT

In non-chlorinated deep bed filters for drinking water treatment, besides particles, biodegradable organic carbon (BDOC) is removed by microorganisms. This work aimed at the improvement of BDOC degradation in deep bed filters, which may be operated in front of GAC adsorbers by the application of permeable synthetic collectors (PSC). First PSC and different GAC were investigated experimentally for their BDOC and turbidity removal performance and pressure drop as well. A model was developed to find an expected optimum combination of PSC and GAC.

The following pilot scale investigations showed that a PSC-layer on top of adsorptively exhausted GAC relieves bacteria sessile on the bottom media from deposition of particles which may be toxic to the bacteria and increase mass transfer resistance. In general the PSC/GAC combination performs considerably better with respect to turbidity and BDOC-removal than a conventional two-media filter.

Key words | bacterial regrowth, BDOC, biodegradation, deep bed filtration, drinking water treatment, permeable synthetic collectors

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INTRODUCTION

In drinking water treatment very often biodegradation is taken advantage of to remove biodegradable dissolved organic carbon (BDOC). This is of interest for several reasons. First, if the water is safe from a hygienic point of view and distributed without safety chlorination BDOC may be built into biomass, thus resulting in increasing suspended bacteria concentrations termed bacterial regrowth. Second, BDOC is adsorbable on activated carbon and as such competes for adsorption sites with trace organic substances such as pesticides. Consequently sufficient BDOC removal before adsorption may improve pesticide adsorption. However, to upgrade existing or planned treatment trains with additional bioreactors for BDOC removal would imply considerable investments. Therefore it is of special interest to improve water treatment steps originally planned and optimized for other purposes, e.g. deep bed filters for particle removal, with respect to biodegradation too.

Here an approach to improve simultaneous BDOC-removal in fast-rate filters was investigated. It implied the application of so-called permeable synthetic collectors (PSCs). These are cylindrical hollow collectors of fibrous structure shown in Figure 1. The distance between the fibres and the porosity can be altered by compressing the PSC layer. The catchment of particles takes place at the outer as well as the inner surface. The PSC's higher storage capacity enables more efficient turbidity removal in comparison with granular filtration material. For more details see, for example, Gimbel and Nahrstedt (1997). In laboratory scale investigations with solid particles these collectors had shown a very high efficiency in particle removal and very low pressure drops when compared with conventional filters.

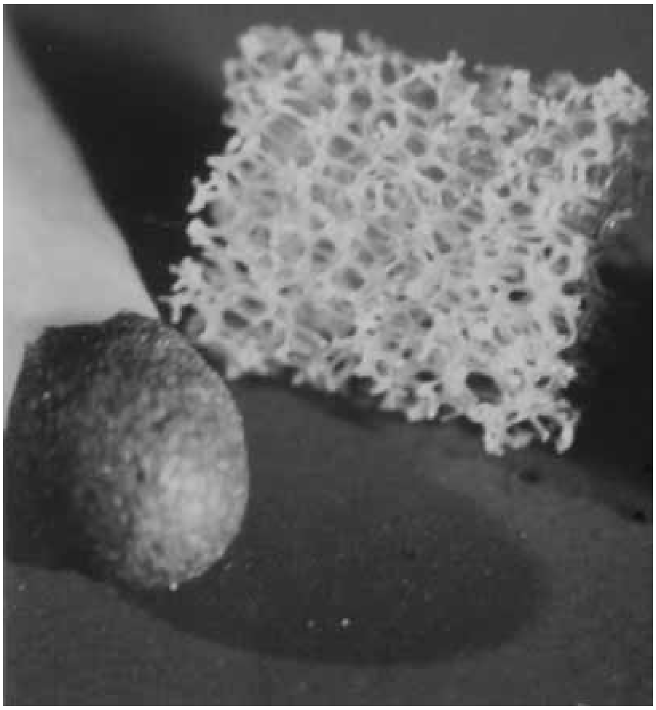

Figure 1 | Permeable synthetic collector (PSC).

EXPERIMENTAL

To investigate the approach a pilot plant was set up in a full-scale plant operated according to the so-called Mülheim Process (Sontheimer *et al*. 1978), shown in Figure 2. In this process river water is treated by pre-ozonation, precipitation/flocculation with polyaluminium-chloride (PAC), post-ozonation, rapid dual media filtration, GAC-adsorption/biodegradation and ground-filtration. Finally pH is adjusted and the water is distributed after safety chlorination.

The position of the pilot plant, which was operated in parallel with the water works dual media filters, is also shown in Figure 2. A flow scheme is given in Figure 3. The pilot plant consists of three columns (inner diameter 288 mm, total height 3.0 m). Flow rate is controlled at the influent of the columns in order to be keep it constant even during sampling. Each column is equipped with nine sampling points of special construction. At these points, the pressure drop can be measured and liquid samples can be taken as well.

Experiments were carried out in two phases. In both phases the first column served as a reference filter. Here a combination of two activated carbons (Hydraffin BD, Hydroanthrasit H) of different densities and grain size was applied, similar to the full-scale plant. In the second column a GAC (Picabiol) was applied which was claimed to be especially suitable as a carrier for heterotrophic bacteria and thus for removal of biodegradable organic substances. In phase 1 of the experiments only the GAC was applied and compared with the reference filter. In phase 2 the upper part of the GAC was replaced by permeable synthetic collectors (PSCs). The third column was operated in phase 1 only. A bed consisting of PSCs was applied and its performance compared with that of the reference filter and the pure GAC-filter, respectively. In order to exclude adsorption of dissolved organic matter the columns with GAC were operated under similar conditions over a period of several months before the investigations were started. Thus, adsorption capacity for DOC was completely exhausted.

Characteristics of the filter materials are given in Table 1, bed depths in the respective phases are given in Table 2. Superficial velocities were 15 m h^{-1}. Between filter runs the filter beds were backwashed with air-scour, air/water and water similar to the full-scale plant filters. Duration of the filter runs was determined by the pressure drop in the reference filter. When it exceeded 500 hPa, which is the criterion for backwashing in the full-scale plant, the filter run was stopped.

Pressure differences between the sampling points were measured with a digital manometer (Mecotec, type DP 200). In the samples turbidity was measured at 12° forward scattering with a Monitek 251 turbidity meter. DOC was measured with a Dohrmann/Rosemount DC 80 after filtration over 0.4 μm polycarbonate filters, acidification to approximately pH 2 and purging of inorganic carbon with nitrogen.

RESULTS AND DISCUSSION

Phase 1 experimental results

Water temperature in phase 1 was about 23°C. Turbidity and DOC concentration in the influent of the pilot plant is

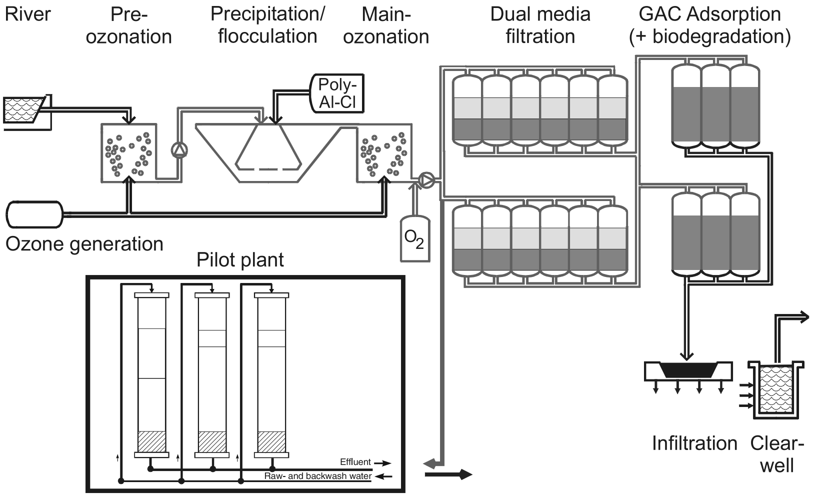

Figure 2 | Waterworks operated according to the Mülheim Process and position of the pilot plant.

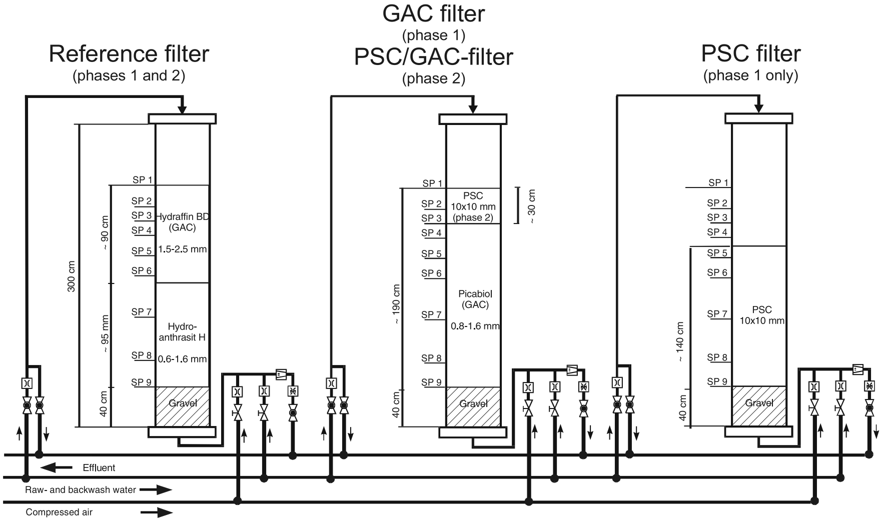

Figure 3 | Flow scheme of the pilot plant and filter media applied.

depicted in Figure 4. During the period of the filter-run of approximately 5 days DOC remained almost constant between 2.3 and 2.6 mg l^{-1}, whereas turbidity was subject to major fluctuations. It usually varied between 0.4 and 1.2 FNU but also one peak of about 2.0 FNU was observed.

Removal of DOC is expressed as efficiency η(DOC). The efficiency for removal of a given quantity X is defined as

$$\eta(x) = \frac{X_{inf} - X_{eff}}{X_{inf}} \tag{1}$$

where the indices inf and eff indicate the influent and effluent, respectively. Removal efficiency for DOC as a function of bed depth is shown in Figure 5. In this diagram data-points shown were obtained by cumulative evaluation of DOC removal during the filter run of

Table 1 | Characteristics of filter media applied

	Filter media			
Parameter	**GAC Hydraffin BD**	**GAC Hydroanthrasit H**	**Picabiol H 120**	**PSC T 2540**
Grain size	1.5–2.5 mm	0.6–1.6 mm	0.8–1.6 mm	÷
Collector size	÷	÷	÷	10×10 mm
Collector fibre radius	÷	÷	÷	100 μm
Bed density	290 kg m^{-3}	500 kg m^{-3}	280 kg m^{-3}	12 kg m^{-3}
Bed porosity ε_0	50%	50%	44%	$>98\%$
BET-surface	650 m^2 g^{-1}	650 m^2 g^{-1}	650 m^2 g^{-1}	÷

Table 2 | Investigated combinations and bed depths of filter media

	Column 1 (reference filter)	**Column 2**	**Column 3**
Phase 1			
Upper part	0.90 m Hydraffin BD		
Lower part	0.95 m Hydroanthrasit H	1.85 m Picabiol H 120	1.37 m PSC (compressed from 1.57 m)
Phase 2			Not in operation
Upper part	0.90 m Hydraffin BD	0.30 m PSC (compressed from 0.50 m)	
Lower part	0.95 m Hydroanthrasit H	1.85 m Picabiol H 120	

approximately 5 days and are thus mean removal efficiencies from ten measurements during this period.

The cumulative amount of a quantity X removed or produced in a filter segment is calculated by

$$\Delta x_{cum,t_N} = \sum_{i=1}^{N} (Q_i \cdot (t_i - t_{i-1}) \cdot \Delta x_i) \text{ with } \Delta X_i = (X_{eff} - X_{inf}) \quad (2)$$

Here Qi is the volumetric flow rate during the time interval $(t_i - t_{i-1})$, and ΔX_i is the difference of the quantity X between influent and effluent of the filter segment at time t_i.

In most cases removal of biodegradable organic carbon in filter beds can be described by a first order reaction (Uhl 2000). As BDOC is a portion of DOC the maximum amount of DOC removable is BDOC. Thus, for DOC

$$\frac{\eta_z}{\eta_{max}} = 1 - e^{-(k_{app} \cdot \varepsilon_{bed}) \cdot EBCT_z} \quad (3)$$

where η_Z is the removal efficiency and $EBCT_Z$ is the empty bed contact time at bed depth Z, $(k_{app} \cdot \varepsilon_{bed})$ is the product of the apparent first order rate constant and the bed porosity.

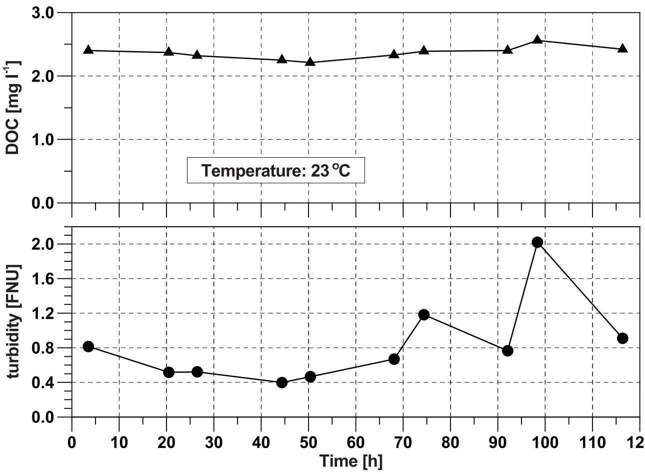

Figure 4 | DOC and turbidity during filter run in phase 1.

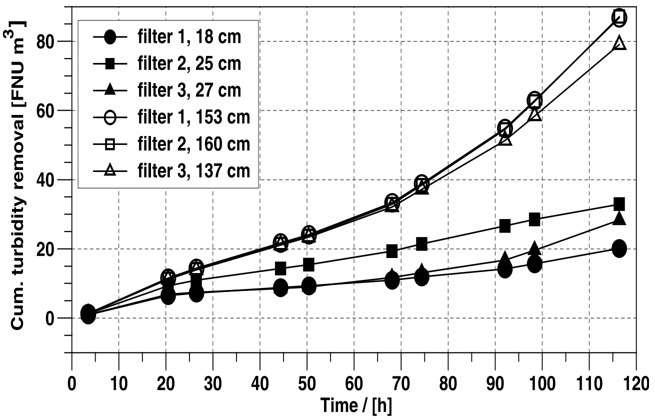

Figure 6 | Cumulative turbidity removal in three filter beds of two different bed depths.

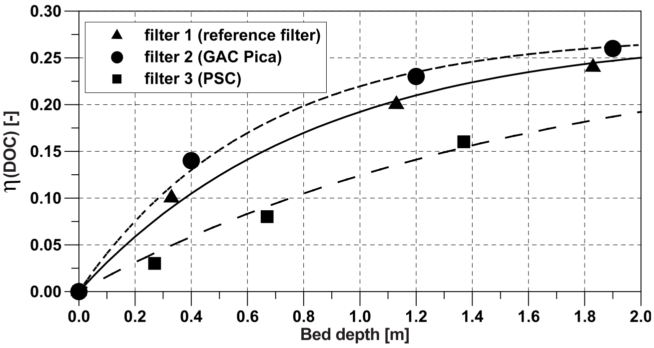

Figure 5 | DOC removal efficiency in different filters and simulation with first-order reaction.

From Figure 5 it can be seen that at a bed depth of 2 m DOC removal is higher in filter 2 with GAC Picabiol when compared with the reference filter. Although the efficiency is not so much higher it should be noted that the difference is about 10% of the overall DOC removal in the reference filter. Obviously the difference in removal efficiency of the two filters is higher at lower bed depths as DOC degradation is faster in the filter with GAC Picabiol. As a result of the maximum concentration of biodegradable organic carbon the removal efficiencies in the respective filters are closer at lower bed depths. However, as different grain sizes were employed, from these findings it may not be concluded that the GAC Picabiol is generally better suited for removal of biodegradable organic carbon than the GACs in the reference filter.

Even in filter 3 with PSCs DOC removal efficiency was considerable. However, it was much lower when compared with the GAC filters.

Comparison of turbidity removal in the three filters can be drawn from Figure 6. It shows the cumulative turbidity removal at comparable bed depths in the upper and lower sections of the filter. At lower bed depths, i.e. between 137 and 160 cm, no significant differences in turbidity removal can be observed between the three filters. At lower bed depths, i.e. between 18 and 27 cm, turbidity removal is found to be highest in filter 2 with GAC Picabiol. This was expected, as there the filter material's grain size was smaller when compared with the reference filter. The findings on pressure drop (see below) emphasized the conclusion that with the GAC Picabiol a much more pronounced surface filtration effect was responsible for turbidity removal. Concerning the PSCs in filter 3 turbidity removal was in general comparable to the other two filter materials. However, a closer analysis (which cannot be made from the graphs shown here) showed that breakthrough of turbidity occurred somewhat earlier in the PSC filter.

Pressure drop over time at comparable bed depths of the three filters is shown in Figure 7. It can clearly be seen that the pressure drop in the PSC bed was very low in comparison with the beds with granular filter material. In

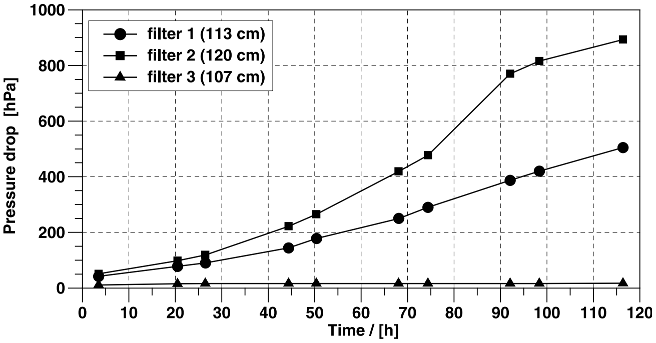

Figure 7 | Pressure drop vs. time at comparable bed depths.

Table 3 | Kinetic constants ($k_{app} \cdot \varepsilon_{bed}$) for BDOC removal by bacteria sessile on the different filter materials

Reference filter	Picabiol	PSC
0.31 min^{-1}	0.42 min^{-1}	0.14 min^{-1}

column 2 with GAC Picabiol the pressure drop was much higher than in the reference filter column 1, namely approximately 900 hPa and 500 hPa, respectively. Or, when the criterion for filter backwashing of 500 hPa was applied, the filter run time of the GAC Picabiol-filter would be around 75 h while the reference filter would be in operation for about 115 h. A closer analysis showed that the differences result mainly from the upper few centimetres of the filter beds, which shows that surface filtration effects play an important role, especially with the GAC Picabiol.

Modelling

In the section above it was shown that the filter with GAC Picabiol performed better than the reference filter with respect to DOC removal. Removal of turbidity was comparable. However, the pressure drop was much higher in comparison with the reference filter, mainly because of surface filtration effects in the first few centimetres of the Picabiol bed. So, when the much shorter backwash intervals are taken into account, the overall performance of the GAC in DOC removal is considerably decreased. The PSCs showed a much lower performance in DOC removal, however considerable. Pressure drop was very low in the PSC bed. Thus it could eventually be possible to combine PSCs and the GAC Picabiol together such that an upper PSC-layer could protect the GAC from flocs. Based on these considerations it was expected that Picabiol's better performance in DOC removal could be profited from when a top layer of PSC was applied. In order to be able to predict the behaviour of a filter with PSCs on top and Picabiol in the lower part, modelling of the performance of all filter materials was carried out.

As discussed above DOC elimination was described as a first-order reaction with respect to BDOC. The relative amount of biodegradable organic carbon (i.e. $\eta_{\max}$) was determined from the measured data shown in Figure 5 by nonlinear optimization to 0.275. Kinetic constants for BDOC removal by bacteria sessile on the different filter materials were derived the same way. They are given in Table 3.

Filtration can usually be described by the Iwasaki-Law according to

$$\frac{\mathrm{dc}}{\mathrm{dz}} = -\lambda(\sigma) \cdot \mathrm{c} \tag{4}$$

where the filter parameter λ is a function of the specific solids deposit and thus varies with time. For a clean filter bed it is equal to the initial filter parameter and is then expected to increase with increasing specific solids deposit σ. λ is expected to decrease again and approach 0 after a specific saturation deposition σ_s has been reached.

To evaluate the function $\lambda(\sigma)$ filter parameters were calculated from the changes in turbidity between the sampling points. Also the specific deposit (in turbidity) was evaluated from the cumulative turbidity removal in the respective segments. Then, after elimination of outliers by a statistical procedure data were grouped after specific solids deposit and mean λ was calculated for the groups. Obtained mean λ were then fitted by a third-order polynomial equation.

Specific pressure drop (i.e. pressure drop per unit bed depth) also varies with time as deposition of flocs and particles in the bed proceeds. For further analysis specific pressure drop was plotted as a function of specific solid

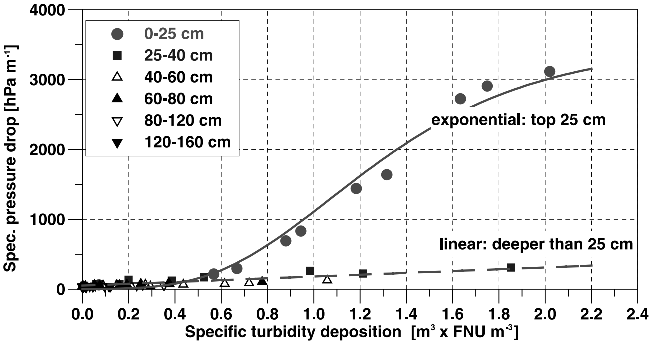

Figure 8 | Specific pressure drop in filter 2 as a function of specific solid deposition (symbols) and exponential (top-layer) and linear fit (layers greater than 25 cm bed depth).

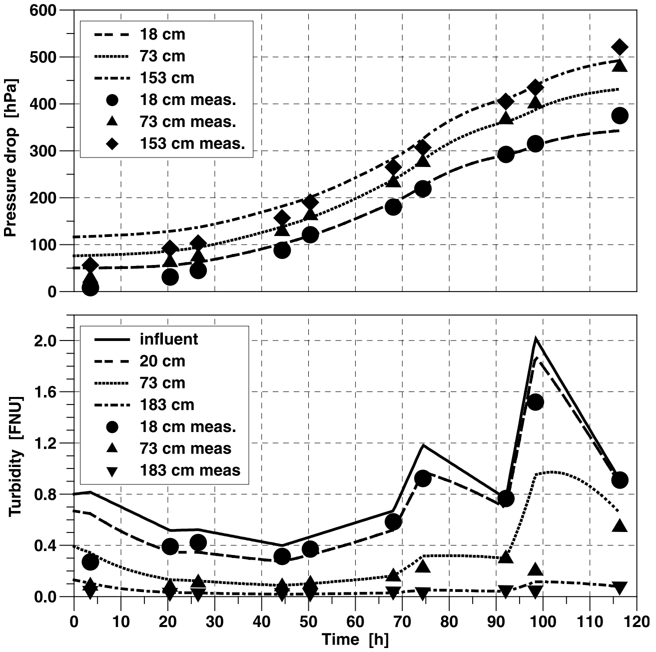

Figure 9 | Results of simulation (lines) of pressure drop and turbidity and measured data points (symbols).

deposition. As an example this is shown in Figure 8. It can clearly be seen that for the first filter element pressure drop varies nonlinearly with specific deposition and clearly is a result of the superposition of deep bed and surface filtration. For the first element pressure drop as a function of specific turbidity deposition was described empirically by an exponential function. For all other elements pressure drop could be well described by a linear function.

The PSC behaved quite differently with respect to pressure drop. As a result of their extreme porosity specific pressure drop was independent from specific turbidity deposition. However, a decreasing linear relationship with bed depth was observed. It is a result of the effect that the PSC was compressed to a certain extent. Compression was higher at the top of the bed, resulting in a higher specific pressure drop.

With the obtained relationships simulations were carried out. For mathematical handling a finite difference method (100 elements in bed depth direction) was applied. A filter run similar to the one investigated was simulated. For influent turbidity linear interpolation was carried out between the measured values. Simulation was made with a 4th order Runga-Kutta method.

Figure 9 shows (reference filter 1 as an example) the results of such a simulation. It can be seen from the graph that the simulation matches the measured data points very well. For the other two filters, matches were also very good.

With the developed model then simulations were carried out for combinations of PSC with GAC Picabiol. They showed that already a PSC layer of a few centimetres should relieve the GAC considerably from flocs and thus enable filter runs with a much lower pressure drop compared with a pure GAC Picabiol filter. The model prediction also showed that at the same time the application of PSCs should have no detrimental effect on DOC removal.

However, as the model is probably not valid for very small layers, for phase 2 experiments a 30 cm PSC-layer was chosen.

Phase 2

From the phase 1 experiments and the modelling it was concluded that BDOC removal could possibly be improved if part of the granular filter material was replaced by permeable synthetic collectors (PSC). At the same time the detrimental effect of GAC Picabiol on pressure drop should be overcome.

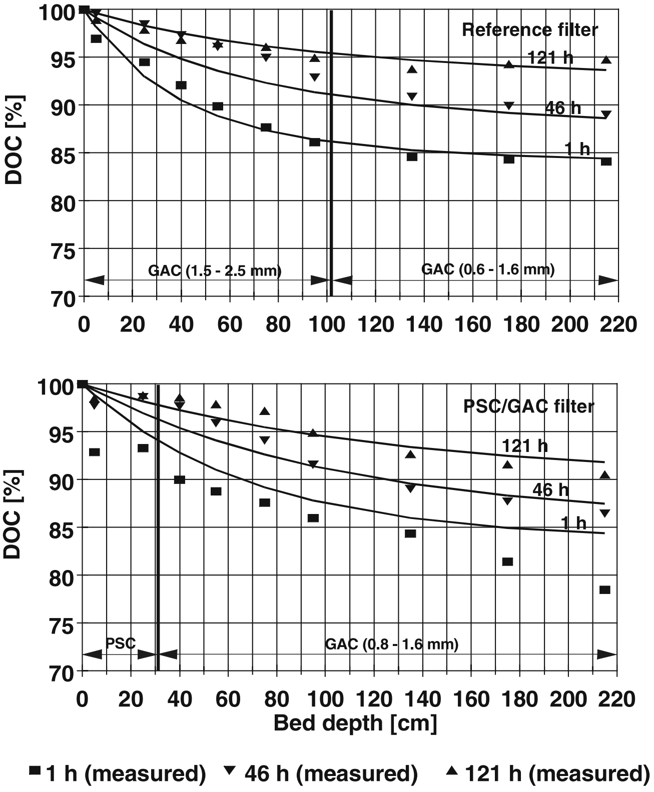

Figure 10 | Relative DOC effluent concentration measured (symbols) and calculated (lines) as a function of bed depth and filter run time in reference filter and PSC/GAC filter. Temperature approx. 5°C.

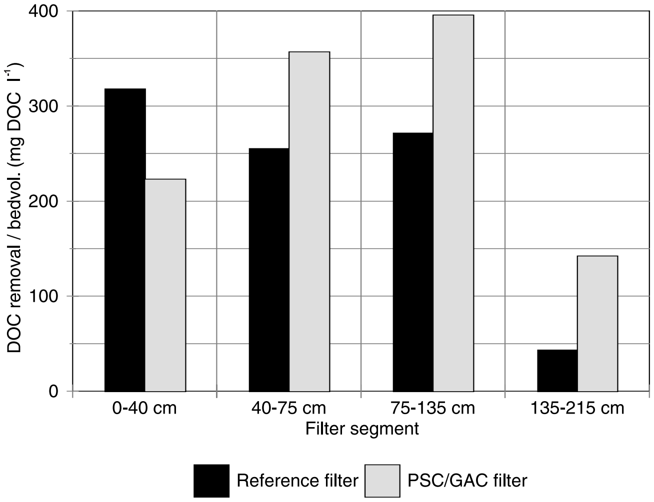

Figure 11 | DOC removal per unit bed volume in different filter segments.

As pointed out above, in column 1, as the reference filter, a combination of two activated carbons of different densities and grain size was applied, similar to the full-sized plant. In column 2 the lower 85% of the bed was GAC. The upper 30 cm was PSC. In contrast to phase 1 water temperature now was much lower: about 5°C compared with 23°C in phase 1.

As expected it was found that the removal of particles and flocs (measured as turbidity and total aluminium concentration) was much higher in the 30 cm PSC layer compared with the similar layer of granular media in column 1. Thus at deeper bed depths minor hindrance of biodegradation by deposited flocs was expected. Also in this phase removal of BDOC in the filter bed could be well described by a first-order reaction. Furthermore, the rate constants could be described as a function of filter run time, more exactly as a function of deposited material.

Figure 10 shows measured and calculated DOC effluent concentrations in column 1 (reference filter) and column 2 with the PSC layer on top as a function of bed depth and operation time. It becomes evident that the detrimental effect of deposited flocs and particles on DOC removal is less when part of the GAC is replaced by PSCs. While after approximately 5 days of operation the DOC effluent concentration in the reference filter is about 95% of the influent concentration, it is decreased to about 90% in the filter with PSCs. It has to be pointed out that in this phase water temperature was lower than in phase 1, resulting in comparably lower removal efficiencies.

For the same filter run Figure 11 shows the relative DOC removal (cumulatively over one filter run) in different sections of the two filters. In the first 40 cm DOC removal was higher in filter 1 as the PSCs in filter 2 are not as well suited as carrier material for sessile bacteria. However, as aluminium flocs and particulates are more effectively removed by PSCs (not shown explicitly here) the following filter sections are relieved from the detrimental effects of deposited material. Thus, in these filter sections DOC removal is higher in column 2. Mechanisms involved may be the inhibition of bacterial metabolism by polyaluminium chloride (Huck *et al.* 1990, 1991) and the hindrance of substrate diffusion to sessile bacteria by deposited inorganic material. There have been similar findings by others, especially at low temperatures (e.g. Prévost *et al.* 1995)

CONCLUSION

In general the results show that the application of permeable synthetic collectors (PSC) on top of granular media is a promising approach to improve the removal of BDOC and particles in deep bed filters for drinking water treatment.

ACKNOWLEDGEMENTS

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