

Evaluation of the effect of recycle of waste filter backwash water on plant removals of *Cryptosporidium*

James K. Edzwald, John E. Tobiason, Christina T. Udden, Gary S. Kaminski, Howard J. Dunn, Peter B. Galant and Michael B. Kelley

ABSTRACT

Pilot-scale experiments investigated the removal of *Cryptosporidium* oocysts and any effects from the recycle (10% rate) of untreated waste filter backwash water (FBW) for two treatment plant types: dissolved air flotation (DAF) and plate sedimentation, with dual media filtration for both plants. Experiments assessed performance for design hydraulic loadings and detention times and for two seasons (summer and winter). DAF clarification achieved about 2 log oocyst removal for both seasons either with or without recycle of FBW. Plate settling in the summer achieved 1.8–1.9 log oocyst removal with no effects from recycle of FBW. Plate settling performance was poorer in the winter at about 1 log oocyst removal without recycle, and decreased slightly with recycle of FBW. No effects were found from recycle of FBW on DAF and filtration performance for turbidity and particle counts (2–15 µm). There were no or minor effects for the same parameters on plate settling performance and no effects on filter performance. For both treatment plants, no oocysts were found in the dual media filter effluent either with or without recycle of FBW.

Key words | coagulation, *Cryptosporidium*, dissolved air flotation, filtration, sedimentation, waste filter backwash

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INTRODUCTION

Approximately 50 to 60% of surface water treatment plants in the United States recycle waste filter backwash water, usually to the front end of the plant prior to, or to rapid mixing with, coagulation (Environmental Engineering & Technology 1999; US EPA 2001). The US EPA (2001) issued regulations on the practice of filter backwash recycle as part of continuing efforts to improve water treatment practice and to minimize effects of recycle on water plant performance. These regulations were largely motivated by concern about the possible effect of recycle of untreated waste backwash water on plant performance with respect to *Cryptosporidium*.

It is often assumed that filtration is the main process removing *Cryptosporidium* oocysts in conventional water plants, thereby concentrating oocysts in the waste backwash water. Consequently, it is also assumed that recycle of untreated backwash water will cause an increase

in the plant influent oocyst concentration leading to detrimental effects on oocyst removals within the plant. The research described in this paper addresses measurement of removals of *Cryptosporidium* oocysts by clarification and filtration, and the effects of recycle of waste filter backwash water (FBW). It is instructive to begin by examining model predictions of the interplay between clarification and filtration regarding the influence of FBW on plant oocyst concentrations following recycle.

Model predictions of plant influent *Cryptosporidium* concentrations following recycle of waste filter backwash water

As stated above, it is often assumed that filters concentrate *Cryptosporidium* oocysts and other pathogens and thereby

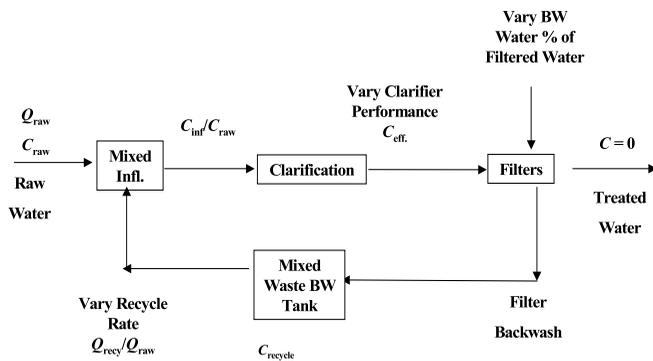


Figure 1 | Model framework for examination of clarifier performance, percent of filtered water used for backwashing, and recycle rate of waste filter backwash water on the plant mixed influent ratio of oocysts (C_{inf}/C_{raw}).

cause an increase in the plant influent oocyst concentration for water plants that recycle waste filter backwash water. A mass balance (oocyst particle balance) model is used as a means to address this assumption. The model examines the conservative case in which the filters are assumed to remove all of the applied oocysts, and there is no treatment of the waste filter backwash water prior to recycle to the front of the plant. Waste filter backwash water is examined for conditions in which it is collected and mixed to produce a homogenous waste of constant oocyst concentration. Three variables are considered in the model: (1) clarifier performance prior to filtration, (2) the percent of filtered water used for backwashing, and (3) the waste filter backwash recycle rate defined as the recycle flow divided by the raw water flow. The model is used to examine how these variables affect mixed influent (following recycle) oocyst concentration in terms of the ratio of oocysts in the mixed influent to the raw water concentration, C_{inf}/C_{raw} . Figure 1 shows the framework for the model. Note that the clarifier is generic and may be any type of sedimentation or dissolved air flotation process. The % water used for backwashing is directly related to the filtered water production (100%—% filtered water production). For most water plants, 2 to 5% of the filtered water is used for backwashing (production rates of 95 to 98%). In the model the plant influent flow is maintained constant by reducing the raw water flow to compensate for the recycle flow. Calculations are presented for conditions

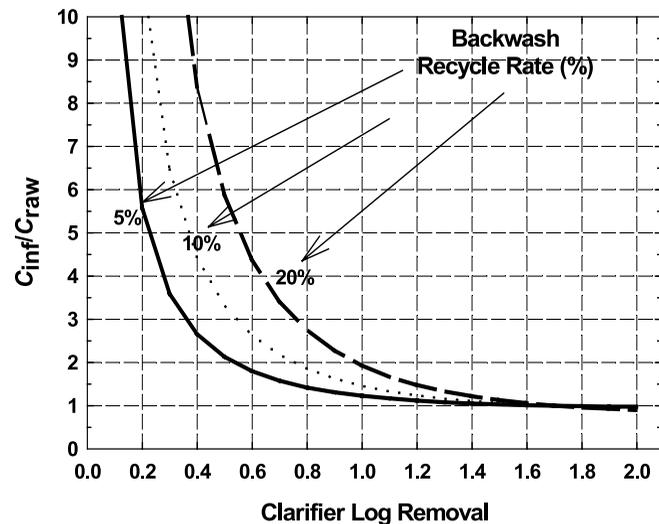


Figure 2 | Effects of clarification performance and recycle rate of untreated waste filter backwash water on the plant mixed influent ratio of oocysts for 2% of filtered water used for backwashing.

approaching steady state, i.e. several backwashes and recycle events occur such that there are small changes in C_{inf}/C_{raw} .

The effect of clarifier performance on the plant influent *Cryptosporidium* concentration (C_{inf}/C_{raw}) from recycling waste filter backwash water is shown in Figure 2 for the case of 2% of filtered water used for backwashing (i.e. 98% filtered water production). Three recycle rates of 5, 10 and 20% are examined. These predictions show that there is an increase in the influent *Cryptosporidium* concentration (ratio >1) for clarifiers (DAF or settling) that have log removals <1.7 (98% efficiency). *Cryptosporidium* concentration increases with increasing recycle rate and decreasing clarifier efficiency (log removal); for example, a clarifier with 0.5 log removal capability (assumed *Giardia* credit for settling under the Surface Water Treatment Rule; US EPA 1989) will cause an increase in the pathogen concentration of 2 to 6 times depending on the recycle rate. On the other hand, if the clarifier achieves >1.7 log removal, then *Cryptosporidium* (or other pathogen) is concentrated in the clarifier sludge and not in the filter backwash water so that recycling can actually slightly dilute the concentration of oocysts in the raw water.

Table 1 | Minimum clarifier *Cryptosporidium* removal efficiency for no impact from recycle of filter backwash on the concentration of oocysts in the plant influent

% of filtered water used for backwashing	Clarifier efficiency (log removal)
2	98% (1.7)
4	96% (1.4)
5	95% (1.3)
10	90% (1.0)
20	84% (0.8)
30	68% (0.5)

The clarifier log removal value at which there is no effect on the raw water *Cryptosporidium* concentration (C_{inf}/C_{raw} of 1) depends on the percent of filtered water used for backwashing. Plants that backwash more frequently (lower filtered water production) use more filtered water for backwashing and will have a more dilute backwash wastewater stream. Thus, the clarifier efficiency (log removal) at which there is no effect from recycling FBW decreases as the percent of filtered water is increased for backwashing. Predictions are summarized in Table 1. Most water plants use 2 to 5% of their filtered water for backwashing. For these plants, there will be no increase in the plant influent oocyst concentration from recycle of mixed, untreated waste backwash water if the clarifier achieves 1.3 to 1.7 oocyst log removal. Clarifier efficiency of 68% (0.5 log removal) is sometimes assumed for pathogens, e.g. the regulatory credit for *Giardia*. If this assumption is extended to *Cryptosporidium*, then the model predicts an increase in the plant influent oocyst concentration due to recycle unless there is very frequent backwashing.

The model provides a framework for examining important variables. It is usually assumed that clarifier performance (% removal) is unchanged with recycle of waste filter backwash water. With the exception of research by Cornwell & MacPhee (2001), there have been no other reported studies on the effects of recycle of FBW

on plant performance for *Cryptosporidium* removal. What is needed is additional well-controlled studies on clarifier performance for removing *Cryptosporidium* and the effects of recycle of waste filter backwash water; this paper addresses that need.

Objectives and scope

The goal of the paper is to assess the effects of recycle of waste filter backwash water (FBW) on *Cryptosporidium* removals by clarification and filtration. In this paper, the recycle of FBW refers to the untreated waste filter backwash water stream recycled to the front of the plant prior to coagulation.

The paper has two objectives. The first objective is to present findings on the removals of *Cryptosporidium* without recycle of FBW by two treatment plant types: a plate sedimentation plant and a dissolved air flotation plant (DAF), with dual media filtration for both plants. Plate settling performance is compared with DAF for *Cryptosporidium*, turbidity and particle counts. The removal of natural organic matter (NOM) measured as UV absorbance at 254 nm (UV_{254}) is also presented. The second objective is to present results on the effects of recycle of FBW on clarification and filtration performance as measured by *Cryptosporidium*, turbidity and particle counts.

Pilot plant studies were used in which the processes were operated at design hydraulic loadings and detention times. Experiments were run in the summer and winter to assess water temperature effects. Coagulation chemistry and the chemistry of the waste backwash waters are important factors and are discussed in the paper. Here recycle of FBW rate was held constant at 10%, and coagulant dosing was held constant based on total influent flow. In a related study (Edzwald *et al.* 2001; Tobiason *et al.* 2003), we report on the effects of recycle of FBW on particles (turbidity and suspended solids) and natural organic matter in which four recycling operational parameters were varied: recycle rate, pH of the waste backwash water, backwash solids level and coagulant dosing strategy.

Table 2 | Raw water quality of Hemlocks Reservoir for the pilot plant experiments

Season	pH	Turbidity (NTU)	Particle counts* (#/ml)	UV ₂₅₄ (cm ⁻¹)
Summer: 17–18°C	7.1–7.3	0.89–1.1	3,760–4,460	0.080–0.087
Winter: 2–5°C	7.4	0.80–0.94	3,560–5,940	0.11–0.12

*Particle counts: 2–15 µm size range.

METHODS

The study conditions, pilot plant facilities, and experimental procedures are summarized here; details are provided in an American Water Works Association Research Foundation report (Edzwald *et al.* 2001).

Water supply

The pilot studies were conducted at the William S. Warner 190 × 10⁵ m³/d DAF plant of Aquarion Water Company of Connecticut in Fairfield, CT, USA. The water supply is Hemlocks Reservoir, the same source used by the full-scale plant. The reservoir is a protected high quality supply of low alkalinity (20–30 mg/l CaCO₃) and low TOC (2.5–3 mg/l). Experiments were run for two seasons (summer and winter) to evaluate effects of water temperature and other water quality variables on performance. Water temperatures were 17–18°C for the summer experiments and quite low (2–5°C) for the winter runs. Important raw water quality parameters for the two seasons are summarized in Table 2. UV₂₅₄ (absorbance at 254 nm) was monitored as a surrogate measure of dissolved natural organic matter (NOM). The data show that the NOM concentration was much higher in the winter than in the summer.

Plate sedimentation pilot plant

The plate sedimentation pilot plant had a flow rate of 19 lpm, and it was operated at typical design flow detention times and hydraulic loadings used by full-scale facilities in the USA, particularly those plants of Aquarion.

Aquarion has two full-scale plate sedimentation plants treating water similar in quality to Hemlocks Reservoir. A schematic of the pilot plant is presented in Figure 3. Flocculation consisted of two stages, each with 14 min detention time with constant mixing. The plate sedimentation gross hydraulic loading was 1.7 m/h. Constant rate filtration was used at a hydraulic loading of 7.3 m/h. Four dual media filters (200 mm diameter columns) were used containing 600 mm of anthracite with effective size (ES) of 0.85 mm, over 300 mm of sand with ES of 0.45 mm. Alum alone was used as the primary coagulant, and base (NaOH) was added to control coagulation pH. To achieve good separation of floc particles by plate settling and filtration, both floc-aid and filter-aid polymer additions were needed, which is common practice in the USA. The same high molecular weight, non-ionic polymer was used (Superfloc[®] 1986N, Cytec Industries Inc., West Patterson, NJ, USA). The floc-aid polymer was added between the first and second stages of flocculation (Figure 3). The filter-aid polymer was added to the effluent of the plate settler.

Dissolved air flotation pilot plant

A schematic of the DAF pilot plant is presented as Figure 4. The pilot plant was operated at a flow of 182 lpm at design detention times and hydraulic loadings of the full-scale Warner DAF plant. Flocculation consisted of two stages, each with 6 min detention time with constant mixing. DAF and filter hydraulic loadings were 14.6 m/h. Constant rate dual media filtration was used with the same depths and media characteristics as for the plate settling pilot train. The full-scale DAF plant employs a dual primary coagulation strategy of alum and a cationic polymer

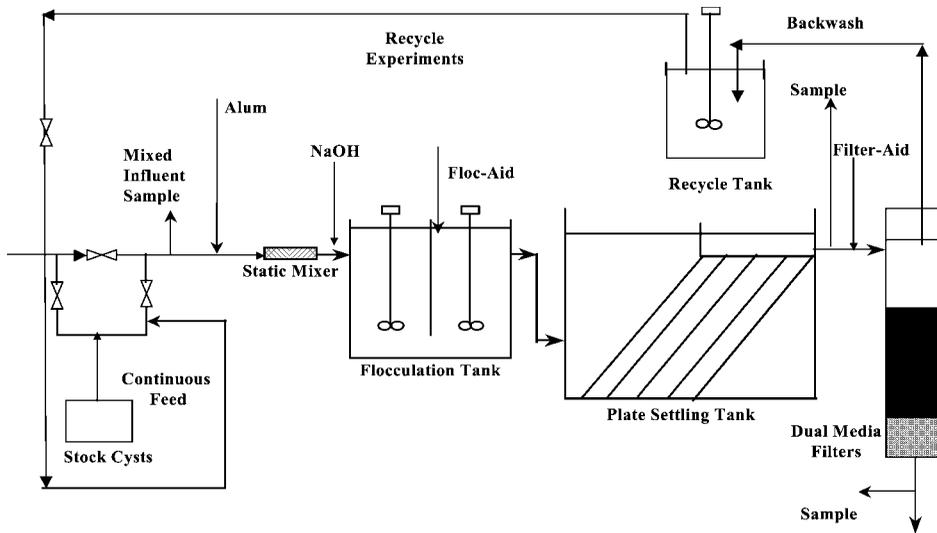


Figure 3 | Plate sedimentation pilot plant with and without recycle of waste filter backwash water.

(Superfloc[®] 572C, Cytec Industries Inc., West Patterson, NJ, USA), and this was used in the pilot studies. Base (NaOH) was added as needed to control the alum coagulation pH. It is noted that DAF and plate settling are both clarification processes, but that DAF is a higher rate clarification process with shorter flocculation times than the plate settling plant.

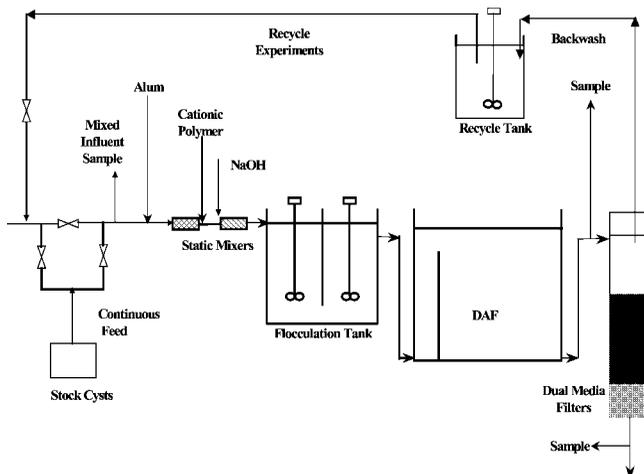


Figure 4 | Dissolved air flotation pilot plant with and without recycle of waste filter backwash water.

Cryptosporidium source, sampling and analysis

Cryptosporidium was below detection levels in the raw water from Hemlocks Reservoir. Oocysts were continuously fed to the raw water entering the pilot trains prior to coagulant addition using the pipe loops shown in Figures 3 and 4. *Cryptosporidium parvum* oocysts were obtained from Parasitology Research Laboratories (PRL, Neosho, Missouri, USA). Mice were the infected hosts for the oocysts. A semi-purified matrix was used in which the matrix was passed through a tea strainer by PRL. This preparation process removed only large suspended particles and left the bulk of the faecal matter with the oocysts. The semi-purified matrix is more representative of what would be present in actual source waters. The research evaluated physical removal of oocysts by clarification and filtration, not viability or infectivity. Thus for safety reasons, all oocysts were inactivated with formalin (2% by volume). The formalin does not affect oocyst charge and coagulation (Kelley 1996), and it will be shown below that the oocyst particle charge was similar to the raw water particle charge.

Sampling locations for oocysts are shown in Figures 3 and 4 and included the following: (1) after oocyst feed and recycle of FBW (mixed influent), (2) after clarification, and (3) after dual media filtration. Sampling of the

mixed influent and clarification effluent utilized wound polypropylene filter cartridges with analysis by the Information Collection Rule (ICR) Method (US EPA 1996). Clarification effluent was sampled for 3–8 h during the course of the runs with sample volumes of 380–760 litres. In evaluating clarification performance for *Cryptosporidium* removal, either duplicate pilot runs were made or one pilot run was made employing duplicate measurements. Composite sampling of the dual media filters was continuous over the entire filter run (several hours for recycle of FBW and 20–24 h for runs without recycle). For summer experiments, the dual media filter sampling cartridges and analysis method were the same as above. The same sampling and ICR Method was used for the winter experiments, but in addition the dual media filters were sampled in parallel using a membrane filter (Gelman Sciences, Ann Arbor, Michigan, USA) with absolute pore size of 1 μm . These samples were analysed in accordance with US EPA Method 1622 (US EPA 1999). The oocyst samples were shipped by overnight express to a US EPA certified laboratory (Environmental Associates Ltd, Ithaca, New York, USA) for *Cryptosporidium* analyses.

Experimental procedures

Coagulant dosing

Primary coagulant dosages for the two pilot plants and both floc-aid and filter-aid polymer dosages for the plate settling plant were established in separate experiments without feeding *Cryptosporidium* and without recycle of FBW. Optimum dosages were based on clarified turbidities and UV_{254} removal goals based on experience with full-scale Aquarion facilities operating under design flow conditions. Turbidity goals for the DAF effluent were seasonal: ≤ 0.5 NTU for the summer and ≤ 1 NTU for the winter. Turbidity goals for the plate sedimentation effluent were also seasonal: ≤ 1 NTU for the summer and ≤ 2 NTU for the winter. The filtered water turbidity goal for both pilot plants and seasons was ≤ 0.1 NTU. The UV_{254} removal goals were 60–70% for both pilot trains. Coagulant dosing was then fixed and used without adjustment for subsequent experiments with the continuous feed of *Cryptosporidium* and for those with recycle of FBW. For

the plate settling plant, floc-aid and filter-aid polymer dosings were also fixed and not changed.

Pilot train experiments

The two pilot trains (DAF and plate sedimentation) were run in parallel allowing assessment of both the effects of recycle of FBW on treatment performance and comparisons of *Cryptosporidium* removals for the two treatment plants. The experiments with and without recycle of FBW were conducted in a similar manner for both pilot trains. At the start of an experiment, raw water by-passed the pipe loop used for feed of *Cryptosporidium* (see Figures 3 and 4). The filters were allowed to ripen for turbidity, which took about 45 to 60 min. After filter ripening, oocysts were then continuously fed to the raw water entering the pilot train using the pipe loop. For the summer experiments, measured oocyst concentrations in the mixed influent were in the range of 2,300 to 4,400 oocysts/100 l. Experience from the summer runs showed that clarification in both pilot trains substantially reduced the oocyst concentrations. To increase the oocyst loadings to the filters for the winter experiments, the feed of *Cryptosporidium* was increased such that mixed influent oocyst concentrations were in the range of 8,200 to 15,900 oocysts/100 l.

Clarification and filter performance without recycle of FBW were examined for continuous operation with filter run times of 20 to 24 h. Data collected were turbidity, particle counts (2–15 μm), UV_{254} (surrogate measure of dissolved NOM) and filter headloss. Particle counts were made with a MetOne particle counter (WGS grab sampler, LB 1010 sensor, Grants Pass, Oregon, USA). The runs were terminated when the filters reached terminal headloss of about 2.3 m.

Waste backwash water was collected and used in subsequent pilot runs with recycle of FBW along with continuous feed of oocysts (Figures 3 and 4). The untreated waste filter backwash water was mixed and recycled at about a 10% rate (recycle flow divided by raw water flow) with recycle beginning after filter ripening. The period of recycle of FBW for the plate sedimentation train experiments was about 9 h with a total run time of about 12 h; a recycle period of 2–3 h was used for the DAF train experiments with a total run time of about 7 h. The

Table 3 | Coagulation conditions for the pilot trains with and without recycle of filter backwash water

Parameter	Summer		Winter	
	Plate settling train	DAF train	Plate settling train	DAF train
Alum (mg Al/l)	2.6	1.7	3.6	2.7–3.0
Cationic polymer (mg/l)	None	1.0–1.2	None	0.9–1.1
Floc tank pH	6.5	6.7	6.6	6.7–6.9
Floc-aid polymer (mg/l)	0.05	None	0.11–0.12	None
Filter-aid polymer (mg/l)	0.028–0.03	None	0.028–0.029	None

shorter recycle time for the DAF train was due to the large volume of waste filter backwash water needed for this larger flow pilot plant. The effects from filter backwash recycle were evaluated by comparing the performance with the runs without recycle.

Backwashing of filters

The pilot filters were backwashed with filtered water from the full-scale Warner DAF plant. The backwashing procedure consisted of a low backwash rate of 35 m/h for 2 min followed by a high backwash rate of 63 m/h for 6 min. The percent of water used for backwashing for the DAF train was approximately 2% (summer) and 4% (winter) of the water filtered, yielding filtered water production rates of 96 to 98%, which is about what the full-scale Warner DAF plant achieves. For the plate sedimentation train, the percent of water used for backwashing was higher at 4–5%. The backwash water volume collected from the four parallel filters for one pilot run was 970 l. This was a sufficient volume of waste backwash water for recycle experiments for the plate sedimentation pilot train. However, three pilot runs were needed to collect a sufficient waste backwash volume of 2,910 l for use in the DAF pilot plant recycle experiments. The waste backwash water was stored, equalized, completely mixed and used untreated in the recycle experiments. Several parameters were measured to characterize waste backwash water quality.

RESULTS AND DISCUSSION

Coagulation chemistry

Coagulant dosing was based on total influent flow (raw water flow plus filter backwash recycle flow of 10%) that was held constant, i.e. the raw water flow was reduced with recycle. Coagulant dosing was established without feed of *Cryptosporidium* and without recycle of FBW. Dosing was selected to produce good clarification performance in accordance with the turbidity and UV₂₅₄ removal goals specified above for the two pilot trains. Coagulation conditions were not changed for feed of *Cryptosporidium* or for recycle of FBW.

Coagulation dosages and pH conditions are summarized in Table 3. Alum dosages for the plate settling plant were higher than for the DAF plant because no cationic polymer was used as a primary coagulant. Alum dosages were higher for both plants in the winter due to higher raw water levels of NOM (higher UV₂₅₄) that exerted a coagulant demand. Alum coagulation was carried out at near optimum pH of 6.5–6.9, and floc particle charge was near zero as shown by the EPM (electrophoretic mobility) data in Figure 5. These charge data are for the DAF train for the summer experiments. The data show that raw water particles and *Cryptosporidium* oocysts had about the same negative EPM. After feed of *Cryptosporidium* without recycle of FBW (top panel) or with feed of *Cryptosporidium* and recycle of FBW (bottom

panel), the particles in the mixed influent had about the same charge (EPM value) as the oocyst particles and particles in the raw water. The EPM data for particles in the waste filter backwash recycle stream (bottom panel) were also negatively charged, but lower in value than either the raw water particles or the oocysts. After coagulation and flocculation, the particles in the flocculation tank and DAF tank effluent had a charge near zero indicating optimum coagulation conditions. Similar results were found for the other season and for the plate settling train experiments.

In summary, coagulation was carried out under optimum conditions to produce treated waters of low turbidities and to produce good removals of UV_{254} ; performance data are presented below. Coagulation was also carried out for good alum pH conditions with pH of 6.5–6.9. The coagulation dosing and pH were established without feed of *Cryptosporidium* and without recycle of filter FBW, and dosing was based on constant total influent flow. The EPM data presented above verified that coagulation was optimum in that floc particles of little or no charge were produced, and the floc charge was not affected either by feed of oocysts or by recycle of FBW. Another important factor affecting these results is the chemistry of the backwash water quality, and this is addressed next.

Backwash water quality and chemistry

Table 4 summarizes the waste backwash water quality. *Cryptosporidium* concentrations in the collected waste backwash water could not be measured due to its high suspended solids concentration, but mass balance calculations indicated that *Cryptosporidium* oocysts in the waste filter backwash water for the DAF pilot runs were 1,400 and 1,600 oocysts/100 l for the winter and summer experiments. These were much lower than the raw water feed and measured mixed influent oocyst concentrations (Figure 4) of 2,300 to 4,400 oocysts/100 l in the summer and 8,200–15,100 oocysts/100 l in the winter, and therefore recycle of FBW could not increase the plant influent oocyst concentrations for the DAF runs. For the plate sedimentation pilot runs, *Cryptosporidium* oocyst concentrations in the waste backwash water were about 1,100 oocysts/100 l for the summer and 30,000 oocysts/100 l for

the winter. For the summer, the FBW oocyst concentration was lower than the raw water feed (2,400 to 4,400 oocysts/100 l), and thus recycle could not increase the plant influent oocyst concentration. For the winter, the FBW oocyst concentration was greater than the feed (11,600 to 15,900 oocysts/100 l) and would cause an increase in the plant influent oocyst concentrations. Of course, the oocyst particle concentrations are low (<1 particle/ml) compared with the bulk particle concentrations in the raw and waste backwash water of 1,000s/ml and therefore do not influence coagulation.

Arora *et al.* (2001) found *Cryptosporidium* concentrations in waste filter backwash water were nearly seven times raw water levels. To account for the measured oocyst concentrations in the waste backwash water, they concluded that pretreatment coagulation and clarification must have been achieving about 1 log removal. If clarification removed no oocysts, then the waste filter backwash water oocyst concentrations should be fifty times the raw water levels for plants using 2% of their filtered water for backwashing. In our work, we evaluated clarification and filtration performance (see below) and calculated waste backwash oocysts. We found that, except for one case (winter, plate settling train), the oocyst concentrations in the waste backwash were lower than the raw water meaning clarification was concentrating the oocysts.

Backwash water quality variables that can potentially influence coagulation include suspended solids or turbidity, dissolved NOM and pH. The waste filter backwash water (Table 4) had suspended solids of about 70–140 mg/l, and turbidities of about 15 to 30 NTU. The backwash water had higher turbidity and suspended solids for the winter experiments because of higher coagulant dosages and lower particle removal efficiencies by DAF, and especially plate settling, for cold waters. The waste backwash water solids and turbidities were much higher than raw water values (turbidities of 0.8–1.1 NTU; Table 2), but did not influence coagulation with recycle of FBW.

The dissolved NOM (UV_{254}) of the backwash water was much lower (0.035 – 0.051 cm^{-1} ; Table 4) than raw water values of 0.08 to 0.087 cm^{-1} in the summer and about 0.12 cm^{-1} in the winter. The UV_{254} of the waste backwash water was only slightly greater than the pilot filter effluent (0.025 – 0.03 cm^{-1}). The waste backwash

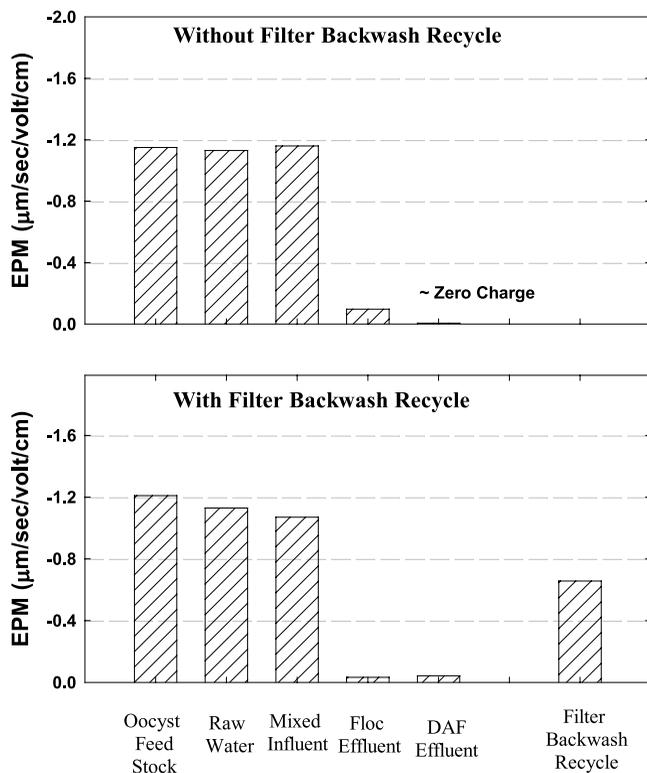


Figure 5 | Charge of oocysts and particles across the DAF pilot train for summer experiments (top plot: no recycle of waste filter backwash water; bottom plot: with recycle).

water had lower concentrations of dissolved NOM than the raw water, and therefore would not be expected to affect coagulation. Finally, the pH of the backwash water was 7.1 to 7.4, which was about the same as the raw water pH conditions. The recycle FBW thus did not affect the pH of coagulation. This pH condition also did not dissolve precipitated NOM or desorb NOM from particles in the waste backwash water tank as indicated by the low UV_{254} values. If utilities backwash filters at higher pH conditions, then the dissolved NOM could increase causing a coagulant demand from recycle of FBW (Edzwald *et al.* 2001; Tobiasson *et al.* 2003).

In summary, the recycle of filter backwash water had no effect on coagulation. The most important reason is that the pH chemistry of the backwash water was similar to the plant pH treatment conditions for clarification and filtration. Thus, dissolved NOM was not high in the backwash water (in fact, was much lower than the raw water)

and did not affect coagulation. Also, coagulation pH was not affected by recycle of FBW. In this study, coagulant dosing was based on total influent flow and was an effective dosing strategy. Evaluation of the effects of reducing or increasing the coagulant dose was beyond the scope of this paper, but is addressed by the authors elsewhere (Edzwald *et al.* 2001; Tobiasson *et al.* 2003).

Effects of recycle of waste filter backwash water on turbidity, particles and UV_{254} performance

DAF train performance

Three separate runs of about 20–24 h were made for both summer and winter seasons without recycle of FBW. These runs provided reference performance data for DAF and filtration. *Cryptosporidium* was fed continuously throughout the runs beginning after filter ripening. DAF and filter performance data for the three summer DAF train runs are presented in Figure 6. The DAF effluent turbidity data show good reproducibility for the three runs and good performance with DAF turbidities generally at 0.4 NTU as summarized in Table 5. DAF effluent particle counts (Table 5) were generally in the range of 200–450 particles/ml compared to 5,080–6,050 particles/ml in the flocculation tank effluent, with consistent performance among the three runs. The winter season DAF performance data for no recycle of FBW are summarized in Table 5. The DAF performance was better in the summer than the winter, but nonetheless DAF performance for the cold water winter runs was still quite good for turbidity (0.5–0.75 NTU) and particle counts (500–1,000/ml).

Filter performance for turbidity was excellent for the three runs without recycle of FBW as shown in Figure 6 for the summer season. The turbidity data (Figure 6) show a short ripening period of about 45 min; however, even at the start of ripening the filtered water quality was good with turbidities of about 0.2 NTU. Following ripening, all four filters produced turbidities of 0.03–0.05 NTU and particle counts (2–15 μm) in the range of 10 to 50 particles/ml (Table 5) with most readings of 25 particles/ml or less. Filter run times were about 24 h with no evidence of particle or turbidity breakthrough. The winter data summarized in Table 5 also indicate good

Table 4 | Waste filter backwash water quality

Parameter	DAF train experiments		Plate settling train experiments	
	Summer	Winter	Summer	Winter
Turbidity (NTU)	13	15	15	29
Suspended solids (mg/l)	79	102	71	141
UV ₂₅₄ (cm ⁻¹)	0.051	0.035	0.042	0.049
pH	7.3	7.1	7.1	7.4
Temperature (°C)	21	9	19	8
<i>Cryptosporidium</i> * (#/100 l)	1,600	1,400	1,100	30,000

*Based on mass balance calculations of measured oocysts applied to the filters and detection limits of oocysts for the filter effluent, volume of water filtered and backwash volume.

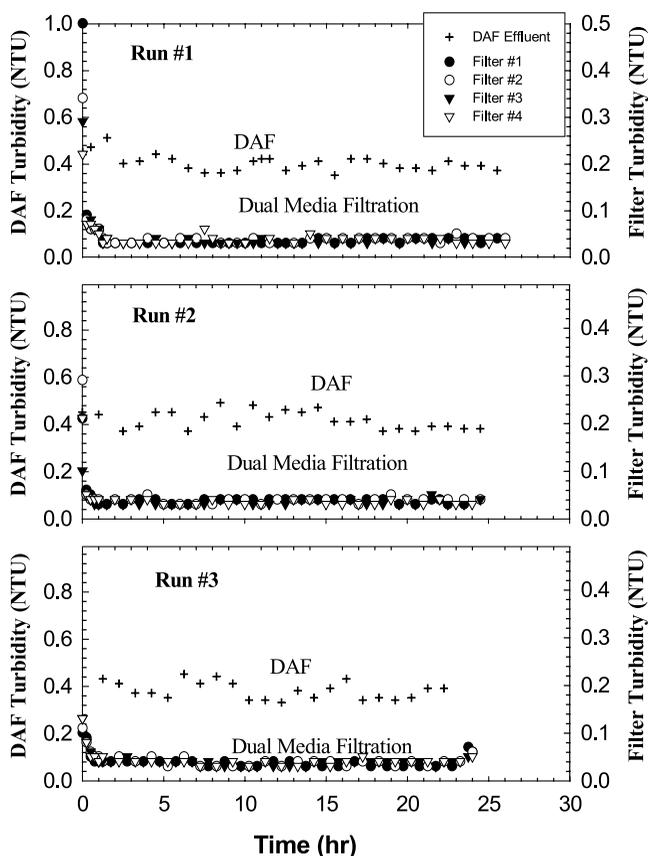


Figure 6 | DAF and filter turbidity performance for summer experiments without recycle of waste filter backwash water.

performance with filter effluent turbidities of 0.04–0.07 NTU and particle counts of 30–60 particles/ml. The filtered water quality is almost as good as that achieved for summer. This winter performance is especially good considering that both DAF and the filters were operated at design hydraulic loadings of 14.6 m/h at water temperatures of 2–5°C. The filter run times were shorter (18–20 h) in the winter due to the cold water conditions and higher particle loadings were applied to the filters (compare DAF effluent quality for the two seasons).

Immediately after each run, the four filters were backwashed according to the backwashing procedure described in the Methods section. The collected filter backwash water was mixed and used untreated in the pilot experiments to test any effects on DAF or filtration performance from the recycle of FBW. The quality of the waste backwash water (Table 4) was presented above.

The effects of recycle of FBW on plant performance are discussed using the summary data in Table 5. For the summer season, DAF turbidities were 0.4–0.5 NTU with recycle of FBW compared to 0.3–0.5 NTU without recycle. DAF particle counts for the summer were generally lower with recycle of FBW at 200–300 particles/ml compared to 200–450 particles/ml without recycle. For the winter, DAF turbidities were equal to or less for recycle of FBW

Table 5 | Summary of DAF and filter performance with and without recycle of filter backwash water

Case	DAF effluent			Filter effluent		
	Turbidity (NTU)	Particle counts* (#/ml)	Oocysts (#/100 l)	Turbidity (NTU)	Particle counts* (#/ml)	Oocysts (#/100 l)
Summer						
Without recycle	0.3–0.5	200–450	20 & 50	0.03–0.05	10–50	ND
With recycle	0.4–0.5	200–300	10 & 100	0.03–0.05	10–50	ND
Winter						
Without recycle	0.5–0.75	500–1,000	45 & 60	0.04–0.07	30–60	ND
With recycle	0.5–0.6	400–700	10 & 560	0.04–0.06	20–50	ND

*Particle counts: 2–15 μm size range.
 ND: not detected.

compared with no recycle. Particle counts of 400–700 particles/ml for recycle of FBW were lower than those found with no recycle as was the case for the summer. For filtration performance, the summer data show the same filter effluent turbidities (0.03–0.05 NTU) and particle counts (10–50 particles/ml) with recycle of FBW compared to no recycle. Winter results also show that filtration was not affected by recycle of FBW.

In summary, recycle of FBW did not affect DAF or filter performance as measured by turbidity and particle counts (2–15 μm). DAF did perform better in the summer season compared to the winter so there was a higher particle loading applied to the filters for the winter runs.

Plate sedimentation train performance

Unlike the DAF train experiments in which three runs were made without recycle of FBW to generate a sufficient volume of waste backwash water for one recycle experiment, only one run was made for the plate sedimentation train. The plate sedimentation experiments with and without recycle of FBW were conducted in parallel with the DAF train experiments allowing comparisons with the DAF plant as well as assessment of the effects from the recycle of FBW. Figure 7 shows plate settler and filter turbidity performance for the summer without recycle of

FBW. The data show good and consistent performance for the plate settler and among the four filters with filter run times of about 23 h.

Table 6 summarizes turbidity and particle count (2–15 μm) performance data for the two seasons. These data are used to compare results of recycle of FBW to those without recycle. For the summer, plate settler effluent turbidities were 0.8–0.9 NTU with or without recycle of FBW indicating no adverse effects from recycle. The plate settler turbidities (1.5–2.0 NTU) were higher in the winter, as expected, but again showed no effect from recycle of FBW. Plate settling effluent particle counts were generally a little higher with recycle of FBW, but some samples in the winter actually showed lower counts. Filter effluent turbidities (Table 6) were 0.03–0.05 NTU for the summer and 0.03–0.07 NTU for the winter. All dual media filter turbidities were less than 0.1 NTU indicating excellent performance, and no effects from recycle of FBW were found either for the summer or winter runs. The filter effluent particle count data (Table 6) also showed no effects from recycle of FBW. Filter effluent particle counts were 10–60 particles/ml in the summer and 20–80 particles/ml in the winter.

In summary, recycle of FBW did not affect plate sedimentation or filter performance as measured by turbidity

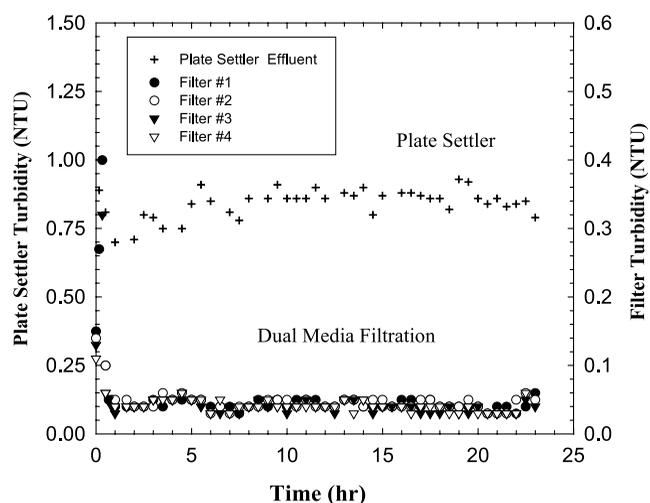


Figure 7 | Plate settler and filter performance for summer experiments without recycle of waste filter backwash water.

and particle counts (2–15 μm). Like DAF, plate settling did perform better in the summer season compared to the winter so the filters in the winter received a higher loading of particles as measured by turbidity. DAF did perform better than plate settling for both seasons producing clarified water with lower turbidities and particle counts being applied to the filters.

UV₂₅₄ performance

Both the DAF and plate sedimentation pilot plants achieved UV₂₅₄ removal of 70–75%, and the removal of dissolved NOM was not affected by recycle of FBW. These results were achieved with alum and cationic polymer coagulation for the DAF plant and alum coagulation for the plate settling train.

Effects of filter backwash recycle on *Cryptosporidium* removals

DAF performance

Cryptosporidium removal data for DAF were collected for two independent runs for both seasons for the case of no recycle of FBW. These experiments were long in duration (16–24 h) and allowed collection of large sample volumes

for *Cryptosporidium* measurements. The runs with recycle of FBW were, by their very nature, of much shorter duration so sample volumes for *Cryptosporidium* analysis were less. While duplicate samples were collected for the recycle experiments, the smaller sample volumes may have contributed to greater scatter in the observed *Cryptosporidium* performance data.

Figure 8 presents the *Cryptosporidium* log removal data for summer and winter runs, and compares oocyst removals without and with recycle of FBW. For the summer season, the two runs without recycle of FBW yielded DAF *Cryptosporidium* log removals of 1.8 and 2.1 (average of nearly 2 log). With recycle of FBW there was scatter in the log removal data for the duplicate samples, but the average oocyst log removal of 2.2 was slightly greater than without recycle. These data indicate no adverse effect on *Cryptosporidium* removals by DAF from recycle of FBW and are in agreement with the turbidity and particle count data presented above. For the winter season, DAF achieved an average oocyst log removal of 2.2 (values of 2.15 and 2.25) without recycle of FBW. With recycle of FBW for the winter, there was considerable scatter in the log removal data for the duplicate samples. If the low log removal value of 1.4 is considered as valid, then one might say recycle of FBW caused a decrease in removals of oocysts. However, using the average log removal of 2.3 and considering the turbidity and particle count data presented above, it is concluded that there is no or minimal adverse impacts on DAF performance. Also, recall from the model presented in the Introduction that if DAF achieves 1.4 log removal or more (for 96% water production or less), then the clarifier is working well enough that untreated waste filter backwash water will not cause an increase in plant influent oocyst concentrations.

The results for the experiments without recycle showed 2 log oocyst removal in the summer and slightly better performance in the winter. One should expect the performance to decrease for cold-water temperatures as shown by the turbidity and particle count data in Table 5. The better *Cryptosporidium* removal performance is explained by the higher feed *Cryptosporidium* concentrations to the pilot plant for the winter that allowed for greater log or percent removals. If the same *Cryptosporidium* influent concentrations were used for both seasons,

Table 6 | Summary of plate sedimentation and filter performance with and without recycle of filter backwash water

Case	Plate settling effluent			Filter effluent		
	Turbidity (NTU)	Particle counts* (#/ml)	Oocysts (#/100 l)	Turbidity (NTU)	Particle counts* (#/ml)	Oocysts (#/100 l)
Summer						
Without recycle	0.8–0.9	1,500–2,000	50	0.03–0.05	10–60	ND
With recycle	0.8–0.9	1,700–2,600	10 & 150	0.03–0.04	10–30	ND
Winter						
Without recycle	1.5–2.0	2,000–2,500	1,100 & 1,800	0.03–0.07	20–80	ND
With recycle	1.5–1.8	1,800–2,600	1,300 & 2,700	0.04–0.07	20–70	ND

*Particle counts: 2–15 μm size range.
ND: not detected.

slightly lower removals would be expected in the winter as found in an earlier study by Edzwald *et al.* (2000).

Plate settling performance

Cryptosporidium removal data for plate settling were collected for one run each without recycle and with recycle of FBW for both seasons. For all but one run, duplicate plate-settling effluent samples were collected.

Figure 9 summarizes *Cryptosporidium* log removal data for summer and winter runs, and compares oocyst removals without and with recycle of FBW. For the summer season, the log removal was 1.9 without recycle of FBW compared to an average slightly lower log removal of 1.75 with recycle of FBW. Considering the scatter in the duplicate measurements for the recycle run, one cannot say whether recycle had a negative effect on *Cryptosporidium* removals. For the winter runs, the variation in log removals from the duplicate measurements was relatively small so average performance is evaluated. The winter data showed a small adverse effect from recycle of FBW given the slightly lower average log *Cryptosporidium* removal of 0.81 compared to an average log removal of 1.04 without recycle.

The oocyst log removals were lower in the winter than for the summer in spite of the much higher oocyst concen-

trations fed to the pilot plant. These results indicate that the cold-water temperatures had a significant effect on performance. Poorer settling performance is expected for cold waters, and was found for turbidity as shown in Table 6. The poorer settling performance for removing *Cryptosporidium* under cold-water conditions also agrees with an earlier study of Edzwald *et al.* (2000).

Overall, the *Cryptosporidium* log removal data show no or minor effects from 10% recycle of FBW on plate settling performance. Our results are in general agreement with the work of Cornwell & MacPhee (2001) who found no negative effects on conventional settling from recycle of waste filter backwash water. Cornwell & MacPhee (2001) actually found a slight improvement in *Cryptosporidium* removals by conventional sedimentation from 0.88 log removal without recycle to 1.1–1.3 log removals with recycle of FBW. This slight improvement might be due to their study conditions in which the settling tank was operated at a longer detention time and a lower hydraulic loading than design conditions. Another difference in the Cornwell & MacPhee (2001) study was higher water temperatures than the cold-water winter conditions reported here.

In comparing plate settling clarification performance with DAF clarification, the data clearly show that DAF

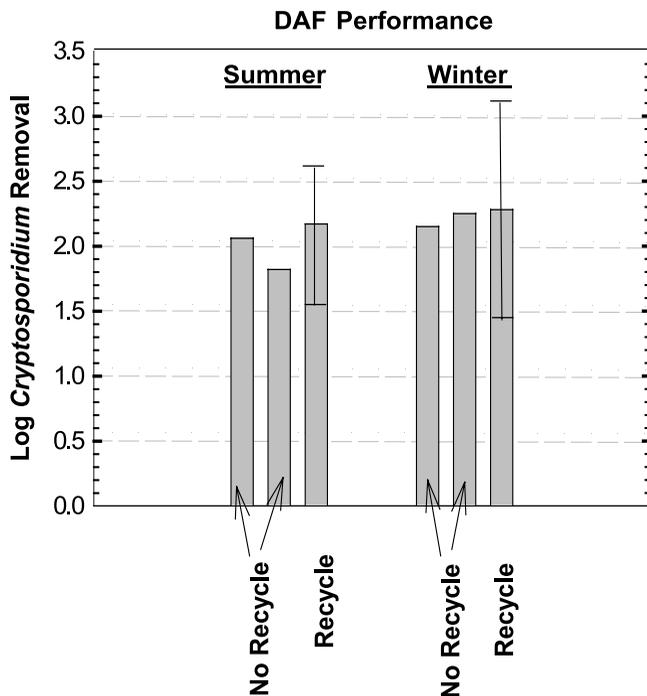


Figure 8 | Comparison of *Cryptosporidium* log removals by DAF for no recycle and with recycle of waste filter backwash water for summer and winter experiments (two experiments or pilot runs for the no recycle cases; for the recycle cases there was only one pilot run for each season so the lines show the spread in duplicate measurements with the bar height showing average removal).

performance was better, especially in cold water, with respect to turbidity, particle counts and *Cryptosporidium* log removals. This confirms the findings of a prior study that examined *Giardia* and *Cryptosporidium* removals (Edzwald *et al.* 2000). The greater removals of oocysts by DAF compared with settling means lower oocyst loadings applied to filters (see the winter oocyst clarification effluent concentrations for DAF (Table 5) versus settling (Table 6)).

Filtration performance

Three points are presented and discussed about filter performance. First, no oocysts were detected for either season in the effluent of the dual media filters for both pilot trains for experiments either with or without recycle of FBW. This was true for both types of filter effluent sampling methods that employed either the ICR cartridge

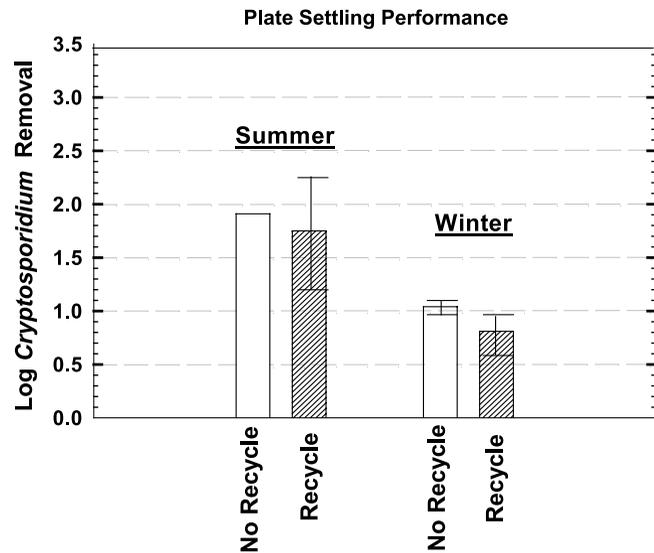


Figure 9 | Comparison of *Cryptosporidium* log removals by plate sedimentation for no recycle and with recycle of waste filter backwash water for summer and winter experiments (each case is one experiment or pilot run; lines show the spread from duplicate sampling over the course of a run and the bar height shows average removal).

filters or the membrane type filters of Method 1622 (US EPA 1999). Thus, there were no effects from recycle of FBW on filtration.

Second, oocyst log removals by filtration for no recycle and with recycle of FBW are not compared because the calculations require a detection limit that depends upon several factors including the sample volume of water collected. For experiments without recycle of FBW the dual media filters were sampled continuously throughout the runs that spanned almost a day, while for the runs with recycle the dual media filters were sampled for several hours. Detection limits are thus higher for runs with recycle of FBW because of less sample volume. Generally, cumulative (clarification plus dual media filtration) oocyst log removals ranged from 4 to 5 with differences due to detection limits rather than treatment plant type or the practice of recycle of FBW.

Third, there were seasonal differences in clarification performance that affected *Cryptosporidium* loadings to the filters, filter performance and waste backwash water quality. The data are examined for the runs without recycle of FBW since the filters were operated to terminal

headloss with run times of 20–24 h. For the summer season, DAF and plate settling achieved about the same log removal of 1.9. Therefore, the oocyst loadings to the filters were approximately the same at about 20–50 oocysts/100 l. The mass balance calculations for the summer runs presented above and summarized in Table 4 reported an oocyst concentration in the waste backwash water for the DAF train at 1,600 oocysts/100 l compared with 1,100 oocysts/100 l in the waste backwash water for the plate settling train. The higher oocyst concentration for the DAF waste filter backwash water is because the filters in the DAF train were operated at twice the hydraulic loading rate than the plate settling train, thus more water was treated by the DAF train. The results for the winter season without recycle of FBW are of particular interest. DAF had a much higher oocyst log removal of about 2.2 log compared with about 1 log for plate settling. Therefore, there was a much higher filter oocyst loading for the plate settling train of 1,450 oocysts/100 l (average from Table 6) compared with 50 oocysts/100 l for the DAF train (average from Table 5). This much higher oocyst loading to the filters for the plate settling train yielded the much higher calculated oocyst concentrations in the waste backwash water of 30,000/100 l compared to 1,400/100 l in the waste backwash water for the DAF train (Table 4).

Overall, the DAF clarification step with about 2 log removal of oocysts means that DAF removes most (99%) of the oocysts entering the treatment plant so that the filters serve as a second barrier in a polishing role. Consequently, the waste backwash water will not have a high enough oocyst concentration to cause an increase in the plant influent oocyst concentration from recycle of FBW. This is supported by the mass balance calculations presented above, and the model presentation in Table 1 which indicated that a clarifier that achieves 1.3 to 1.7 oocyst log removal (depending on the % of filtered water used for backwashing) will prevent an increase in plant influent oocysts from recycle of untreated waste backwash water. The plate settling train, on the other hand, achieved only about 1 log oocyst removal for winter. Here, the mass balance calculations showed high enough oocyst concentrations in the waste backwash water to increase plant influent oocyst concentrations due to recycle.

CONCLUSIONS

The research described in this study evaluated removals of *Cryptosporidium*, turbidity and particle counts (2–15 μm) with and without the recycle of waste filter backwash water. The research assessed the performance of two treatment plant types: a DAF plant and a plate sedimentation plant. The treatment trains were operated at design detention times and hydraulic loadings. Experiments were carried out for summer and winter water temperatures. Coagulant dosing was based on total influent flow (raw water flow plus recycle flow) that was held constant (i.e. the raw water flow was reduced with recycle). Waste filter backwash water was mixed, untreated and recycled at a 10% rate. Based on the experimental conditions of the research, the following conclusions are made.

1. There was no effect on coagulation from the recycle of waste filter backwash water (FBW). An important reason for this is that the pH chemistry of the backwash water was similar to the pH treatment conditions in the pilot plants for clarification and filtration. Thus, dissolved NOM was not high in the waste backwash water and did not exert a coagulant demand.
2. For the DAF treatment train, the turbidity and particle count (2–15 μm) data showed no effects from recycle of FBW on DAF clarification or dual media filtration. For the plate sedimentation pilot train, the turbidity data showed no effects from recycle of FBW on plate settling or dual media filtration. Particle count data showed no or minor effects from recycle on plate settling. No effects were found on dual media filtration.
3. For DAF, there was no effect of recycle of FBW water on *Cryptosporidium* removals. Log removals were about 2-log for both summer and winter with and without recycle of FBW. Plate sedimentation achieved about 2-log removal for the summer with no effect from recycle of FBW. For the cold-water temperatures in the winter, plate settling achieved about 1 log removal of oocysts without recycle of FBW and a small reduction to 0.8 log removal with recycle of FBW.

4. DAF clarification exceeded plate settling performance for turbidity, particle removal and oocyst removals for both seasons, and especially under cold-water conditions.
5. No oocysts were found for either season in the effluent of the dual media filters from either pilot train (DAF or plate sedimentation) for runs with or without recycle of FBW. Thus, there were no effects of FBW recycle on filter performance for removing oocysts for either pilot treatment plant. Based on the plant influent oocyst concentrations and detection limits for oocysts in the filter effluent samples, cumulative (clarification plus dual media filtration) oocyst log removals were 4–5 for both plant types.
6. Mass balance calculations were used to estimate *Cryptosporidium* concentrations in the waste filter backwash water. Plate settling removals of oocysts were poor in the winter causing high oocyst loadings applied to the filters and a high concentration of oocysts in the waste backwash water. Plate settling performance for the summer season and DAF performance for both seasons were good enough that the oocyst concentrations applied to the filters were sufficiently low so that the waste filter backwash water had lower calculated oocyst concentrations than that being fed to the raw water entering the pilot plants.

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