Effects of media, backwash, and temperature on full-scale biological filtration

BY MONICA B. EMELKO, PETER M. HUCK, BRADLEY M. COFFEY, AND E. FRANKLYN SMITH

Full-scale biofiltration experiments demonstrated that good removal of biodegradable organic matter (BOM) following ozonation could be achieved without compromising particle removal. BOM removal by granular activated carbon (GAC) filter adsorbers and dual-media filters was measured using total organic carbon (TOC) and certain BOM components (carboxylic acids). The authors investigated how filter backwashing with water, water and air scour, and water and air scour at collapse-pulsing conditions affect filter biomass, BOM removal, and particle removal. At 21–24°C, the media type did not affect BOM removal. At 1–3°C, GAC provided substantially better removal of oxalate and TOC than did anthracite. For both media types, cold water oxalate removals were significantly impaired, compared with those achieved in warm waters. BOM removal was more resilient than particle removal to changes in backwash protocol. Phospholipid biomass concentration was not directly related to BOM removal by filters.

The increasingly widespread use of ozonation in North America to address pathogen inactivation and chlorinated disinfection by-product (DBP) reduction criteria has focused more attention on the role of biodegradable organic matter (BOM) in drinking water treatment. The amount of BOM present in natural waters increases during ozonation (Westerhoff et al, 1996; Langlais et al, 1991). The presence of BOM is undesirable because it may result in the biological instability of drinking water and often leads to bacterial regrowth in the distribution system (e.g., Zheng et al, 2002; Carlson & Amy, 1998; Servais et al, 1993; Huck, 1988).

BOM describes a suite of biodegradable compounds that includes humic substances, amino acids, carbohydrates, and ozonation by-products. Organic ozonation by-products include oxo-acids (Xie & Reckhow, 1992), carboxylic acids (Win et al, 2000; Andrews, 1993), and aldehydes (Najm & Krasner, 1995). Many of these ozonation by-products are readily biodegradable and can be removed by biological filtration in which heterotrophic bacteria attach to the medium as biofilm oxidize BOM and use it as a source of carbon (Yavich et al, 2004; Melin & Ødegaard, 2000; Wang et al, 1995; Krasner et al, 1993).

Biological filtration reduces the amount of biodegradable organic carbon that can result in distribution system regrowth or contribute to the formation of chlo-
Biodegradable organic matter describes a suite of biodegradable compounds that includes humic substances, amino acids, carbohydrates, and ozonation by-products.

Implementation of single-stage biological filtration offers an effective treatment strategy when sufficient reduction of BOM can be achieved without compromising particle removal or hydraulic performance.

The use of appropriate backwashing strategies to ensure long-term performance of biofilters has been emphasized in several reviews and investigations of biological filtration processes (Bablon et al., 1988; Bouwer & Crowe, 1988; Camper et al., 1987; Graese et al., 1987). In nonbiological filters, processes such as air scour improve cleaning efficacy by increasing media collisions and abrasion (Amirtharajah, 1993). The simultaneous use of air and water at subfluidization velocities to achieve collapse-pulsing conditions has been reported as an optimal backwashing protocol for nonbiological filters (Amirtharajah et al., 1991) and has not demonstrated adverse effects on assimilable organic carbon removal by biological filters (Ahmad et al., 1998).

Although backwash conditions may influence the amount of biofilm present in a biological filter, the effects of specific backwashing strategies on BOM removal are not fully known. Some research suggests that removal of dissolved organic carbon (DOC) in biofilters may be controlled by biomass concentration (Carlson & Amy, 1998), which was not affected by air-scour backwashing in one study (Servais et al., 1991). Sufficient biomass is required to remove BOM in biological filters; therefore, backwashing strategies originally developed for nonbiological filters must be reexamined to ensure that adequate BOM removal is achieved concurrently with good particle removal. Furthermore, the sensitivity of BOM removal to operational parameters such as temperature and media type must be elucidated so that meaningful biofiltration design and operational strategies can be developed. The relationships among water temperature, the presence of biomass, and the removal of BOM are not clearly understood. The experiments described in this article examined the effect of water temperature, media type, and backwashing strategy on particle and BOM removal as well as biomass concentration in full-scale biological filters. These experiments contributed to a larger study focused on optimizing filtration in biological filters (Huck et al., 2000).

MATERIALS AND METHODS

Facility description. The Mannheim Water Treatment Plant located in Kitchener, Ont., is a conventional surface water treatment plant with postsedimentation ozonation and biological filtration processes following final disinfection; related benefits include a reduction of chlorine demand and a decrease of corrosion potential (Rittmann & Huck, 1989). Under some conditions, the removal of taste-and-odor-causing compounds can also be effectively achieved with biologically active filters (Manem & Rittmann, 1992; Lundgren et al., 1988). For many existing drinking water treatment plants, retrofitting with separate filtration processes optimized for sequential particle and BOM removal may not be feasible because of hydraulic or space constraints.
tion. The Mannheim facility has two identical treatment trains, one of which is shown in Figure 1. The plant typically produces finished water with turbidities of <0.1 ntu year-round. Mannheim’s design capacity is 72,000 m³/d (19 mgd). Mannheim’s four biologically active rapid filters are fed from a common header, each treating 25% of the total flow. All of the filters were operated in a constant rate, increasing head mode during the experimental periods. Two of the filters are granular activated carbon (GAC) filter adsorbers consisting of 54 in. (137 cm) of GAC over 12 in. (30 cm) of sand, and two are dual-media filters consisting of 48 in. (122 cm) of anthracite over 12 in. (30 cm) of sand. Each filter is 726 sq ft (67.4 m²) in area.

Mannheim treats water from the Grand River, which is affected by agricultural and municipal uses. The water is relatively high in organic content, a significant fraction of which is nonhumic in origin. Grand River water quality parameters are summarized in Table 1. Under normal plant operation, the river water passes through four in-series cells of a ~38-mil-gal (145,000-m³) reservoir before reaching the plant. Some sedimentation occurs in the reservoir (average detention time of seven days). On occasion, if the river water quality is poor (e.g., following heavy rainfalls), the raw water intake is closed, and the raw water storage reservoir is drawn down.

Flow rates through the plant were ~6 mgd (23,000 m³/d) during all experimental periods except the cold water period, when flow rates were 4 mgd (15,000 m³/d). Filter loadings were 2.4 ± 0.2 gpm/sq ft (5.8 ± 0.5 m³/h) during all experimental periods except the cold water period, when rates were 1.7 ± 0.1 gpm/sq ft (4.2 ± 0.2 m³/h). The only changes in plant operation during experimentation were adjustments to the backwash protocol (Table 2). The plant operated at 21–32% of its design capacity, resulting in relatively long empty bed contact times (EBCTs) in the filters (17–36 min). Sampling taps distributed through the depth of the filters allowed for investigation of shorter EBCTs.

**Experimental design.** The experimental objectives were to (1) assess the efficacy of concurrent BOM and particle removal by GAC filter adsorbers and dual-media filters and (2) evaluate the effect of three backwash strategies on concurrent BOM and particle removal. The standard Mannheim backwash strategy consisted of air scour followed by a chlorinated low-rate water wash and then a chlorinated high-rate water wash. Following backwash, filters were run to waste until the effluent turbidity decreased to <0.2 ntu.

The first series of experiments investigated media type, water temperature, and air scour during backwashing.
to assess their effect on BOM removal and traditional performance (e.g., filter effluent turbidity, ripening profile) over several filter cycles. One GAC filter adsorber and one dual-media filter were monitored before, during, and immediately after the discontinuation of air scour from the backwash protocol. This experiment was conducted during warm (21–24°C) and cold (1–3°C) water conditions. A second series of warm water (21–25°C) investigations was conducted to assess the seasonal reproducibility of the findings. The filters were monitored for three consecutive cycles of stable operation during each of the experimental seasons. Air scour was then removed from the backwash protocol. During the first season of warm water evaluations, the GAC and anthracite filters were backwashed without air scour for eight and 10 consecutive cycles, respectively. During the cold water and second season of warm water conditions, only four consecutive filter cycles were backwashed without air scour. The backwash program was then returned to the original protocol (including air scour), and monitoring continued for another three consecutive cycles. Experiments were conducted during periods of relatively consistent raw and pretreated (before filtration) water quality and were continued as long as feasible to identify trends without imposing on plant operations.

Turbidity was measured continuously during the experiments. TOC, carboxylic acids, and aldehydes were used to assess BOM removal immediately before and 6–10 h after backwash. BOM parameters were measured both before and after backwash to examine variability in BOM removal throughout a filter cycle. All statistical comparisons were made using Student’s t-tests at the 5% significance level.

Biomass samples were collected from the top of the filters during the cold water season and the sec-

### TABLE 2  Summary of backwash procedures

<table>
<thead>
<tr>
<th>Backwash Protocol</th>
<th>Standard Mannheim</th>
<th>No Air Scour</th>
<th>Collapse Pulsing</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Draining of filter</td>
<td>To 1 ft below trough</td>
<td>To 1 ft below trough</td>
<td>To 1 ft below trough</td>
</tr>
<tr>
<td>2. Valving change</td>
<td>Inlet valve closes</td>
<td>Inlet valve closes</td>
<td>Inlet valve closes</td>
</tr>
<tr>
<td>3. Backwash</td>
<td>Drain valve opens</td>
<td>Drain valve opens</td>
<td>Drain valve opens</td>
</tr>
<tr>
<td>4. Filter-to-waste</td>
<td>Until turbidity falls to 0.2 ntu after peaking</td>
<td>Until turbidity falls to 0.2 ntu after peaking</td>
<td>Until turbidity falls to 0.2 ntu after peaking</td>
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Samples were taken from each of the Mannheim treatment plant’s four biologically active rapid filters, which are fed from a common header—each treating 25% of the total flow.
ond warm water season. Approximately 1 g of filter media was collected from the filter surfaces during each of these experiments, and subsamples were analyzed in triplicate. For the purposes of the statistical analysis, the mean of the triplicate analyses represented one sample of biomass. The biomass samples were collected immediately before and within 2 h after filter backwash. Additional biomass samples were collected 6–10 h after the water-only (no air scour) backwashes during the second season of warm water evaluations.

For each filter type, top-of-filter biomass was sampled from one filter using the standard backwash protocol and another filter for which air scour was absent from the backwash protocol. Additional data collected before, during, and after the backwash changes indicated comparable turbidity and BOM removal for the parallel filters, suggesting that the biomass comparisons were reasonable. During the cold water experiments, biomass samples were collected during only five filter cycles, all of which occurred between backwashes using the normal protocol.

The second series of backwash investigations examined the effect of a collapse-pulsing backwash protocol at water temperatures ranging from 9 to 12°C. Because this particular backwashing strategy had not been previously implemented at Mannheim, the experiments were planned for only one filter (GAC/sand). The filter was monitored for three consecutive filter cycles before, during, and immediately after the change in backwash protocol. The water and air-scour flow rates were calculated by the method described by Amirtharajah and co-workers (1991). TOC and carboxylic acids samples were collected immediately before and 6–10 h after backwashing. Aldehydes were not measured because of their relatively low measured influent concentrations during the air-scour experiments. Because the filters were producing water for consumption during these experiments, backwashing occurred only when necessary.

As part of normal plant operation at Mannheim, the media were replaced in the GAC filter adsorber before the collapse-pulsing experiments but after the air-scour experiments. Therefore, the removal data from the collapse-pulsing experiments cannot be compared directly with those from the air-scour experiments.

**Biomass measurements.** Removal of organic carbon and BOM components was evaluated by sampling at filter influent, mid-depth, and effluent points. Carboxylic acid concentrations were measured by an ion chromatographic method (Peldszus et al., 1996) that used a concentrator column, guard column, and conductivity detector equipped with a micromembrane suppressor. Samples were immediately preserved with chloroform, refrigerated, and analyzed within 72 h of collection. Carboxylic acids examined in this study included acetic (detection limit of 5 µg/L), glycolic (2 µg/L), butyric (1 µg/L), formic (2 µg/L), α-ketobutyric (2 µg/L), pyruvic (3 µg/L), and oxalate (9 µg/L).

TOC concentrations were measured using a total carbon analyzer according to method 5310C (Standard Methods, 1998) using ultraviolet-persulfate oxidation followed by a carbon dioxide–selective membrane. Samples were not filtered to remove particulate carbon because previous studies indicated that DOC consistently composed > 90% of the TOC measured at the Mannheim filter effluent and influent locations. Each reported sample value was the average of three measurements (coefficient of variation was typically < 2%).

**Biomass measurements.** Biomass was determined using the phospholipid method described by Findlay and colleagues (1989). This method provides a measure of viable biomass and has been successfully applied to drinking water biofilters by other researchers (Urfer & Huck, 2001; Miltner et al., 1995; Wang et al., 1995). Biomass is estimated by measuring the organically bound phos-
phorous (phospholipids). The lipids are extracted from the biomass attached to the surface of the filter media by a chloroform–methanol–water mixture and digested with potassium persulfate. The released phosphate is complexed with ammonium molybdate and malachite green and is measured colorimetrically. The concentration of biomass was expressed in nanomoles of phosphorous per unit filter volume (nmol P/cm³ filter media). Bulk densities of 0.43 and 0.8 g/cm³ were used for GAC and anthracite, respectively. Further details of this method as applied during this study are available elsewhere (Urfer & Huck, 2001).

**Traditional performance measures.** Head loss, turbidity, temperature, and filter flow rate were monitored continuously by the treatment plant’s supervisory control and data acquisition (SCADA) system. Turbidity was recorded continuously by on-line turbidimeters, which were calibrated using dilute formazin solutions as specified by the manufacturer. Turbidity measurements included settled water, maximum during ripening, and filter effluent turbidities. Differential pressure transducers continuously measured head loss. Filter run times and filter-to-waste periods were determined from the SCADA data.

**RESULTS AND DISCUSSION**

**Effect of water temperature, media type, and air scour.** Figure 2 shows TOC removals by the GAC filter adsorber (part A of the figure) and the dual-media filter (part B) during warm and cold water conditions. In the box-and-whisker plots, the square represents the median, and the top and bottom of the box represent the 75th and 25th percentiles, respectively. The ends of the vertical lines indicate the maximum and minimum values reported. During these investigations, the adsorptive capacity of the GAC was essentially exhausted, as would be expected after several years of continuous use and as confirmed by the manufacturer.

Throughout the experiments, the median TOC removals ranged from 13 to 23% (Figure 2), with overall removals within the 5–75% removal range of TOC in attached growth biological reactors reported by Bouwer and Crowe (1988). Although TOC removals by the GAC filter adsorber during the cold water season were slightly higher than those observed during the warm water season, these differences were not statistically significant ($\alpha = 0.05$; Figure 2, part A). Similarly, the dual-media experiments did not demonstrate a statistically significant difference in TOC removals ($\alpha = 0.05$) as a function of water temperature (Figure 2, part B). Given almost identical EBCTs, a comparison of the TOC removal by the two filters demonstrated some advantage of GAC over anthracite for TOC removal (23% for GAC compared with 14% for anthracite) at cold water temperatures ($\alpha = 0.05$). At warm water temperatures, TOC removals for the two media types were not statistically different ($\alpha = 0.05$). In this experimental scenario in which air scour was removed for a limited number of backwash cycles, the presence or absence of air scour during the backwash protocol did not result in different TOC removals ($\alpha = 0.05$) within a given media type, regardless of water temperature (Figure 2). The data suggest that GAC provides only a small benefit over anthracite for TOC removal by biological filters (Figure 2).

Carboxylic acids were consistently detected both before and after filtration. Oxalate was selected as a representative carboxylic acid because it was present at the highest concentrations on a weight basis. The other carboxylic acid
acids detected (acetic, formic, glycolic, and pyruvic) had removals comparable to oxalate.

For oxalate removal, Figure 3 shows a seasonal advantage of GAC filter adsorbers over dual-media filters. Figure 4 elaborates on these findings and shows oxalate removal profiles over the depths of the GAC filter adsorber (part A of the figure) and the dual-media filter (part B). Filter influent oxalate ranged from 400 to 600 µg/L. At warm water temperatures, median removals of oxalate were 92% in the GAC and 93% in the anthracite filter (Figure 3). The difference in oxalate removal between the two types of filters at warm water conditions was not statistically significant ($\alpha = 0.05$). A significant difference in oxalate removal between the two warm water experimental periods ($\alpha = 0.05$) was not discerned, suggesting that filter performance was seasonally reproducible (Figures 3 and 4).

Most of the oxalate removal occurred in the upper portions of the filters, corresponding to shorter EBCTs (Figure 4). Despite approximately 70% longer EBCTs during cold water conditions than during warm water conditions, the median oxalate removal by the GAC filter was ~72% when the filter was backwashed with air scour and 56% when air scour was not used (Figure 4, part A). The anthracite filter did not remove any oxalate at cold water temperatures (Figure 4, part B). These data suggest that water temperature was a critical factor affecting the removal capacity of biofilters for this BOM component.

Effect of media. TOC (Figure 2) and carboxylic acid (Figures 3 and 4) removal data indicated that BOM removal may be impaired at low temperatures, but this impairment could be partially mitigated with GAC. The demonstrated advantage of GAC over anthracite at cold water temperatures (Figures 3 and 4) provides a benefit in addition to that described by Krasner et al (1993), who indicated that better ozonation by-product removal is maintained by GAC filters exposed to temporary perturbations and reductions in removal capacity. Coffey and colleagues (1995) also reported better removal of glyoxal by GAC filters during colder water temperatures.

One reason that carboxylic acid removal by the GAC surpassed that of the anthracite during cold water conditions may be the higher external surface area provided by the medium because of its greater roughness (bacteria are unable to penetrate the GAC micropores). In addition, GAC may allow for better biofilm retention by providing attachment sites that are protected from the fluid shear stresses in the filter (Chang & Rittmann, 1987). Attachment benefits may help to maintain a minimum amount of biofilm necessary for BOM removal at cold water conditions. Although organics adsorbed on GAC may be important in maintaining biofilm at colder water temperatures, the demonstrated BOM removal advantage of GAC at
cold temperatures (Figures 2–4) is not likely associated with adsorption because the adsorptive capacity of the filters was essentially exhausted during most of the experiments reported here. There may be some renewal of adsorption sites because of biodegradation of adsorbed material, though this is likely small in relation to the filter influent TOC.

Effect of air scour during backwash. Significant differences in oxalate removal were not observed in either the GAC ($\alpha = 0.05$) or dual-media filters ($\alpha = 0.05$) during the warm water evaluations of backwashing with air scour. These results were consistent with the trends in TOC removal (Figure 2). At colder water temperatures, the presence of air scour resulted in statistically higher oxalate removal ($\alpha = 0.05$) in the GAC filter adsorber (Figure 4, part A). However, the variability and apparent production (slightly negative removal) of oxalic acid in the filter indicate that this difference may not be meaningful from a practical perspective.

Biomass. Biomass measurements investigated the relationship between biomass at the top of the filters and BOM removal capacity. Surface biomass concentrations as a function of media type and water temperature are shown in Figure 5. This figure combines samples collected immediately before and within 2 h after backwash.

Describing biomass concentrations on a per unit filter volume basis normalizes results for the different media types and densities. During warm water conditions, the dual-media filter had significantly more attached biomass per unit filter volume ($\alpha = 0.05$) on its surface than did the GAC filter adsorber (Figure 5); however, biomass levels in both filters were low compared with those observed at two other locations reported by Huck et al (2000). This difference in biomass between the dual-media and GAC filters was unexpected because the filters demonstrated comparable BOM removal (Figures 2 and 3), and it may suggest that BOM removal may not be directly related to biomass as measured by the phospholipid method. Such an interpretation should be made with caution, however, because surface biomass is not necessarily representative of the biomass profile across the depth of the filter.

At low temperature, the GAC and anthracite filters contained significantly less biomass at the top of the filters relative to that present at warm water temperatures ($\alpha = 0.05$; Figure 5). Although the cold water experiments did not demonstrate a difference in top-of-filter biomass between the two types of media ($\alpha = 0.05$), the GAC filter removed significantly more oxalate than did the anthracite filter (Figure 3). Given that the GAC filter also removed more TOC during warm water conditions, comparable biomass concentrations under warm and cold water conditions were initially not expected. Some research has suggested that DOC removal can be limited by biomass concentration (Carlson & Amy, 1998). However, on the basis of results from several locations, including those results reported here, Huck et al (2000) concluded that BOM removal was not directly related to filter biomass levels as measured by the phospholipid method.

Figure 6 sheds light on the effect of backwashing on top-of-filter biomass. The differences in biomass (comparing top-of-filter biomass before and after backwash) as a result of normal (chlorinated water and air scour) backwashing were not statistically significant in either filter type under warm water temperatures ($\alpha = 0.05$). During cold water temperatures, only the GAC filter demonstrated a significant difference in top-of-filter biomass as a result of backwashing ($\alpha = 0.05$); however, the cold water biomass levels were low, and the actual difference was small.

The two filter media did not have statistically different top-of-filter biomass concentrations at the start of the filter cycle (immediately after backwash) at cold water temperatures ($\alpha = 0.05$). However, at the end of the filter cycle (immediately before backwash), the GAC had significantly more surface biomass per unit volume of media ($\alpha = 0.05$) than did the anthracite (Figure 6), even though the overall biomass concentrations were low. This difference was obscured when the before-and-after backwash biomass data in Figure 5 were combined. The data in Figure 6 suggest that biomass retention and/or growth at the top of the GAC filter surpassed that of the anthracite filter during cold water conditions, although by a small absolute amount. This additional top-of-filter biomass may be interpreted as having contributed to the additional BOM removal capacity of the GAC filters (relative to anthracite) at cold water temperatures (Figure 3 and Figure 4, part A); however,
because no differences in oxalate removal before and after backwashing were observed in either filter type ($\alpha = 0.05$), such interpretation may not be appropriate.

The biomass measurements in Figure 7 (which are different from those in Figure 5) were made within 6–10 h of the start of a filter cycle. Given comparable biomass concentrations at the top of the filters immediately before and within 2 h after backwash with air scour at warm water conditions (Figure 6), biomass concentrations at 6–10 h after backwash were expected to be representative of those throughout the course of a filter cycle. These measurements demonstrated that significantly more biomass ($\alpha = 0.05$) was present at the top of both the GAC and anthracite filters when the filters were backwashed without air scour at warm water temperatures (Figure 7). The actual differences in top-of-filter biomass as a result of backwash protocol were substantial and concurred with the findings of other research indicating biomass loss associated with air scour during backwashing (Lu & Huck, 1993).

Compared with filter cycles following backwashes with air scour, oxalate removal in the GAC filter adsorber was significantly lower when air scour was absent from the backwash protocol under cold water temperatures ($\alpha = 0.05$; Figure 4, part A). This result appears contradictory to the results in Figure 7, which indicated significantly more biomass when air scour was absent from the backwash protocol under warm temperatures (cold temperatures were not tested). In light of the work of Carlson and Amy (1998), it is possible that either the biomass concentrations and/or the BOM removal would have reached different steady-state levels if the experiments had been continued for a longer period of time. Regardless, these results support the hypothesis that there is not necessarily a direct relationship between top-of-filter phospholipid biomass and BOM removal.

Biomass concentrations were clearly sensitive to media type, water temperature, the presence or absence of air scour during backwashing, and in some cases, the time at which sampling occurred relative to backwashing. Interpretations of the biomass data as they relate to BOM removal should be considered with caution. In the case of GAC under cold water conditions, more measured biomass may correspond to increased...
Biomass respiration potential (BRP) results appear to be good indicators of the BOM removal capacity of the filter biomass. Therefore, BRP results potentially can be used in certain cases instead of BOM measurements for the assessment of the BOM removal capacity of drinking water biofilters operated under different conditions. Urfer and Huck (2001) demonstrated that the ratio between biomass activity and phospholipid biomass at different filter depths indicated a substantial increase with depth, which indicated increased biomass activity per unit amount of viable biomass deeper in the biofilters, where biofilm thickness is low. The comparison of the filter profiles of biomass activity and dissolved BOM, expressed as theoretical oxygen demand, showed a high correlation among these profiles, suggesting that BRP can be a good indicator of the BOM removal capacity of filter biomass.

**Particle control.** Filter effluent turbidities (excluding filter-to-waste periods) were not affected by the presence or absence of air scour during backwashing, regardless of water temperature and media type ($\alpha = 0.05$). Average effluent turbidities from each of the individual filters were always <0.1 ntu even when accounting for brief turbidity peaks (≥0.2 ntu) corresponding to filters that had just completed backwash (filters in service after filter-to-waste). The combined effluent from all four filters was always <0.1 ntu. These data demonstrate that excellent particle removal (as measured by turbidity) can be maintained in biological filters regardless of the presence or absence of air scour during backwashing.

Within a given season, the percentage of terminal head loss reached in the filters during normal operational conditions versus experimental conditions did not change appreciably. Furthermore, no differences were observed in initial head loss or rate of head loss buildup for a given media type within a given experimental season. The rate of head loss buildup did not vary as a result of the absence or presence of air scour during backwash; however, the duration of the experiments may not have been long enough to observe more gradual changes in performance.
Although the presence or absence of air scour during backwashing did not result in substantial differences in BOM removal, some performance measures of the GAC filter adsorber changed appreciably when air scour was eliminated from the backwash protocol during warm water conditions. The filter-to-waste period was defined as the period from the completion of the backwash to the time at which the filter effluent turbidity was improving and reached 0.2 ntu after spiking. Therefore, an increase in this period corresponded to an increased volume of wasted water. For plants where filter-to-waste is unavailable, an extension of this ripening period would likely result in an increase in the turbidity of the blended filter effluent.

The duration of the filter-to-waste period in the GAC filter adsorber increased considerably when air scour was eliminated from the backwash during both warm water seasons (Figure 8). This increase was commensurate with a substantial increase in the maximum filter effluent turbidity during ripening (Figure 9). Backwashing protocol did not affect filter performance under cold water conditions (Figures 8 and 9). The filter-to-waste period in the dual-media filter did not increase when air scour was eliminated from the backwash during warm water seasons. These data suggest a potential performance benefit of anthracite over GAC under warm water conditions when air scour is not possible; however, this must be weighed against decreases in removal of at least some BOM components by dual-media filters under cold water conditions (Figure 3). In contrast, the dual-media filter demonstrated no measurable differences in either filter-to-waste period or the maximum turbidity reached during ripening in either cold or warm water conditions (Figures 9 and 10).

The maximum turbidity reached during ripening may be an important factor for meeting regulatory criteria. An increase in maximum turbidity during ripening (as demonstrated in the GAC filter adsorber) may require increased efforts to blend the water to desirable turbidity levels if filter-to-waste is not available. Higher turbidity may also be associated with increased pathogen passage through filters. However, the mixture of components that causes turbidity may be different in biological filters as opposed to conventional filters. Nonetheless, current turbidity regulations do not account for specific turbidity components and require that all filters must meet the same turbidity standards.

**Effect of collapse-pulsing backwash.** Application of the rigorous collapse-pulsing backwash did not affect carboxylic acid removal by the GAC filter adsorber. The data shown in Figure 11 did not indicate any significant differences in oxalate removals between backwashing with the normal chlorinated backwash with air scour and the collapse-pulsing protocol (α = 0.05). Similar results were obtained for the other carboxylic acids measured (acetate, formate, glycolate, and pyruvate). No aldehydes were detected at concentrations above the method detection limits during these experiments. TOC removal also appeared unaffected by the application of the collapse-pulsing backwash (α = 0.05; results not shown).

Comparison of collapse pulsing to the existing backwash protocol yielded no significant differences (α = 0.05) in either maximum turbidity during filter ripening or the
duration of the filter-to-waste period. However, collapse pulsing resulted in significantly shorter run times ($\alpha = 0.05$; Figure 12) and initiation of backwashing because of turbidity breakthrough as opposed to time (full duration of filter cycle). Figure 11 indicates that filter run times returned to baseline once the backwashing strategy reverted to normal from collapse pulsing.

The collapse-pulsing experiments were concluded after three consecutive backwashes because of the effect of the decrease in filter run time on plant operations. Although these experimental outcomes do not necessarily imply that collapse pulsing cannot be successfully used for backwashing biologically active filters, they do suggest that collapse pulsing for biological filters requires optimization.

Filter effluent turbidity was not significantly ($\alpha = 0.05$) affected by implementation of the collapse-pulsing backwash because the filters were always backwashed at the onset of turbidity breakthrough. The average effluent turbidity from the GAC filter adsorber was always <0.1 ntu even when accounting for brief turbidity peaks ($\leq 0.2$ ntu) corresponding to the completion of filter ripening following backwash. This indicated that excellent particle removal could be maintained in biological filtration processes regardless of the implementation of a collapse-pulsing backwash strategy.

CONCLUSIONS

The Mannheim investigation demonstrated the influence of water temperature, media type, and backwashing strategy on full-scale biological filtration practice. The following specific conclusions could be made from this investigation:

* Biological filters (GAC filter adsorbers and dual-media filters) consistently met high standards of particle removal (i.e., the filter effluent turbidity was always <0.1 ntu), regardless of water temperature, media type, and backwash protocol.
* Most of the oxalate removal occurred in the upper portions of filters.
* Water temperature significantly affected oxalate removal. Compared with oxalate removal in warm temperatures, oxalate removal in cold temperatures decreased significantly in both GAC filter adsorbers and dual-media filters. GAC offered some advantage over dual-media for oxalate removal under cold water temperatures; however, BOM in the distribution system may be less of a problem during cold water temperatures.
* For TOC removal, neither medium (anthracite or GAC) demonstrated a significant temperature effect. At low temperatures, however, TOC removal by GAC was significantly better than by anthracite.
* BOM removal was insensitive to backwash conditions, whereas conventional performance parameters were sensitive to these conditions, allowing conventional performance parameters to be optimized without compromising BOM removal.
* BOM removal was not directly related to top-of-filter phospholipid biomass.

ACKNOWLEDGMENT

The authors acknowledge the financial support of the Awwa Research Foundation (AwwaRF) and the Natural Sciences and Engineering Research Council (NSERC) of Canada. Partners in the NSERC Industrial Chair in Water Treatment at the time this work was completed were the City of Brantford (Ont.), the City of Ottawa (Ont.), the Regional Municipality of Waterloo (Ont), the Windsor (Ont.) Utilities Commission, Water Technology International, Conestoga-Rovers and Associates Ltd., Hewlett-Packard Canada Inc., NSERC, and the University of Waterloo. The support of the AwwaRF project officers, advisory committee, and partners is appreciated.

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