The effect of biological pre-filtration on the performance of conventional surface water treatment

Gerald Heinicke, Frank Persson, Wolfgang Uhl, Malte Hermansson and Torsten Hedberg

ABSTRACT

Many waterworks that apply conventional treatment of surface water, by flocculation and filtration, have to deal with seasonal changes of the raw water quality, increasing concentrations of natural organic matter (NOM), and the necessity to improve particle removal. A pilot plant was operated to closely resemble the full-scale treatment at a surface water treatment plant in Göteborg, Sweden. Treatment consisted of flocculation, sedimentation and rapid granular activated carbon (GAC) filtration. To assess the effects of biological pre-filtration, the feed water to the pilot plant was switched weekly between surface water and biofiltered water which had passed through adsorptively exhausted GAC at an empty bed contact time (EBCT) of 34 minutes. The processes were investigated with regard to NOM, the bacterial re-growth potential, as well as their function as a barrier for suspended particles that originate from the raw water. Biological pre-filtration improved particle removal and made it less dependent on the post-sedimentation GAC rapid filter, thereby improving robustness. Episodically elevated concentrations of earthy-musty odour compounds, which are not reliably removed by flocculation and filtration, were reduced by the biofilters. The process combination may be of particular interest for waterworks with variable raw water quality.

Key words | autofluorescent particles, biofiltration, conventional treatment, NOM, odour, pre-treatment

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INTRODUCTION

The majority of Swedish surface waterworks use conventional treatment, i.e. flocculation, sedimentation and rapid filtration through sand or granular activated carbon (GAC), or coagulation followed by direct filtration. Progress in analytical methods and a better understanding of health risks have revealed threats to drinking water quality of both chemical and microbial origin that were not considered before. During the past decades, uncommonly high and variable colour values have been observed in Western and Northern European surface waters, a development which has been discussed in relation to climate change (Forsberg 1992; Freeman *et al.* 2001; Nordtest 2003). A number of Swedish waterworks have in recent years experienced episodes of unusually high particle and NOM concentrations in raw water, which have stressed treatment capacities to their limits. Thus, conventional Swedish surface waterworks, typically designed more than thirty years ago, face a number of challenges and may need to upgrade their treatment.

After the Milwaukee outbreak in 1993, improved particle removal was demanded, particularly in cases of variable raw water quality (Miller 1994; Fox & Lytle 1996). The removal of particles which originate from raw water has been shown to be only moderate over a well-functioning conventional treatment plant (Bergstedt & Rydberg 2002). Quantitative microbial risk assessment studies have indicated that it is the pathogens that pass treatment during normal operation, rather than during occasional events of

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process disturbance, that are responsible for the largest part of the risk for waterborne disease in conventional surface waterworks (Westrell *et al.* 2003). It is therefore desirable to improve particle removal, and thereby the microbial barrier, of conventional treatment plants. Also, dissolved substances causing taste and odour in trace concentrations, such as trans-1-10-dimethyl-trans-9-decalol (geosmin) and 2-methylisoborneol (MIB), are not reliably removed by conventional treatment (Sävenhed *et al.* 1987; Bruce *et al.* 2002), and improved removal is desirable.

Traditional biological treatment processes include riverbank filtration, artificial recharge, and slow sand filtration. Recharge and bank filtration have retention times of one to several weeks, and the produced water is usually of groundwater character (Kuehn & Mueller 2000). These processes necessitate favourable geological conditions, while slow sand filtration is area and labour demanding. Biofiltration at higher a hydraulic load than slow sand filtration was investigated as pre-treatment to flocculation (Zhang *et al.* 1998). It was found that biofiltration facilitated particle aggregation in flocculation, and decreased the coagulant demand. Terauchi *et al.* (1995) furthermore mentioned an equalising effect of biological pre-filtration on feed water variability for a number of parameters, including turbidity.

The objective of this study was to evaluate conventional treatment of typical Swedish surface water, and the potential benefits of biological pre-filtration. Of special interest was the function as a barrier for particles of raw water origin and the removal of NOM, as well as substances causing taste and odour. Ozonation was not considered as an option, in order not to introduce further biological instability to the water.

MATERIAL AND METHODS

Full-scale treatment and pilot plant

Lackarebäck waterworks located at Göteborg, Sweden, receives soft, moderately humic surface water (Table 1). At the waterworks, a 1-m^3/h pilot plant, closely resembling the full-scale treatment was operated (Figure 1, Table 2).

The treatment consisted of flocculation, sedimentation, and filtration through GAC (F200, Calgon Carbon Inc., USA) that had previously been in full-scale operation for 2.5 years. The feed water was switched weekly between raw water and biofilter effluent.

The hydraulic retention time in each of the four flocculation chambers was 27 minutes. Power input was by gate impellers; the G-values calculated according to Hernebring (1981), with the assumption that $\alpha = 0.6$, were approximately 70, 20, 5 and 2 s^{-1} at 10°C, based on torque measurement and rotation speed. The sedimentation tank (with a sludge pocket) had a tilted bottom, the horizontal projection surface of which was approximately 1.6 m^2, resulting in a surface load of 0.63 m/h.

Two biofilters of stainless steel columns, 60 cm in diameter with 2 m bed height of GAC (F200) were operated in parallel at a filtration rate of 3.5 m/h. The carbon had previously been in operation for four years and was largely exhausted for NOM adsorption (methylene blue value <30 mg/g compared to 200–250 mg/g for fresh GAC). The filtrate from the two biofilters was blended in a covered stainless steel storage tank. A 15-minute backwash with raw water was carried out weekly, at a target expansion of 35%, and preceded by a 5-minute surface backwash through a perforated pipe which was embedded near the surface of the bed. Biofiltrate samples were taken weekly before the filter backwash. Samples of the rapid filtrate were taken 45 minutes after backwash of the rapid filter.

Flocculation batch testing

Flocculation batch testing in round 1-liter jars was carried out to assess the effects of the aluminium dose. Raw water and biofiltrate were flocculated with doses of 1.30, 1.95 and 2.60 mg/l Al, in triplicates. The pH was adjusted to 6.4 by addition of HCl or NaOH. Single-blade impellers (70×40 mm) were set to induce G-values closely similar to those in the pilot plant, i.e. 59, 18, 3 and 2 at the given temperature (5°C). Each of the 4 rotation speeds was kept for 10 minutes. Then the flocs were allowed to settle for 30 minutes prior to decanting 250 ml of the supernatant. Unfiltered samples were taken for measurements of turbidity and pH, while samples for UV_{254} absorbance and flow cytometry were filtered through 2 layers of pre-rinsed filter paper (Type 003, Munktell, Sweden), to remove remaining floc.

Table 1 | Raw water quality during the investigation

Parameter	Median	n	Parameter	Minimum	Average	Maximum	n
pH	7.1	157	TOC (mg/l)	4.0	4.7	5.6	59
Alkalinity (mg/l HCO_3)	18	157	UV_{254} (m^{-1})	10.7	12.8	18.2	61
Hardness (mg/l Ca^{2+})	7	24	BDOC (mg/l)	0.7	1.1	1.4	19
Turbidity (FNU)	0.8	157	AOC (μg C/l)	17	39	69	19

Analytical methods

The enumeration of autofluorescent particles (FL particles) by flow cytometry was introduced as a tool to monitor the microbial barrier function in water treatment (Bergstedt & Rydberg 2002). In the investigated raw water, the autofluorescent particles were identified as microalgae, by microscopy. Total particles (forward scatter) and the fraction of autofluorescent particles were enumerated with a flow cytometer (Biodetect AS Microcyte Advanced, Oslo, Norway), in separate sub samples. Since autofluorescent particles are not produced during treatment, they are indicators for the removal of biological particles originating from the raw water. Two size intervals were monitored; 0.4–1 μm (bacterial size) and 1–15 μm (protozoan size range), after calibration with polystyrene standard microspheres (Biodetect AS). The removal of algae (Akiba *et al.* 2002) and FL particles 1–15 μm (Bergstedt & Rydberg 2002) has been shown to correlate with *Cryptosporidium parvum* removal.

UV_{254} absorbance was measured by passing 100 ml of the 0.45 μm-filtered sample through a spectrophotometer (Aquamate, Spectronic Unicam Ltd.) equipped with a 2-cm flow cell.

Total organic carbon (TOC) samples were taken in glass bottles muffled at 550°C for 4 hours, and closed with black polypropylene caps soaked in ultrapure water. Samples were acidified to pH <2 by adding 0.1% (v/v) of 37% HCl and stored at 4°C. TOC analysis was carried out with a Shimadzu 5000 TOC analyser with normal sensitivity catalyst in the TC-IC mode. The TOC value was determined as the average of three vials spread over an instrument run.

Quantitative analysis of NOM fractions was performed by the Liquid Chromatography – Organic Carbon Detection (LC-OCD) methodology. The method combines size-exclusion chromatography with high sensitivity organic carbon detection and allows for simultaneous quantification of several NOM fractions (Huber & Frimmel 1991).

For BDOC measurements, the sand-inoculum method according to Allgeier *et al.* (1996) was modified as follows. In 1 l glass flasks sealed with PTFE lined caps, 550 ml of sample was incubated with 100 g of biologically active sand acclimatised to local raw water, or rapid filtrate from conventional treatment for low-TOC samples, prior to BDOC incubation. The flasks were incubated on a shaker (30 rpm) at room temperature. Samples were filtered through muffled glass fibre filters (GF/F, Whatman, Maidstone, UK)

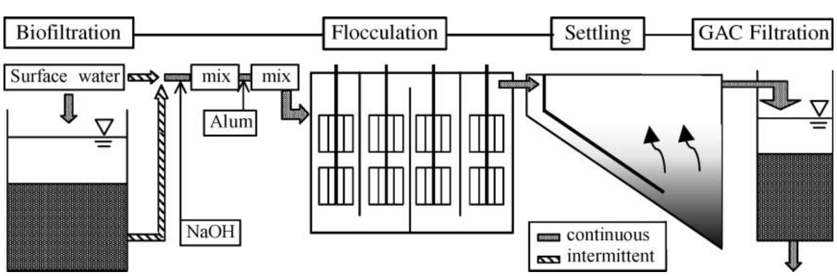

Figure 1 | Schematic of the pilot plant, which consisted of conventional treatment (flocculation, sedimentation and rapid filtration through GAC) and could be operated with or without biological pre-filtration.

Table 2 | Process parameters of full-scale and pilot conventional treatment

Parameter	Full-scale	Pilot scale
Flocculation pH; alum dosage	6.4; 2.6 mg/l Al	6.4; 2.6 mg/l Al
Pre-chlorination	0.3 mg/l if raw water > 12°C	none
Production during test period	3625 m^3/h (2917–4625)	1 m^3/h
Pre-flocculation pH adjustment	Lime slurry 5 mg/l Ca	NaOH
Flocculation tanks, total HRT*	6 tanks, 105 minutes	4 tanks, 108 minutes
Energy input by gate impellers (10°C)	$G = 20$ to $2\,s^{-1}$	$G = 70$ to $2\,s^{-1}$
Sedimentation surface load	1.04 m/h	0.63 m/h
GAC Filtration rate, EBCT	4.5 m/h, 13.5 minutes	4.8 m/h, 12.5 minutes
Backwash frequency	24 h	48–72 h

*HRT: Hydraulic residence time. Retention times and surface load in full-scale given for average production

prior to DOC analysis. The BDOC concentrations were calculated as the difference between initial DOC and the DOC after 14 days.

The analysis of assimilable organic carbon (AOC) with *Pseudomonas fluorescens* strain P17 (van der Kooij *et al.* 1982) was performed according to Långmark *et al.* (2005) with duplicate 500 ml water samples.

Earthy-musty odour episodes in raw and drinking water at Lackarebäck waterworks have earlier been associated with geosmin and MIB by the column-sniffing methodology described by Sävenhed *et al.* (1987). The samples were taken in glass bottles with glass caps and refrigerated until analysis. Trace analysis of geosmin and MIB was performed by closed-loop air stripping (2 h, 55°C) and GC-MS (HP 1800A, HP-1 column). The detection limit was 0.5 ng/l, using deuterated geosmin as internal standard.

Data evaluation and statistical methods

The conventional treatment pilot plant was operated from February 2003 to May 2004. Since the feed water to the flocculation train was switched weekly between raw water and biofiltrate, samples after conventional treatment with and without pre-filtration were taken alternately, a week apart. To avoid bias from seasonal variation, pairs of data were formed from consecutive weeks with and without biological pre-filtration. The statistical significance was determined by the student t-test (paired, 2-tail). Since the biofilter effluent was blended before feeding the flocculation train, the biofiltrate value represents the average of two biofiltrate samples for each sampling occasion.

RESULTS AND DISCUSSION

For flow cytometry, UV_{254} and TOC, there was no significant difference between the two raw water datasets taken during weeks with and without biological pre-filtration ($p > 0.75$). This allowed for pair wise comparison of conventional treatment with or without pre-filtration, even though only one pilot plant existed. The pilot plant produced water which was similar in quality to the filtrate from full-scale treatment. The pilot plant achieved slightly, but in statistical terms significantly better removal of UV_{254}, TOC and total particles ($p < 0.05$), while there was no difference in the removal of autofluorescent particles ($p > 0.09$). Also the long-term variation within the datasets was comparable. Therefore it was concluded that results from the pilot plant could be applied to the full-scale treatment.

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Particles

The seasonal pattern of FL particles in raw water is shown in Figure 2. The algae concentrations exhibit two distinct peaks over the year; a spring bloom in March / April, sustained by increasing irradiation and nutrient stocks built up during winter, and a second, larger bloom which typically begins in June and peaks in August. The low count on August 18 was due to an increase of intake depth from 8 to 16 m. Thereafter, the limited supply of deep water was exhausted and water with higher algae concentrations again reached the intake.

The average removal of particle fractions over the year is shown in Figure 3. Of total particles, the biofilters removed on average 79% of the small (0.4–1 μm) particles and 88% of the large fraction (1–15 μm) (Figure 3a, b). The removal of FL particles was significantly lower, at 56% for the small FL particles, and 63% for the large FL particles ($p < 0.01$) (Figure 3c, d).

On average, 10% of the small FL fraction passed the treatment train. With pre-filtration, this was reduced to 5% ($p < 0.01$). Corresponding values for large FL particles are 1.8%, and 0.5% with pre-filtration (Figure 3c, d, $p = 0.02$). The observation that a considerable fraction of raw water derived particles passed a conventional treatment train which consistently achieved turbidity values below 0.05 NTU is relevant for the assessment of microbial risk. Apart from cryptosporidium, this size range is also critical for other chlorine-resistant protozoa (Ribas *et al.* 2000) for which physical removal is the most important mechanism of elimination in drinking water treatment. The observed improvement in the reduction of large FL particle concentrations with biological pre-filtration was on average 3.6 fold.

The removal of FL particles by the processes during different algae seasons is illustrated in Figure 4. The percentage of FL particles removed by the biofilters was highest in times of algae blooms, and lowest during the winter, showing that biofiltration equalised peak loads of particles, as also demonstrated by Persson *et al.* (2005*a*). With pre-filtration, compared to conventional treatment, it was found that the percentage of FL particles removed by the post-sedimentation BAC-filter was reduced. The lesser amount of particles entrapped in the filter bed may well reduce the risk of peak loads released to the drinking water, both at the beginning of each filter run and in case of disturbances. For example, a decrease of coagulant dosage towards sub-optimal conditions shifted the removal of added faecal indicator bacteria from the sedimentation step to the rapid filter, resulting in higher bacterial numbers in the first filtrate after filter backwash compared with normal coagulant dosage (Johansson & Scott 2004).

NOM

The average raw water concentrations of NOM parameters are summarised in Table 1.

Bulk organic matter

The analysis of filtered (DOC) and unfiltered (TOC) raw water samples revealed that there was no measurable particulate NOM fraction. Raw water UV_{254} absorbance varied between 11 and 13 m^{-1} during spring and summer 2003, with a steep increase to 18 m^{-1} in early 2004. A corresponding increase in specific UV absorbance

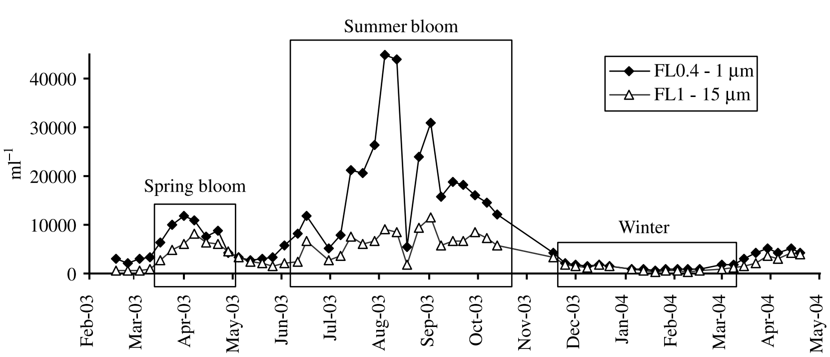

Figure 2 | Time series of autofluorescent particles (FL) in raw water.

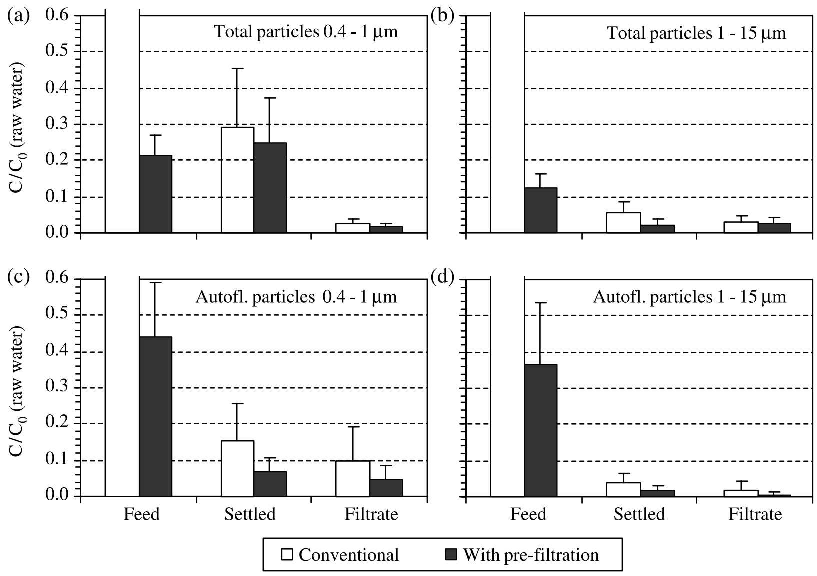

Figure 3 | Fractions of raw water particle concentrations remaining after treatment processes on the pilot plant (paired data, n = 22). Analysis by flow cytometry. P: total particles; FL: autofluorescent particles. Raw water = 1.0.

(SUVA = UV_{254}/DOC) in raw water from 2.5 l/(mg·m) in summer 2003 to 3.5 l/(mg·m) in early 2004 was observed. The notable increase in UV_{254} during Winter 2003/2004 was caused by a rainy December with more than 12 times as much precipitation as during December 2002. In the typical Nordic catchment with coniferous forest and a thin soil layer on bedrock, periods of high precipitation are known to replace the humic-enriched pore water in the soil (Grip & Rodhe 1994). In that way, pedogenic humic matter is flushed into surface waters.

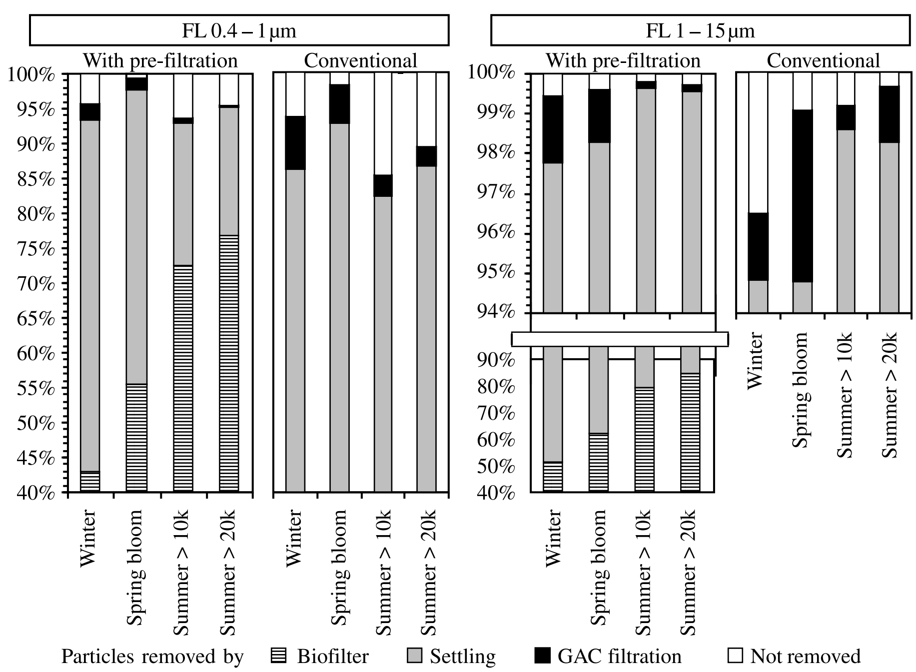

Figure 4 | Seasonal variation of autofluorescent (FL) particle removal by specific processes in the pilot plant (paired data). Algae periods defined after the raw water concentration of FL 0.4–1 µm particles. Winter: <2 000/ml; Spring bloom: >5000; Summer: >10000, which includes the data points with >20000 FL particles.

Biofiltration reduced TOC by 9%, and increased the cumulative removal of TOC from 52% to 57% after conventional treatment (Figure 5). UV_{254} was reduced by 11% with biofiltration, with a corresponding increase in cumulative removal from 72% to 75% (Figure 5). The effect of pre-filtration on conventionally treated water was significant for both TOC and UV_{254} ($n = 24, 21$, $p < 10^{-4}$).

Biodegradable organic matter (BOM)

BDOC in raw water ranged from 0.69 to 1.40 mg/l with an average of 1.12 mg/l, representing on average 25% of raw water DOC (Table 1). During BDOC incubation, DOC did not level out completely within 14 days as it did in other studies (Volk *et al.* 1994). BDOC consists of monomeric as well as polymeric components and may also include humic matter (Volk *et al.* 1997). The retarded degradation indicated a large proportion of slowly biodegradable BDOC in this moderately humic water. AOC consists of easily biodegradable low molecular weight compounds (Escobar & Randall 2001; Hem & Efraimsen 2001) and ranged from 17 to 70 μg C/l in raw water, with an average of 40 μg C/l (Table 1).

The biofilters removed BDOC with an average efficacy of 23% (Figure 5). Conventional treatment with biological pre-filtration reduced the average BDOC by 69%. This was significantly higher ($p < 0.05$) than for conventional treatment alone, which removed 59% in both the pilot plant and the full-scale. The biofilters' removal efficacy for AOC was 19%. Conventional treatment reduced AOC to an average of 4 to 6 μg C/l, with no significant effect from pre-filtration. AOC values were below 10 μg C/l, i.e. typical for biostable water (van der Kooij 1992). This was in agreement with the low degree of biofilm formation measured on glass slides in filtrate from the full-scale plant (data not shown). BDOC however remained higher than the proposed limit of biostability, i.e. 0.15 mg/l for non-chlorinated water (Servais *et al.* 1995). The slow character of BDOC in this water may contribute to a modest aftergrowth potential even at comparably high BDOC concentrations.

NOM fractionation

To further characterise raw water NOM composition and its removal by the treatment steps, LC-OCD analysis was performed during autumn 2003 (Table 3).

The TOC was 4 mg/l, with a non-chromatographable fraction of 0.4 mg/l, *i.e.* either particular matter or hydrophobic substances not eluting from the column. Humic substances represented around half of the TOC. The humic fraction, with its SUVA of 4.5 – 4.8 l/(mg·m) and molecular weight around 750 amu, was dominated by pedogenic fulvic acids, *i.e.* originating from soil. Building blocks, i.e. fragments of humic substances with a molecular weight <350 amu, made up the second largest fraction (27% of the TOC). Highly substituted aromatic acids are an example of substances in this fraction. Biopolymers, i.e. high molecular weight products of algae and bacteria, represented 5% of the TOC. Low molecular weight neutrals and aliphatic acids

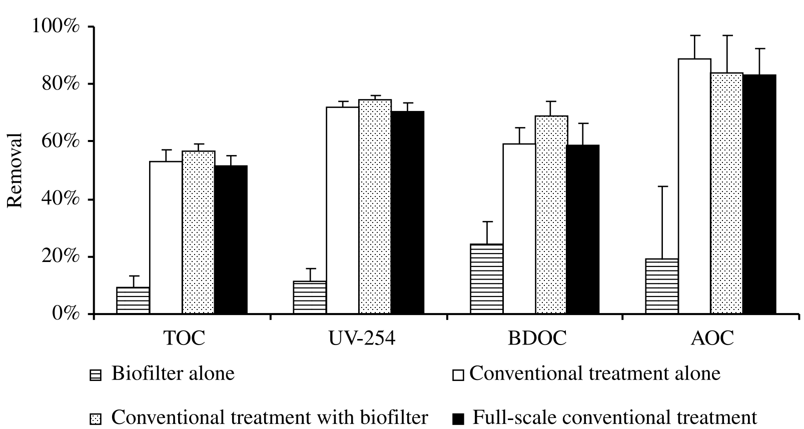

Figure 5 | Removal of NOM over the experimental period. Error bars show one standard deviation. Paired data for conventional treatment with and without pre-filtration: TOC: $n = 22$, UV254: $n = 20$, BDOC: $n = 4$, AOC: $n = 6$. For biofiltration alone: TOC: $n = 59$; UV_{254}: $n = 44$, BDOC: $n = 8$, AOC: $n = 8$.

Table 3 | Composition of TOC in raw water by LC-OCD (n = 2)

Parameter	mg/l (±SD)
TOC	4.060 ± 0.019
HOC*	0.419 ± 0.108
CDOC**	3.642 ± 0.090
Biopolymers	0.208 ± 0.010
Humics	1.945 ± 0.035
Building blocks***	1.069 ± 0.017
LMW acids	0.058 ± 0.009
LMW neutrals	0.362 ± 0.058

*hydrophobic and particulate TOC
** chromatographable DOC
*** aromatic and highly substituted compounds <350 amu.

were present in concentrations of 420 and 50 μg/l, constituting 10% and 1% of the TOC, respectively.

The relative removal of the LC-OCD fractions over the pilot plant is shown in Figure 6. Similar to the results of the ordinary TOC measurements, the biofilters removed approximately 9% of the TOC measured by LC-OCD. Of the removed 0.37 mg/l of TOC, the majority (0.23 mg/l) was in the non-chromatographable fraction. Additionally, 0.1 mg/l of humic substances were removed, as well as part of the biopolymers. The biofilters did not alter the molecular weight characteristics of the humic acid fraction. Non-chromatographable TOC (HOC) consists of particulate matter and hydrophobic substances. Since no considerable particulate NOM fraction was present, HOC was assumed to be of hydrophobic nature. This was confirmed by the fact that the HOC fraction passed an ultrafiltration membrane largely unaffected (data not shown). Conventional chemical treatment specifically removed humic substances. As a result, building blocks constituted the majority of TOC in post-sedimentation GAC filtrate.

Taste and odour

The seasonal pattern of geosmin and MIB concentrations consisted of a summer peak, mid June to mid September, followed by a time of moderate concentrations of 2–3 ng/l until November, and concentrations below 2 ng/l the rest of the year (Figure 7). The summer peak coincided with high FL particle numbers measured by flow cytometry. Distinct drops in the geosmin concentrations followed upon the increase of intake depth from 8 m to 16 m on August 12, 2003 and August 19, 2004. MIB was only detectable during the summer peak. During the odour season, the full-scale plant had geosmin levels in drinking water of 1.5 to 3.5 ng/l. Geosmin removals over the full-scale treatment were 61% (SD = 6%, n = 9)

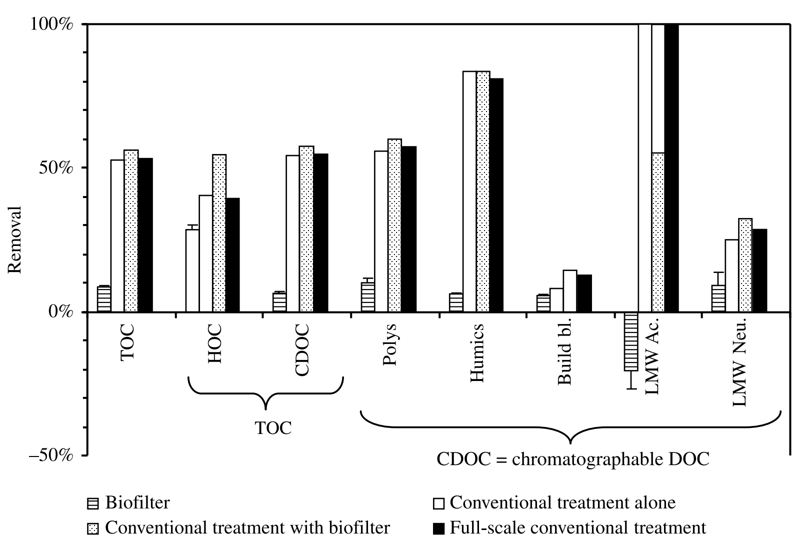

Figure 6 | Removal of TOC fractions by flocculation, analysed with LC-OCD. n = 2 for the biofilters, error bars show one standard deviation. Otherwise n = 1. bl. = blocks, Ac. = Acids, Neu. = Neutrals.

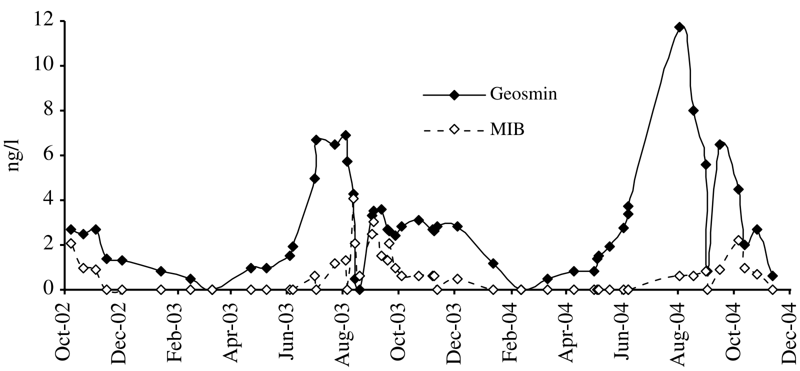

Figure 7 | Seasonal pattern of geosmin and MIB in raw water. Values shown as zero are below the detection limit of 0.5 ng/l.

during the summer peak and 33% (SD = 8%, n = 8) during autumn. The detection of geosmin and MIB by GC-MS in drinking water correlated with consumer complaints, although the observed concentrations were in the low range of published odour threshold values (Young *et al.* 1996).

The biofilters removed geosmin to below the detection limit in 10 out of 12 samples, and MIB was always removed to below the detection limit (data not shown). When geosmin was detected in biofiltrate, the removal was at least 83%. Consequently, the biofilters alone reduced geosmin and MIB to a considerably higher degree than conventional treatment. Detailed investigations of geosmin and MIB removal by biofiltration of raw water are described in Persson *et al.* (2005*b*).

Batch testing

The results of batch flocculation-tests with raw water and biofiltrate at different dosages of aluminium and after flocculation, sedimentation and paper filtration are shown in Figure 8. For FL-particles (0.4–1 μm), the results are presented in Figures 8a. The effect of pre-filtration and alum dose on UV_{254} absorbance is illustrated in Figure 8b. Biofiltration reduced UV_{254} absorbance, and the difference was carried on through the batch test. Data from the batch tests are in accordance with the results from the pilot plant operated on raw water three days before, and on biofiltrate four days after (data not shown). It has generally been assumed at Lackarebäck waterworks that the normal coagulant dose of 2.6 mg/l Al in full-scale production was a deliberate overdosage to safeguard rapid filtrate quality in case of changes in raw water quality. Results from the batch testing however indicated that a 25% decrease in alum dosage negatively affected the removal of both particles and NOM. With biological pre-filtration, a 25% dose reduction produced similar numbers of FL particles and a lower UV_{254} than was achieved without biofiltration at the standard-dose.

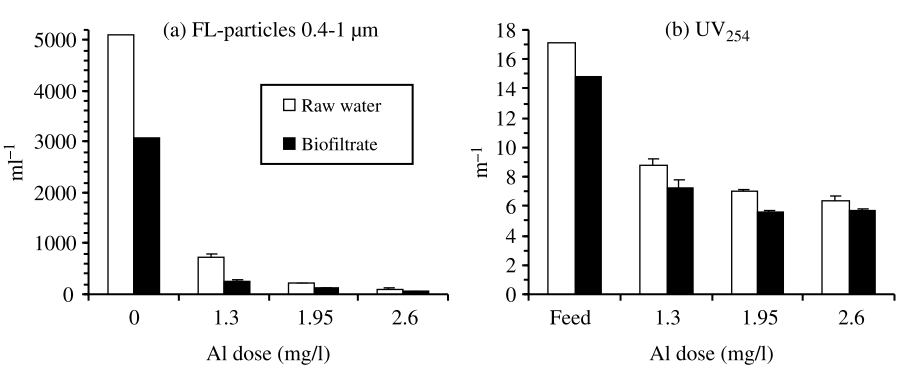

Figure 8 | Batch test. FL particles 0.4–1 μm (a) and UV_{254} (b) in raw water and biofiltrate (Feed), and after flocculation, sedimentation and paper filtration. Error bars for the treated samples are standard deviations of triplicate jar tests.

Practical application

Conventional treatment in full and pilot-scale removed less than 90% of the biological particles of raw water origin, measured as autofluorescent particles by flow cytometry. An increase in particle removal over treatment is therefore recommended. Integrating biological pre-filtration into an existing conventional treatment train implies considerable investment costs. Similar to the implementation of processes involving subsurface passage, local conditions determine whether an implementation of biological pre-filtration is feasible. At Lackarebäck waterworks, the raw water pressure is high enough to pass the water through additional filters without requiring pumping.

Biological pre-filtration may be particularly interesting when aesthetical problems with raw water quality exist, like episodes of elevated concentrations of taste and odour compounds, or dissolved iron and manganese species. In each specific case, the benefits of biological pre-filtration (improved particle and NOM removal, odour, iron and manganese and reduction of variability) need to be weighed against the costs and compared to other options of process upgrade such as ozonation-biofiltration or ultrafiltration.

CONCLUSIONS

Biological pre-filtration improved the filtrate quality produced by conventional treatment. Generally, the removal of particles as well as NOM and its biodegradable fraction was improved. Batch tests showed that, with biological pre-filtration, the coagulant dose could be lowered by 25% to achieve the same water quality. In the light of recent risk assessment studies, the improvement gained by biological pre-filtration should rather be applied to improve the microbial barrier function. The additional filtration step made particle removal less dependent on the post-sedimentation GAC filter. This would increase robustness of the treatment process against variations in raw water quality and disturbances in filter function.

The removal of the odorants geosmin and MIB over the biofilters alone was higher than over full-scale conventional treatment. Biological pre-filtration therefore is an interesting option to control seasonal odour episodes related to algae growth.

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