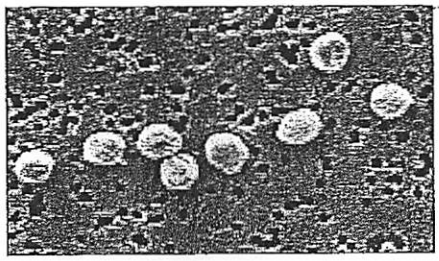
microbial pathogens

Physicochemical removal of protozoan pathogens is receiving increased attention because of the difficulty of chemically inactivating these organisms, particularly *Cryptosporidium parvum*. Most research examining the removal of these and other pathogens by filtration has been conducted under steady-state conditions with optimized pretreatment. This study evaluated the removal of *Cryptosporidium* and changes in surrogate parameters at various points in the filter cycle and under nonoptimal conditions at two pilot plants with different coagulation regimes. The study found a reproducible 2-log difference in *Cryptosporidium* removals between the two locations under optimal conditions, with similar low effluent turbidity levels and particle counts. Either suboptimal coagulation or the early stages of breakthrough at the end of a filter run produced substantial deterioration of *Cryptosporidium* removal capability. Filter ripening or the imposition of a hydraulic step generally had much less effect on removals.



EFFECTS OF filter operation on *Cryptosporidium* removal

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The primary goal of drinking water suppliers is to protect public health by providing water that is free of microbial and chemical contaminants. The emergence of parasitic protozoa such as *Giardia lamblia* and *Cryptosporidium parvum* as etiological agents of waterborne disease has prompted renewed evaluation of the efficacy of water treatment processes. Increasingly stringent regulations for drinking water quality will require effective removal of these organisms. Although disinfection or inactivation plays a crucial role in this regard, physical removal is also important. The multibarrier approach to pathogen removal suggests that where granular media filtration is used, it must be effective.

It is well-known that filter effluent turbidity and particle counts may vary in the different phases of a typical filter cycle and as a result of operational events. During ripening, both turbidity and particle counts are elevated. As the filter becomes loaded toward the end of a cycle, particles may begin to break through. Hydraulic surges can increase filter effluent turbidity and particle counts. Coagulation upsets result in suboptimal pretreatment and may consequently cause an increase in filter effluent turbidity and particle concentrations.

A full report of this project, Filter Operation Effects on Pathogen Passage *(catalog number 90874), is available from AWWA Customer Service (1-800-926-7337). Reports are free to AWWA Research Foundation subscribers by calling 303-347-6121.*

TABLE 1 Major raw water quality and operating parameters at Ottawa and MWDSC*

Parameter†	Ottawa	MWDSC
Raw water quality		
Alkalinity—*mg/L as $CaCO_3$*	19–23	107–134
pH	7.1–7.4	7.7–8.4
Temperature—*°C*	1–24	13–25
TOC—*mg/L*	~5	2.6–2.9
Turbidity—*ntu*	1.0–2.7	0.4–2.4
Coagulant dose		
Alum‡—*mg/L*	38	5
SiO_2—*mg/L*	2	NA§
Cationic polymer—*mg/L*	NA	1.5
Coagulation/filtration pH	5.9–6.1	7.7–8.0
Rapid mix		
G—s^{-1}	in-line	600
HDT—min	NA	1.7
Flocculation		
G for stages 1, 2, and 3—s^{-1}	60, 40, 20	75, 50, 25
HDT—*min*	30	20
Sedimentation		
HDT—*min*	100	80
Filtration		
Filtration rate—*gpm/sq ft (m/h)*	2.6 (6.35)	4.0 (9.8)
Media depth		
Anthracite—*mm (in.)*	457 (18)	508 (20)
Sand—*mm (in.)*	279 (11)	203 (8)
Media size		
Anthracite—*mm*	1.07	1.0–1.1
Sand—*mm*	0.52	0.43–0.50
Media uniformity and coefficient		
Anthracite	1.35	<1.65
Sand	1.32	<1.65

*MWDSC—Metropolitan Water District of Southern California
†$CaCO_3$—calcium carbonate, TOC—total organic carbon, SiO_2—activated silica, *G*—velocity gradient, HDT—hydraulic detention time
‡As dry alum
§NA—not applicable

The objective of this study was to establish whether known increases in filter effluent turbidity and particles under these nonoptimal conditions also implied elevated *C. parvum* oocyst levels in filter effluents. Specifically, the study assessed the degree of pathogen and surrogate removal that can be reasonably expected from "benchmark" filtration systems (i.e., relatively standard design) under optimized operation and the following conditions: suboptimal coagulation, filter ripening, turbidity and particle breakthrough (end-of-run), and hydraulic surges.

BACKGROUND

The literature on *C. parvum* removal by filtration (particularly under nonoptimal conditions) is relatively limited, but studies on the removal of surrogates and of *Giardia* offer useful insights.

Influence of operational factors. Adequate chemical pretreatment during coagulation and flocculation is critical for maintaining good particle removal during filtration (Patania et al, 1995; Tobiason & O'Melia, 1988). For *Giardia* cysts, several investigations have demonstrated little (<1 log) to no removal by granular activated carbon filters (Patania et al, 1995), sand and dual-media filters (Al-Ani et al, 1986), and tri-media filters (Horn et al, 1988) during no-coagulation conditions. A study of a pilot-scale direct filtration plant found that mean *Giardia muris* cyst removals decreased by ~ 1–2.5 log during suboptimal and minimal coagulation, compared with removals under optimal operating conditions (Logsdon et al, 1981). Similar decreases in cyst removal as a result of suboptimal coagulation have been demonstrated at other direct (Ongerth & Percoraro, 1995) and conventional pilot plants (Patania et al, 1995).

Other researchers showed that large changes in flow rate caused deterioration of filtered water quality by the detachment of previously retained particles (Tuepker & Buescher, 1968; Cleasby et al, 1963). The degree of deterioration was related to the magnitude and rapidity of the rate change and was independent of the duration of the disturbance. Effects of increased flow rates on *Giardia* removal have been observed; however, the increases in cyst passage were considerably higher than the increases in turbidity (Logsdon et al, 1981).

Logsdon and colleagues (1981) reported that *Giardia* cyst passage through filters was significantly higher during ripening than during stable operation, even at low effluent turbidity levels. Similar findings were obtained at two pilot plants (Patania et al, 1995), but the differences between stable filter operation and ripening were less dramatic. At a third pilot plant, *Giardia* removals during ripening were comparable to those achieved during stable filter operation (Patania et al, 1995).

Possible sources of breakthrough in filters include particles that pass through directly from the influent (nonattachment) or particles that become detached (Lawler et al, 1995). According to some researchers (Moran et al, 1993; Ginn et al, 1992), both nonattachment and detachment occur during breakthrough conditions. As particle detachment and nonattachment

increase, increased pathogen passage through filters would also be expected.

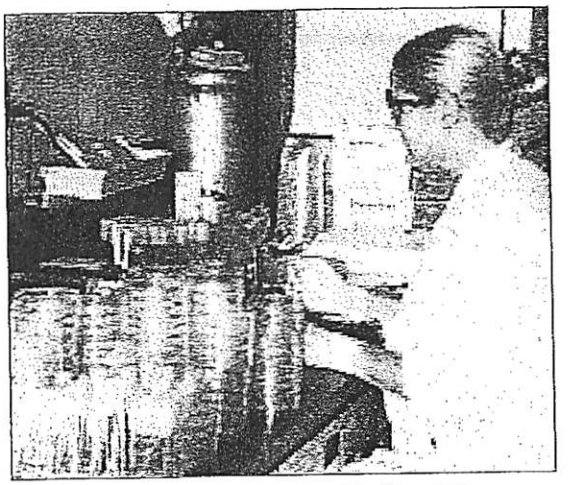
Logsdon et al (1981) demonstrated that turbidity breakthrough at the end of a filter cycle (when filter effluent turbidity was > 0.4 ntu) could be accompanied by a substantial passage of *Giardia* cysts, even if the cysts were not present in the filter influent. A considerable increase in cyst passage was also observed during early breakthrough conditions when filter effluent turbidity was just above 0.2 ntu. Patania et al (1995) also reported lower *Giardia* removal through filters during breakthrough.

Removal of surrogates. Several pilot- and full-scale studies have demonstrated that organism-sized particles and turbidity are approximate indicators of pathogen removal but not reliable surrogates (Nieminski & Ongerth, 1995; LeChevallier & Norton, 1992). Plummer and co-workers (1995) reached similar conclusions about turbidity, as well as ultraviolet absorbance at 254 nm and dissolved organic carbon. Patania and colleagues (1995) indicated that achieving a goal of 0.1 ntu was indicative of effective cyst–oocyst removal. Although the risk of *Cryptosporidium* passage appeared to increase with increasing filtrate turbidity in several studies (Hall & Croll, 1996; Hall et al, 1995; Nieminski & Ongerth, 1995), other researchers did not observe significant oocyst passage during the first hour of operation after backwash when filter effluent turbidity was high (filter ripening) (Fuller et al, 1995).

Bacillus spores were found to demonstrate a significant correlation with *Cryptosporidium* removal at both pilot and full scale (Scott et al, 1997). Other studies also found that aerobic spores were indicative of treatment efficiency but did not conclude that the spores were adequate surrogates for oocyst removal (Swertfeger et al, 1999; Nieminski & Bellamy, 1998; Lytle et al, 1996).

Removal of *C. parvum*. A number of studies have investigated *C. parvum* oocyst removals by granular media filtration at or near optimized stable operating conditions. Full-scale removals have been reported at levels from 2–3 log (e.g., Kelley et al, 1995; Nieminski & Ongerth, 1995) to > 4 log (e.g., Baudin & Laîné, 1998). Pilot-scale data have suggested that filters can achieve oocyst removals of 2–3 log (e.g., Fox et al, 1998; Kelley et al, 1995; West et al, 1994), 3–4 log (Yates et al, 1997a), and > 5 log (e.g., Patania et al, 1995; LeChevallier et al, 1991a). Differences in analytical reliability, processed sample volume, method detection limits, and influent microorganism concentrations can all contribute to the reported differences in the *Cryptosporidium* removal capacities of filters.

Patania et al (1995) examined conventional filtration, low-rate surface filtration, and in-line filtration at pilot scale and demonstrated that filtration was ineffective for oocyst removal without chemical pretreatment. Other pilot-scale studies also indicated that suboptimal coagulation conditions decrease oocyst removal by filters by at least 1 log (e.g., Dugan et al, 1999; Charles et al, 1995; Ongerth & Pecoraro, 1995). Results reported earlier from the current study showed a substantial negative effect of suboptimal coagulation (Coffey et al, 1999).



Inactivated *Cryptosporidium* oocysts and *Bacillus subtilis* spores seeded in the experiments were enumerated in the laboratory.

Cryptosporidium removals of > 3 log have been maintained during filter ripening, despite a decrease in removals when compared with stable operation (e.g., Swaim et al, 1996). Several pilot-scale studies have indicated that oocyst removals decrease by ~ 0.5–1 log during filter ripening (e.g., Swaim et al, 1996; Hall et al, 1995; Patania et al, 1995). These findings were confirmed at full scale by Baudin and Laîné (1998), who demonstrated ~ 1-log deterioration in oocyst removals during ripening.

Two studies concluded that oocyst removals are comparable during turbidity breakthrough and stable filter operation (Baudin & Laîné, 1998; Patania et al, 1995). Patania and co-workers (1995) noted that the filter effluent turbidity increased by only ~ 0.1 ntu during their evaluation of breakthrough. Those authors speculated that oocyst removal might have deteriorated if sampling had continued beyond this point. Huck et al (1999) reported a substantial deterioration in performance during breakthrough.

Bench-scale studies have indicated that formalin-inactivated oocysts and viable oocysts of *C. parvum* are comparably removed by both dual- and tri-media filters (Emelko, 2001). This finding is significant, because studies in which oocysts are spiked (typically pilot-scale investigations) use inactivated oocysts for safety reasons.

METHODS AND RESEARCH PLATFORMS

Experimental design. The experiments in this study were conducted at two pilot plants—one in Ottawa, Ont., and the other at the Metropolitan Water District of Southern California (MWDSC) treatment plant in La Verne, Calif. These locations represented two basic types of

TABLE 2 Summary of removals and filter effluent quality during stable operation

Date	Research Platform	Log Removal Mean ± Standard Deviation			Filter Effluent Value Mean ± Standard Deviation	
		C. parvum	*B. subtilis*	Particles*	Particles *number/mL*	Turbidity *ntu*
8/6/98	Ottawa	4.9 ± 0.21		3.2 ± 0.29	3.7 ± 2.9	0.02 ± 0.00
9/9/98	Ottawa	5.7 ± 0.06		3.8 ± 0.10	0.9 ± 0.2	0.02 ± 0.00
9/23/98	Ottawa	5.8 ± 0.03		2.8 ± 0.24	8.7 ± 5.6	0.03 ± 0.00
10/6/98	Ottawa	5.8 ± 0.15		4.6 ± 0.18	0.2 ± 0.1	0.02 ± 0.00
3/9/99	Ottawa	5.2 ± 0.38	2.1 ± 0.14	4.1 ± 0.10	0.4 ± 0.1	0.03 ± 0.00
5/31/99	Ottawa	5.6 ± 0.20	4.6 ± 0.05	3.7 ± 0.18	1.2 ± 0.6	0.03 ± 0.00
7/27/99	Ottawa	5.6 ± 0.02	4.5 ± 0.24	3.0 ± 0.22	5.1 ± 1.5	0.04 ± 0.00
1/19/00	Ottawa	5.3 ± 0.38	4.2 ± 0.01	†	4.8 ± 0.6	0.03 ± 0.00
7/16/98	MWDSC‡	2.6 ± 0.07	2.0 ± 0.13	2.2 ± 0.09	6.3 ± 1.2	0.05 ± 0.00
7/28/98	MWDSC	3.3 ± 0.07	2.7 ± 0.26	2.6 ± 0.04	4.5 ± 0.4	0.05 ± 0.00
8/18/98	MWDSC	4.1 ± 0.65	2.3 ± 0.17	3.4 ± 0.04	1.5 ± 0.2	0.05 ± 0.00
9/22/98	MWDSC	3.8 ± 0.16	1.9 ± 0.46	2.8 ± 0.01	5.2 ± 0.2	0.05 ± 0.00
9/29/98	MWDSC		3.2 ± 0.37	3.3 ± 0.14	3.1 ± 0.4	0.05 ± 0.00
10/27/98	MWDSC	3.2 ± 0.15	2.3 ± 0.17	2.5 ± 0.14	10 ± 3.2	0.05 ± 0.00
11/24/98	MWDSC		2.1 ± 0.86	2.0 ± 0.02	32 ± 1.4	0.05 ± 0.00
12/15/98	MWDSC	2.9 ± 0.11	1.8 ± 0.06	1.8 ± 0.02	37 ± 1.8	0.05 ± 0.00
2/9/99	MWDSC	2.1 ± 0.15	1.9 ± 0.07	2.2 ± 0.01	21 ± 1.7	0.06 ± 0.00
3/9/99	MWDSC	2.4 ± 0.18	1.9 ± 0.04	2.9 ± 0.07	3.9 ± 0.6	0.05 ± 0.00
4/27/99	MWDSC	2.9 ± 0.29	1.9 ± 0.06	2.2 ± 0.02	27 ± 1.2	0.05 ± 0.00
	Ottawa average	5.5 ± 0.37	3.8 ± 1.07	3.6 ± 0.63	3.1 ± 3.5	0.03 ± 0.01
	MWDSC average	3.0 ± 0.66	2.2 ± 0.52	2.5 ± 0.50	13.8 ± 12.6	0.05 ± 0.00

*Log net decrease from raw water to filter effluent
†Plant influent data not available
‡MWDSC—Metropolitan Water District of Southern California

coagulation: a relatively high dosage for combined total organic carbon (TOC) and particle removal (Ottawa River water) and a relatively low dosage optimized for particle removal (MWDSC-treated Colorado River water). Inactivated *C. parvum* oocysts and pure-cultured *Bacillus subtilis* spores were seeded at both locations. Removals of turbidity and particles were also monitored. These experiments were designed to document pathogen removal from benchmark systems and were part of a larger study (Huck et al, 2001). In the investigations reported in this article, no attempt was made to improve pathogen removal or mitigate adverse conditions.

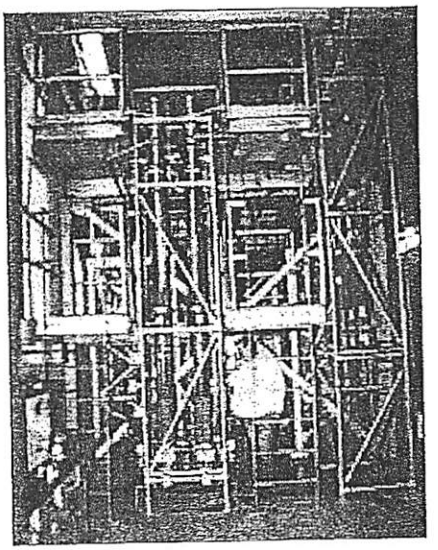
The conditions investigated were stable filter operation, suboptimal coagulation, ripening, breakthrough, and hydraulic step. In addition, control experiments were performed to evaluate losses of seeded organisms to the pilot-plant filters and appurtenances. The study also examined several subconditions within suboptimal coagulation and breakthrough. End-of-run experiments were performed at MWDSC because it was not possible to actually achieve breakthrough in that pilot plant. Experiments for each of the principal conditions were conducted at least in triplicate at each location.

Research platforms and experimental approach. Table 1 summarizes major raw water quality and operating parameters for the two locations. Both of the pilot plants received water that was low in turbidity and particles, with averages in the range of ~ 5,000 particles/mL (>2 µm). Major differences between the raw waters included alkalinity and temperature (Ottawa's lowest temperature was much colder than MWDSC's). Each pilot plant was operated to mimic as closely as possible the full-scale treatment plant at the same location.

The filters at both pilot plants featured media depths and sizes typical of the utilities' full-scale plants (and typical of many existing treatment plants). The operational mode chosen was conventional treatment with dual-media filtration. At MWDSC, the benchmark filter design contained 508 mm (20 in.) of anthracite over 203 mm (8 in.) of sand. At Ottawa, the filter design contained 457 mm (18 in.) of anthracite over 279 mm (11 in.) of sand. At MWDSC, the backwashing regime consisted of chlorinated water with surface wash. At Ottawa, chlorinated water and air-scouring were used.

The Ottawa pilot plant used a high coagulant dose of ~ 40 mg/L alum and 2 mg/L activated silica to achieve

removal of both TOC and particles. The MWDSC pilot plant used a low coagulant dose of 5 mg/L alum and 1.5 mg/L cationic polymer for particulate removal only. At both pilot plants, chlorine (~2 mg/L) was added at rapid mix as a preoxidant. Because of Ottawa's higher coagulant dosage and lower alkalinity, coagulation pH was lower (~ 6 compared with ~ 8 at MWDSC). The optimized coagulation conditions were selected to meet the 0.1-ntu turbidity goal of the Partnership for Safe Water, a voluntary treatment optimization program sponsored by AWWA and the US Environmental Protection Agency.



Pilot-scale dual-media filters were used in this research.

At each pilot plant, rapid mix was followed by three-stage tapered flocculation. The overall flocculation hydraulic detention times (HDTs) were 30 min at Ottawa and 20 min at MWDSC. HDTs of the sedimentation step were 100 min at Ottawa and 80 min at MWDSC. Further operating details for the pilot plants are described in Huck et al (2001).

The pilot-scale filters in both locations were seeded with jar-coagulated suspensions of ~ 10^8 formalin-inactivated *C. parvum* and ~ 10^7–10^9 *B. subtilis* spores. Except for three experiments described separately, microorganisms were seeded into the filter influent, using a procedure established by members of the project team in previous investigations (Yates et al, 1997a; Yates et al, 1997b). This seed location was selected to minimize significant losses of microorganisms in upstream unit processes and to better characterize their removal during filtration. The data collected from the seeding experiments consisted of replicate samples (either four or five) taken from the filter influent and filter effluent at each location. The filter influent and filter effluent data were normally collected over a 1-h period when the seed suspension was added at the filter influent. A single-factor, analysis of variance (ANOVA) statistical test[1] was used to interpret the data, which were pooled from the replicate experiments at each location.

Detailed study data and the results of limited seeding of *G. lamblia*, MS-2 bacteriophage, and *Escherichia coli* at MWDSC are described elsewhere (Huck et al, 2001). In this article, the authors calculate and discuss changes (i.e., net decrease) in particle counts as a result of treatment. The changes are not referred to as particle removals because they are calculated using the plant influent (rather than the filter influent as in the case of the seeded microorganisms) and the filter effluent. (Filter influent particle counts were not measured for technical reasons.) Because coagulation, flocculation, and sedimentation can all affect particle counts, a general quantitative relationship would not necessarily be expected between the change in particle counts from raw to finished water and the removal of seeded microorganisms by filtration alone.

Seeding protocols. The seed suspension of oocysts or spores was diluted to 1.5 L with preoxidized influent water and jar-coagulated under coagulant and mixing conditions that mimicked pilot-scale treatment. The jar-coagulated organisms were then seeded directly into the influent of the filter by a peristaltic pump for 60 min. During seeding, the seed suspension was constantly agitated with a magnetic stirrer to ensure steady distribution of the organisms during the procedure.

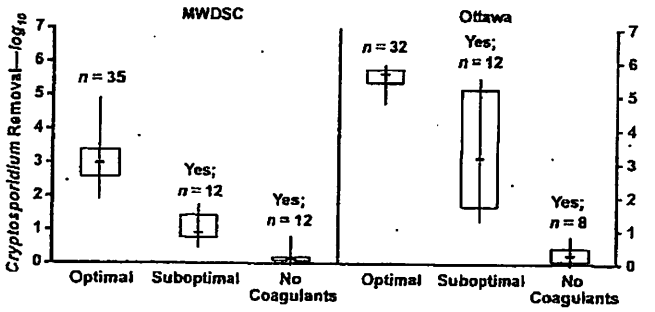
The targeted seeded influent concentration for *Cryptosporidium* was ~ 10^5 oocysts/L. Samples were collected in sterile bottles containing sodium thiosulfate. Filter effluent samples were collected in 1-L Wheaton bottles from the continuously running effluent line. Filter influent samples were collected in 250-mL amber bottles from the water column directly above the filter media using a continuous recirculation peristaltic pump.

Analytical methods. *C. parvum.* *C. parvum* oocysts were obtained from a commercial laboratory.[2] For each test, ~ 10^8 oocysts were obtained—already inactivated with 5% formalin. Prior to seeding, a small portion of the stock suspension was removed for enumeration using a hemacytometer.[3]

Filter influent samples were analyzed in sample volumes of 10 mL and filter effluent samples in volumes of 500 mL (or less if the filter effluent turbidity was elevated). Oocysts were collected by direct vacuum filtration of the sample through 27 mm (1.06 in.) diameter, 0.45-µm-pore-size polycarbonate membranes. Standard immunofluorescent assay techniques were used to stain the samples. Slides of Ottawa samples were analyzed at the University of Waterloo, Ont.; slides from MWDSC were shipped to a commercial laboratory[4] for presumptive microscopic analysis. As a procedural check, recovery experiments were performed at both locations using both filter influent and effluent water matrixes. The measured *Cryptosporidium* levels reported here were not adjusted by the recovery.

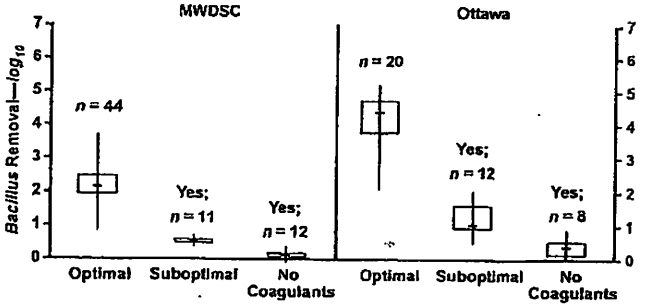
B. subtilis. The analysis for *B. subtilis*[5] was performed according to a previously described method (Rice et al, 1996). This method generally consisted of filtration of samples onto 47 mm (1.8 in.), 0.45-µm gridded cellulose acetate membranes[6] and growth at 37°C for 24 h on plates of nutrient agar with trypan blue (0.015 g/L).

FIGURE 1 Effect of coagulation on filters' removal of *Cryptosporidium parvum*



MWDSC—Metropolitan Water District of Southern California, n—number of data points. "Yes" designation indicates that the mean for a given condition was statistically different from the optimal or stable operation condition at the 5% level.

FIGURE 2 Effect of coagulation on filters' removal of *Bacillus subtilis*



MWDSC—Metropolitan Water District of Southern California, n—number of data points. "Yes" designation indicates that the mean for a given condition was statistically different from the optimal or stable operation condition at the 5% level.

Spores were identified by their blue color. Typically, duplicate sample volumes of 0.1 and 1.0 L were used to enumerate filter influent and effluent, respectively.

Particle counting. Each particle-counting instrument was calibrated by the manufacturer according to ASTM (American Society for Testing and Materials) F 658-87 and met the resolution requirements of USP (US Pharmacopeia) 788. The calibration was verified on site using commercially available, calibrated, monodisperse polymer microspheres.[7] The particle counters[8] measured total particles from 2 to 150 µm, with the data reported as cumulative particles ≥ 2 µm.

Turbidity. Turbidity was monitored using online turbidimeters that were calibrated using dilute formazin solutions as specified by the manufacturer. Calibration was checked by comparison with a bench-top turbidimeter with an accuracy of ± 2%, using standards of 0.80 and 6.6 ntu. MWDSC and Ottawa testing used the same model of turbidimeter[9] at plant influent, filter influent, and filter effluent locations. An additional turbidity meter[10] was used at the filter effluent sampling location in Ottawa. Filter influent turbidity at Ottawa was measured by grab samples analyzed with a handheld turbidimeter.[11]

Head loss. Differential pressure transducers continuously measured head loss at the MWDSC and Ottawa pilot plants. Additional details about methods and the quality assurance–quality control program may be found elsewhere (Huck et al, 2001).

RESULTS

Controls. As noted previously, a control experiment was performed at each location to quantify the possible losses of seeded microorganisms to the pilot-plant systems. In these experiments, no media were in the filters, and no coagulant was added. As was standard practice, the microorganisms were seeded in the filter influent. Thus, these experiments were designed to give an indication of possible adsorption of seeded microorganisms on surfaces within the pilot plant, including any sample tubing.

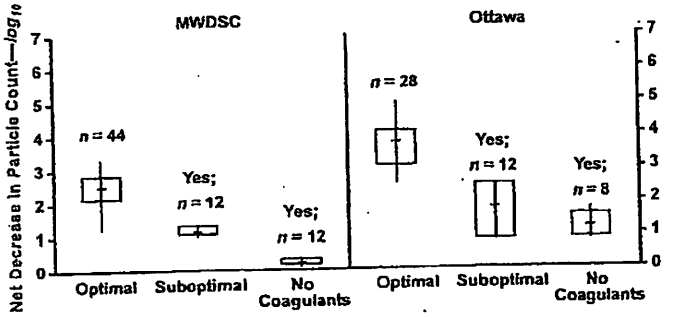
In both locations, the removals of *C. parvum* and *B. subtilis* in the control experiments without media were < 0.10-log units (Huck et al, 2001). These results convincingly demonstrated that losses of seeded microorganisms to the pilot-plant apparatus were essentially negligible. Therefore, the removals attributed to filtration under each of the tested operating conditions could be attributed to the filters themselves.

Stable filter operation. The purpose of these experiments was to document the best removals that could be obtained under optimal conditions in each location. Seeding and sampling were conducted in the early-to-middle portion of the filter cycle, after ripening was complete. Because these experiments provided a baseline for comparison, they were conducted periodically throughout the experimental program. In all, eight stable operation experiments were conducted at Ottawa and eleven at MWDSC. In addition, several stable operation experiments were conducted in which seeding was performed at the rapid mix. These results are discussed separately.

Table 2 summarizes the results for the stable operation experiments. The most striking finding was the > 2-$\log_{10}$ difference in *C. parvum* removals between the two locations, despite essentially the same effluent turbidity values and very similar (and low) filter effluent particle counts. At Ottawa, 5.5 ± 0.4 $\log_{10}$ removal of *C. parvum* was obtained, whereas at MWDSC, 3.0 ± 0.7 $\log_{10}$

removal was observed. The filter influent concentrations in both locations were similar: approximately 10^6/L in Ottawa and 10^5–10^6/L at MWDSC. *C. parvum* was always found in the filter effluent samples at MWDSC, typically at concentrations of at least 100 oocysts/L. At Ottawa, filter effluent *C. parvum* concentrations were usually < 10 oocysts/L. Often a count of zero was obtained for the 500-mL sample volume normally examined. Because of the high observed removals, the Ottawa experimental protocols and data were carefully scrutinized during the study, and nothing was found to suggest that the results were anomalous.

FIGURE 3 Effect of coagulation on net decrease in particle count from raw water to filter effluent



MWDSC—Metropolitan Water District of Southern California, n—number of data points. "Yes" designation indicates that the mean for a given condition was statistically different from the optimal or stable operation condition at the 5% level.

The reasons for the difference in *C. parvum* removals between the two locations are not definitively known, and the experimental program was not designed to identify them. Differences in raw water quality and coagulation may be important. Although the two filter designs were quite similar, small differences may play a role. The matter merits further investigation.

Although there was some variation in removals calculated on the basis of individual influent–effluent sample pairs, the calculated removals from run to run were quite reproducible, as indicated by the relatively low overall standard deviations. The Ottawa experiments included runs at low temperature. No deterioration in performance was observed at temperatures as low as 1°C (Huck et al, 2001).

Removals of *B. subtilis* were 3.8 ± 1.1 $\log_{10}$ in Ottawa and 2.2 ± 0.5 $\log_{10}$ at MWDSC; in both locations, removals were lower than those for *C. parvum*. Although *B. subtilis* removals were substantially higher in Ottawa, the difference between the two locations was not as great as the difference for *C. parvum*. In both locations, the seeded concentration of *B. subtilis* was lower than that of *C. parvum*. Although *B. subtilis* spores were invariably detected in the filter effluent samples at Ottawa and always at MWDSC, it is possible that the lower seeded concentrations contributed to lower observed removals.

However, it appears that *B. subtilis* gives a conservative indication of a filter's ability to remove *C. parvum* under stable operating conditions. It also appears that to at least some extent, differences in *B. subtilis* removals in different filters indicate variations to be expected in *C. parvum* removals. Furthermore, the removals of *B. subtilis* during stable operation in Ottawa, which were 1.6 $\log_{10}$ higher than removals at MWDSC, lend credence to the substantially higher removals of *C. parvum* observed in Ottawa. Overall reproducibility of the calculated *B. subtilis* removals was almost as good as for *C. parvum*.

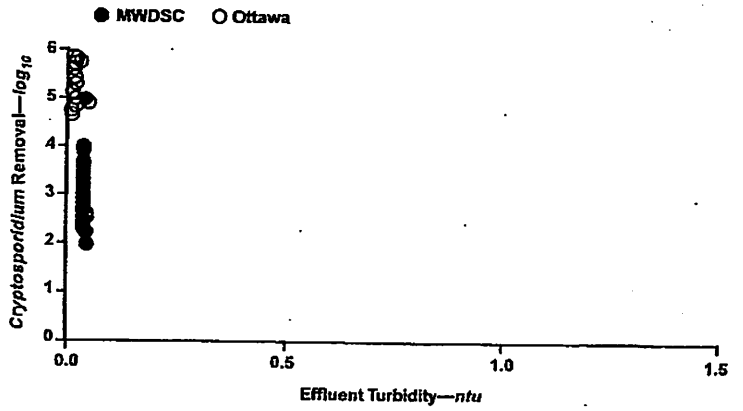
Table 2 also summarizes changes in particle count (≥ 2 µm) and particle filter effluent concentrations for the two locations. In Ottawa, the mean net decrease in particle count (from raw water to filter effluent) during the stable operation experiments was 3.6 ± 0.6 $\log_{10}$, whereas at MWDSC, it was 2.5 ± 0.5 $\log_{10}$. Mean filter effluent particle numbers in the two locations were approximately 3/mL in Ottawa and 14/mL at MWDSC. The MWDSC average was influenced by several runs with effluent particle numbers > 20/mL. Although raw water values were roughly similar in both locations (on the order of 5,000/mL), it should be noted that different particle counters were used. Furthermore, many of the filter effluent particle counts were at or near the detection limit of the instrument, particularly in Ottawa.

Given these qualifications, it is not possible to quantitatively compare the net decrease in particle count determined for stable operation in this study to *C. parvum* removals under the same conditions. However, different observed net decreases in particle counts in different filters (with roughly similar influent particle counts) may be indicative of differences in *C. parvum* removals by these filters.

It is questionable whether the observed different filter effluent particle counts in Ottawa and MWDSC represent a real difference. Given the substantial difference in *C. parvum* removal at the two locations, however, it is possible that small differences in particle counts may be indicative of measurable differences in the *C. parvum* removal capability of the two treatment systems. Certainly in the breakthrough experiments discussed later in this article, small increases in effluent particle counts late in the run in Ottawa signaled a much greater deterioration in the filter's ability to remove *C. parvum*.

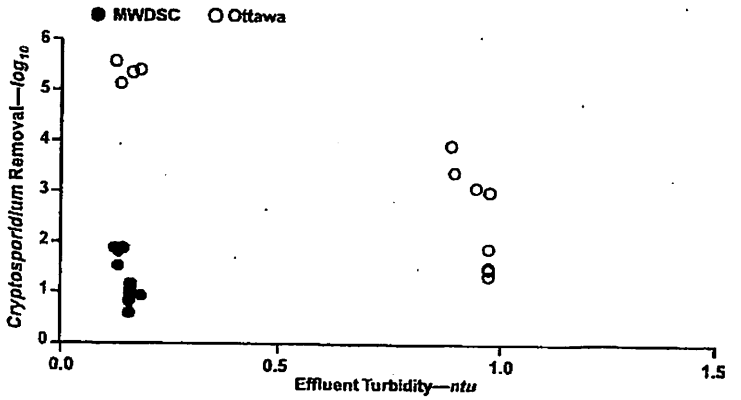
Table 2 also shows filter effluent turbidity values for the two locations. As with the particle data, the values shown correspond to the times at which the microorganism samples were taken. Log removals for turbidity are

FIGURE 4 *Cryptosporidium parvum* removal versus filter effluent turbidity (optimal coagulation conditions)



MWDSC—Metropolitan Water District of Southern California

FIGURE 5 *Cryptosporidium parvum* removal versus filter effluent turbidity (suboptimal coagulation conditions)



MWDSC—Metropolitan Water District of Southern California

not calculated because they are limited by the relatively low influent values and also by the fact that many filter effluent values are very close to the instrument detection limit. In all but one stable operation experiment, filter effluent turbidity was ≤ 0.05 ntu. The mean filter effluent turbidity was 0.03 ntu in Ottawa and 0.05 ntu at MWDSC. Both of these values were considered to be indicative of excellent filtration performance; in fact, it could be argued that there is no meaningful difference between the overall average values obtained in the two locations. If there is a real difference, it is extremely subtle and could not be reliably used to predict the differences in *C. parvum* removal observed at the two locations.

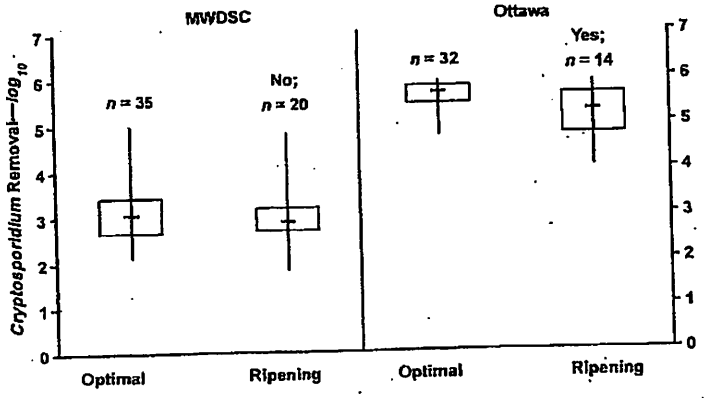
In two experiments at MWDSC and one at Ottawa, microorganisms were seeded at the rapid mix in the pilot plant rather than being jar-coagulated offline and seeded at the filter influent. In these experiments, filter influent concentrations of *C. parvum* at both locations were at least several orders of magnitude lower than usual because of substantial losses through the sedimentation step and because the seed was dispersed over a longer period of time. In these runs, *C. parvum* removals were much lower (1.3 $\log_{10}$) at MWDSC, although reproducibility there was not good (Huck et al, 2001). Oocysts were detected in all filter effluent samples.

Removals could not be quantified in Ottawa, because a count of zero oocysts was obtained for all filter effluent samples. Filter influent oocyst counts increased and then decreased during the experiment, as would be expected, with a maximum value of 710 oocysts/L. On the basis of the maximum influent value, removal at Ottawa was at least 2.6 $\log_{10}$. Filter influent concentrations of *B. subtilis* spores were low in Ottawa and close to normal levels at MWDSC. In Ottawa, removals were much lower than normal (1.1 $\log_{10}$), and low numbers of spores were detected in the filter effluent. At MWDSC, the calculated removals were the same as for normal stable operation. Overall, the results of the small number of experiments involving seeding at the rapid mix are not considered an accurate reflection of oocyst removal capabilities of the filters in either pilot plant.

Coagulation impairment. Two basic types of impaired coagulation experiments were performed: no coagulation and suboptimal coagulation. Results were then compared with the stable operation (i.e., optimal) results discussed earlier. As noted previously, the optimum coagulant dosage in Ottawa was nearly eight times greater than at MWDSC, and the coagulation pH was lower (~ 6 at Ottawa versus ~ 8 at MWDSC).

No coagulation. These experiments simulated a worst-case condition of total coagulant failure. They also served as additional controls to determine microorganism losses through the pilot-plant facilities. In these tests, coagulation was discontinued; the filter was then backwashed prior to beginning the no-coagulant run in which microorganisms (which also received no coagulant) were seeded. Previous seeding of *C. parvum* oocysts at MWDSC's pilot plant had indicated a loss of ~ 0.3 log (50%) of oocysts when no chemicals were added to the water (Yates et al, 1997a; Yates et al, 1997b).

FIGURE 6 Effect of ripening on filters' removal of *Cryptosporidium parvum*



MWDSC—Metropolitan Water District of Southern California, n—number of data points. "Yes" designation indicates that the mean for a given condition was statistically different from the optimal or stable operation condition at the 5% level; "No" indicates the mean was not statistically different.

At Ottawa, an additional experiment was conducted in which the activated silica feed was discontinued, but otherwise coagulation remained as normal. This run simulated a coagulant aid failure and was conducted to investigate whether the use of activated silica was an important factor in the high observed removal of *C. parvum* oocysts under optimal coagulation conditions. Several different short-term loss-of-coagulant scenarios were also tested in Ottawa (Huck et al, 2001).

Suboptimal coagulation. These experiments determined how pathogen passage was affected by changes in coagulation conditions (without a change in raw water quality). The coagulant dosage (alum and polymer at MWDSC; alum and activated silica at Ottawa) was reduced 40–65% from optimum in an attempt to achieve a targeted suboptimal turbidity of 0.2–0.3 ntu. In some tests, however, the target effluent turbidity was exceeded. The suboptimal coagulant dosage was also applied in the jar coagulation of the microorganism seed suspensions.

Figures 1 and 2 summarize the removal of seeded *C. parvum* and *B. subtilis* at Ottawa and MWDSC. Figure 3 summarizes the net decrease in particles at both locations. The box-and-whisker plots in these figures represent the minimum, 25th percentile, median, 75th percentile, and maximum values for removals. Results for the various partial coagulation scenarios in Ottawa are discussed later.

Each removal is expressed as the $\log_{10}$ difference between paired sets of data taken at the filter influent and filter effluent. The net decrease for particle counts was calculated the same way, using raw water and filter effluent values, as noted previously. The number of data points used in the statistical comparisons (single-factor ANOVA) is shown on the figures. The "Yes" designation indicates that the mean for a given condition was statistically different from the optimal or stable operation condition at the 5% level.

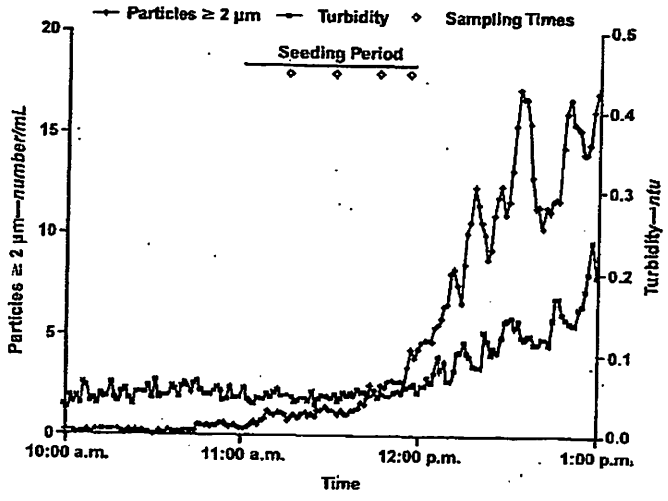
In general, similar trends were seen for all three parameters at both locations. Suboptimal coagulation had a substantial adverse effect on removal or net decreases. At both MWDSC and Ottawa, significantly greater $\log_{10}$ removals or net decreases were obtained during optimized coagulation (i.e., 2–4 h into the filter cycle when effluent turbidity was ≤ 0.10 ntu) than during suboptimal coagulation or coagulant failure. At both locations, average *C. parvum* removals were reduced by just over 2 $\log_{10}$ under suboptimal coagulation.

All differences were statistically significant at the 1% level ($\alpha = 0.01$) as well as at the 5% level. Removals of *C. parvum* were higher than those of *B. subtilis* under suboptimal conditions, as was the case under optimal conditions. The differences in *B. subtilis* removals between suboptimal and optimal conditions were also substantial and were statistically significant ($\alpha = 0.01$). The difference in net decrease in particle counts in both locations was also statistically significant compared with optimal conditions. The essentially zero removals of both organisms for the no-coagulant condition again confirmed that seeded organisms were not being lost in the pilot plants and demonstrated the crucial importance of at least some level of coagulation for rapid filters.

At MWDSC, suboptimal coagulation resulted in an average effluent turbidity of 0.16 ntu, well below the level of 0.3 ntu specified by the Interim Enhanced Surface Water Treatment Rule. (IESWTR). At Ottawa, the coagulant reduction resulted in an average effluent turbidity of 0.56 ntu. The suboptimal coagulation experiments at Ottawa varied more substantially than at MWDSC, most noticeably in terms of *C. parvum* removal and filter effluent turbidity. This reflected the greater difficulty in hitting the target suboptimal conditions in Ottawa and may indicate that such regimes are very vulnerable to underdosing (close to the coagulant demand).

The relationship between seeded *C. parvum* or *B. subtilis* and net decrease in particle count was examined under all of the coagulation conditions (Coffey et al, 1999). At MWDSC, *C. parvum* and *B. subtilis* removals were highly correlated to decrease in particles (R^2 values of 0.87 and 0.82, respectively). At Ottawa, the strength of the correlation was not as high (R^2 values of 0.60 for

FIGURE 7 Turbidity and particle response of filter during onset-of-breakthrough experiment at Ottawa pilot plant on Jan. 21, 1999



C. parvum and 0.25 for *B. subtilis*). The elevated filter effluent particle counts observed under suboptimal coagulation conditions are tabulated in Huck et al (2001).

Figures 4 and 5 show the effect of coagulation condition on filter effluent turbidity and *C. parvum* removal; *C. parvum* removals are shown for individual influent–effluent data pairs. In Figure 4 (optimal conditions), turbidity was always < 0.1 ntu. Although Ottawa's *C. parvum* removals were almost always greater than MWDSC's, in each location the removals calculated from individual influent–effluent sample pairs varied considerably, a fact that underlines the need for replication in this type of work.

As shown in Figure 5 (suboptimal coagulation conditions), filter effluent turbidity was in the range of 0.1–0.2 ntu in all MWDSC experiments of this type. Some Ottawa data were available for this range, but in other Ottawa experiments, the effluent turbidity was closer to 1 ntu. When turbidity was 0.1–0.2 ntu, Ottawa *C. parvum* removal did not appear to decrease, whereas MWDSC *C. parvum* removal did. This would suggest that the sensitivity of turbidity for monitoring coagulation effects on *C. parvum* removal may be site-specific and perhaps dependent on the coagulation regime used. It is possible that particle counts may be a more sensitive indicator of poor coagulation performance.

When coagulant was absent for only a short duration in Ottawa (several hours prior to and during seeding), *C. parvum* removals were seriously impaired (by several log units) but at least 2-log removal did occur (Huck et al, 2001). *B. subtilis* removals were reduced by about the same extent under this condition. The absence of activated silica for the entire run had essentially no effect on the removal of either organism (Huck et al, 2001). Although it is possible that some silica remained in the filter from previous runs, this finding suggests that the use of silica (which was one difference between Ottawa and MWDSC) was not responsible for the very high *C. parvum* removals seen under optimal coagulant conditions in Ottawa.

Results of these experiments indicate that even at filter effluent turbidity levels < 0.3 ntu, substantial deterioration of filtration performance may result if coagulation is not optimized. *C. parvum* removals were more sensitive to coagulation conditions than turbidity removals were. The sensitivity of turbidity for measuring coagulation effects on *C. parvum* removal may depend on the coagulation regime. Filter effluent particle monitoring may provide a more sensitive measure of coagulation performance and *C. parvum* removal. Plants using a relatively high alum dose (such as Ottawa) may be able to provide some reduced level of *C. parvum* removal by filtration during a short-term (several-hour) coagulant feed failure. (A short-term coagulation failure was not tested at MWDSC.)

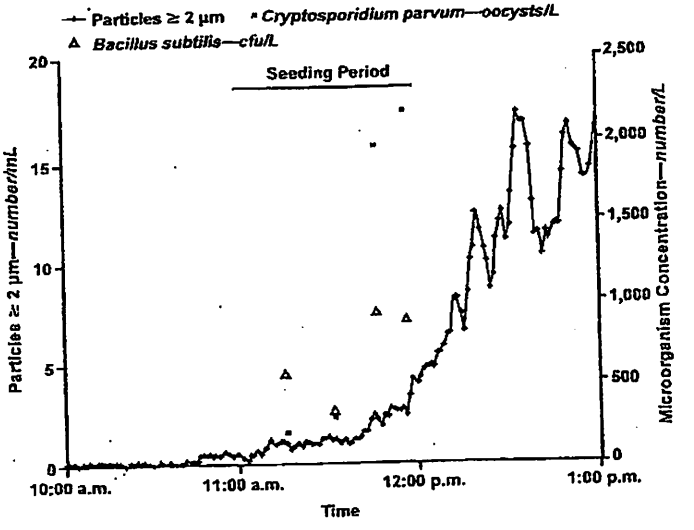
Ripening. Ripening experiments were conducted at both locations. The seeding period in Ottawa was only 30 min because the filter typically ripened to stable operating conditions of filter effluent turbidity levels < 0.1 ntu and particle concentrations < 5–10 particles/mL during that time. The duration of ripening in the MWDSC filter was similar (~30–40 min). Microorganisms were seeded for 1 h at MWDSC. In Ottawa, samples were collected at 5-min intervals during ripening, whereas at MWDSC samples were generally taken at 10, 20, 40 and 60 min.

As expected, both traditional performance measures (turbidity and particle counts) and filter effluent microorganism concentrations varied during the ripening period. At Ottawa, peak filter effluent turbidity and particle counts during ripening ranged from 0.41 to 0.69 ntu and 91 to 840 particles/mL, respectively, and the durations of the ripening period were generally comparable among the three experiments conducted. The ripening pattern at MWDSC was generally similar to that in Ottawa. For the most part, *C. parvum* trends tracked changes in filter effluent turbidity and particle counts, i.e., filter effluent oocyst levels decreased as the ripening period progressed. However, specific particle count or turbidity values were not necessarily correlated with specific filter effluent *C. parvum* concentrations (Huck et al, 2001).

The box-and-whisker plots and statistical comparisons for *C. parvum* (Figure 6) were based on the entire

ripening period. On this basis, ripening did not result in dramatic differences in overall removals relative to stable (optimized) filtration. At Ottawa, *C. parvum* removals during ripening were 5.1 ± 0.7 $\log_{10}$ (mean ± standard deviation); at MWDSC, they were 2.9 ± 0.6 $\log_{10}$. Ottawa removals were 0.5 $\log_{10}$ lower than during stable operation, whereas at MWDSC, removals were only 0.1 $\log_{10}$ lower. At Ottawa, the difference was statistically significant at the 5% level, whereas at MWDSC, it was not. The Ottawa result was consistent with previous studies (Swaim et al, 1996; Hall et al, 1995; Patania et al, 1995), which demonstrated a 0.5–1.0-$\log_{10}$ deterioration in oocyst removal during filter ripening. The MWDSC result was consistent with other studies (e.g., LeChevallier et al, 1991b) that did not yield statistically different oocyst removals between ripening and stable filter operation.

FIGURE 8 Particle and microorganism response of filter during onset-of-breakthrough experiment at Ottawa pilot plant on Jan. 21, 1999



However, when only early ripening at MWDSC was considered (sample times of 10, 20, and 40 min), the difference in oocyst removals between stable filter operation and ripening became statistically significant at the 5% level (results not shown). In general, the ripening data in this investigation suggest a brief, minimal-to-moderate increase in *C. parvum* passage through the filters that was concurrent with elevated filter effluent turbidity and particle counts. It should be noted that these experiments were designed to evaluate the passage of oocysts present in the filter influent during ripening, not the passage of oocysts that might be present in the backwash remnant water. The latter would be significant on a site-specific basis but could lead to increased oocyst passage during ripening in some instances.

Trends in *B. subtilis* removal during ripening were qualitatively comparable to those observed for *C. parvum* (Huck et al, 2001). At Ottawa, *B. subtilis* removals during ripening were lower and significantly different (5% level) from those achieved during stable operation. The same result was found for *B. subtilis* at MWDSC, where the difference for *C. parvum* had not been statistically significant at the 5% level. For *B. subtilis*, however, the differences between stable operation and ripening were substantially greater than for *C. parvum* in both locations. This suggests that *B. subtilis* spores are probably not good quantitative surrogates for *C. parvum* oocyst removal by filtration.

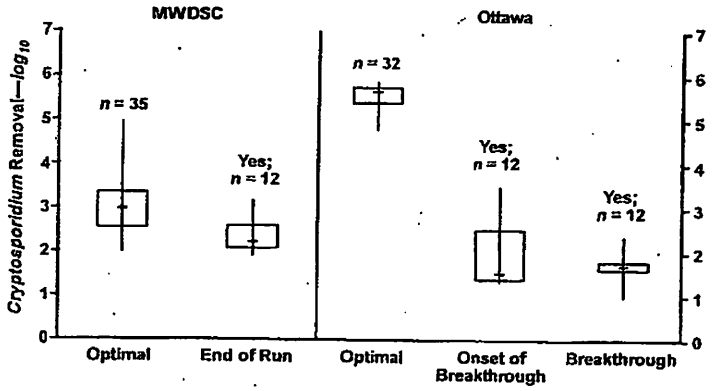
The net decrease in particle counts was also lower during ripening at both Ottawa and MWDSC, when compared with stable filter operation. Although not large, this difference (based on the entire ripening period) was statistically significant at the 5% level at both locations. The actual differences (0.5 $\log_{10}$ at Ottawa and 0.2 $\log_{10}$ at MWDSC) were comparable to the decreases in *C. parvum* removal.

Breakthrough. All of the breakthrough experiments conducted at MWDSC and Ottawa were performed after periods of stable operation. In both locations, jar-coagulated *C. parvum* oocysts and *B. subtilis* spores were seeded into the filters for 1h; samples were collected at 15, 30, 45, and either 55 or 60 min after the start of seeding.

At MWDSC, neither turbidity nor particle breakthrough could be achieved for technical reasons. Therefore, the experiments were performed as "end-of-run" experiments at ~ 72 h into the filter cycle. In Ottawa, breakthrough experiments were originally intended to be conducted when filter effluent turbidity exceeded 0.2 ntu. Because breakthrough was difficult to predict, seeding and sampling commenced in all cases when filter effluent turbidity levels were greater than ~ 0.4 ntu.

An additional set of experiments, termed "onset-of-breakthrough," was conducted at Ottawa. Filter effluent turbidity levels of < 0.3 ntu were targeted because the IESWTR requires filter effluent turbidity levels < 0.3 ntu in greater than 95% of measured samples. The first onset-of-breakthrough experiment at Ottawa was conducted on Jan. 21, 1999, when filter effluent turbidity levels were increasing but were still < 0.1 ntu. (In fact, this experiment was intended to be a stable operation experiment and only captured onset-of-breakthrough fortuitously.) Because of the striking results obtained in this experiment, two additional such experiments were performed at Ottawa on Dec. 20 and Dec. 22, 1999. In these two runs, filter effluent turbidity levels were 0.2–0.3 ntu. In these latter

FIGURE 9 Effect of breakthrough, onset-of-breakthrough, and end-of-run conditions on filters' removal of *Cryptosporidium parvum*



MWDSC—Metropolitan Water District of Southern California, n—number of data points. "Yes" designation indicates that the mean for a given condition was statistically different from the optimal or stable operation condition at the 5% level.

experiments, jar-coagulated *B. subtilis* spores were seeded for 1 h, and then *C. parvum* oocysts were seeded for 1 h as breakthrough commenced. Samples were collected only during the hour of *C. parvum* seeding.

Filter effluent turbidity and particle concentrations during the end-of-run experiments at MWDSC were similar to those obtained during the stable filter experiments. Furthermore, the filter effluent turbidity levels and particles remained constant throughout the end-of-run seeding period at MWDSC.

In contrast, the onset-of-breakthrough that occurred in Ottawa was a very dynamic period, particularly for *C. parvum*. In the January 1999 breakthrough experiment (Figure 7), the filter effluent turbidity was 0.04–0.07 ntu, and particle counts ranged from 0.3 to 4.3 particles/mL during the seeding and sampling period. Although these might be considered modest changes, they were accompanied by a drastic reduction in the filter's ability to remove incoming *C. parvum* oocysts (Figure 8). An increase in filter effluent *B. subtilis* concentrations was also observed, but it was not as severe as the increase in filter effluent oocyst concentrations (Figure 8). In general, the onset-of-breakthrough experiments at Ottawa demonstrated a relatively modest degradation of the traditional performance parameters that was accompanied by tremendous increases in filter effluent *C. parvum* concentrations. These data suggested that small increases in particle counts during early breakthrough could signal substantially increased noncapture of oocysts.

In the breakthrough experiments at Ottawa, both filter effluent turbidity and particle counts continued to change rapidly (Huck et al, 2001). The elevated turbidity and particle counts were accompanied by high filter effluent *C. parvum* concentrations (generally > 10^4 oocysts/L).

By seeding *B. subtilis* first and then *C. parvum* during the actual sampling, the December 1999 onset-of-breakthrough experiments at Ottawa were designed to investigate whether the passage of oocysts through the filter during early breakthrough conditions was largely a function of nonattachment. (The high effluent oocyst concentrations observed would suggest this.) Although the high concentration of spores observed in the filter effluent pointed to some detachment, this interpretation was unclear because during sampling more spores were present in the filter influent than in the effluent.

Median removals of *C. parvum* during end-of-run conditions were significantly different (at the 5% level) than during stable operation at MWDSC (Figure 9). However, no significant differences in net decrease in particle count were observed (Figure 10).

At Ottawa, median *C. parvum* removals during the onset-of-breakthrough and breakthrough experiments were substantially lower and statistically different (5% level) than during stable operation (Figure 9). These results were consistent with the statistically significant differences (5% level) observed for the net decrease in particle counts (Figure 10).

In Ottawa, results for *B. subtilis* paralleled those for *C. parvum*, with removals during the onset-of-breakthrough and breakthrough periods significantly lower (at the 5% level) than during stable operation (Huck et al, 2001). At MWDSC, the end-of-run *B. subtilis* removals, although also statistically different from those for stable operation at the 5% level, were actually somewhat higher (0.5 $\log_{10}$) than during stable operation. The reason for this result is not known, but it may be because of the fact that very low filter effluent *B. subtilis* numbers were observed in one of the three end-of-run experiments.

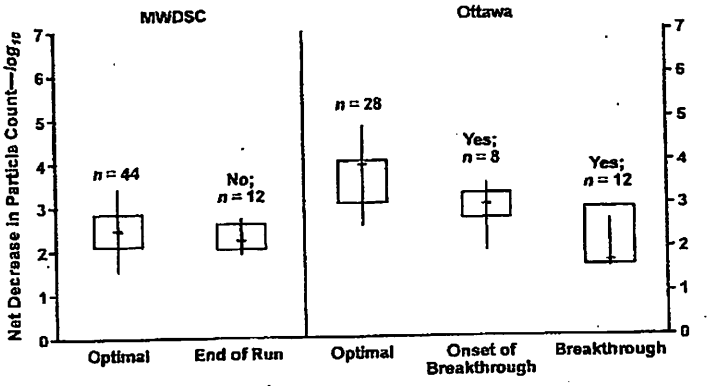
Oocyst removal during end-of-run conditions at MWDSC was ~ 0.6 $\log_{10}$ lower than during stable operation. In Ottawa, the onset-of-breakthrough and breakthrough oocyst removals were ~ 3.5 $\log_{10}$ and 4 $\log_{10}$ lower, respectively, than during stable operation. Ottawa results were in general agreement with other research (Logsdon et al, 1981) demonstrating that turbidity breakthrough at the end of a filter cycle could be accompanied by considerable passage of *Giardia* cysts. The Ottawa onset-of-breakthrough results were very different from those obtained by other researchers (Patania et al, 1995). In that study of *Giardia* and *C. parvum* passage through filters during breakthrough, effluent turbidity levels increased from 0.1 to 0.2 ntu or higher. Those researchers found that whereas *Giardia* removal was ~ 0.5 $\log_{10}$ lower during breakthrough, no difference was observed

in *C. parvum* removals during stable operation versus breakthrough. It is possible that other factors, such as chemical pretreatment, may affect the degree of pathogen passage that occurs during early breakthrough filtration.

Hydraulic step. Each of the hydraulic step experiments consisted of a 25% increase in filtration rate that took place over a period of < 1 min and was imposed during stable (optimized) operating conditions. This higher rate was maintained throughout the remainder of the filter cycle.

C. parvum and *B. subtilis* were seeded in the filter influent over an extended period of time (5 h at Ottawa and 8 h at MWDSC), and the hydraulic step was imposed immediately after the seeding period. Thus, oocysts appearing in the effluent would result from detachment rather than noncapture. Results from these experiments (three replicates in each location) were variable, even though the protocol remained the same, including the point in the filter cycle at which the step was applied. Because of space limitations, results are discussed only briefly here.

FIGURE 10 Effect of breakthrough, onset-of-breakthrough, and end-of-run conditions on net decrease in particle count from raw water to filter effluent



MWDSC—Metropolitan Water District of Southern California, n—number of data points. "Yes" designation indicates that the mean for a given condition was statistically different from the optimal or stable operation condition at the 5% level. "No" indicates the mean was not statistically different.

In the first experiment in Ottawa, the filter effluent turbidity and particle concentration temporarily increased to 0.37 ntu and 297 particles/mL, respectively. This increase was accompanied by a substantial increase in oocyst levels, with effluent concentrations of *C. parvum* reaching 4,412 oocysts/L (Huck et al, 2001).

The hydraulic step had much less effect in the second experiment. Although particle concentration peaked at ~ 400/mL, the filter effluent turbidity increased only slightly and no appreciable changes in filter effluent *C. parvum* concentrations were observed. A third hydraulic step experiment was performed, but turbidity and particle data were not available because of difficulties with the data acquisition system. Filter effluent oocyst concentrations were slightly elevated (a maximum value of 76 oocysts/L).

The similar experiments at MWDSC were more reproducible. In general, filter effluent turbidity was ~ 0.05 ntu, and the particle concentration ranged from 8 to 24 particles/mL. The filter effluent *C. parvum* concentrations generally decreased after the completion of seeding, despite the implementation of the hydraulic step. Thus, the hydraulic step for the most part had little effect on filter effluent concentrations at MWDSC.

B. subtilis results in both locations generally followed the same trend as for *C. parvum* (Huck et al, 2001). Except for the one experiment in Ottawa, the data suggested that little detachment of microorganisms occurred as a result of a 25% increase in flow. The reasons for the lack of effect and for the variable results in Ottawa are not understood. It may be that the effect of the flow change was sensitive to the exact way in which it was imposed. This variability may be higher at pilot scale than at full scale.

Ottawa results showed that particle counts were not directly indicative of oocyst passage through filters as a result of a hydraulic step (Huck et al, 2001). The results also suggested that turbidity might be a better indicator of the effect of a hydraulic step, but the authors believe firm conclusions cannot be based on these limited experiments.

The variation in observed results underlines the need for further investigation, so that the potentially severe effects of hydraulic changes on *C. parvum* passage (as observed during the first Ottawa experiment) can be minimized.

CONCLUSION

The authors' detailed investigation of *Cryptosporidium* removal by granular media filtration in two different waters led to the following conclusions.

- Under optimal operating conditions, *Cryptosporidium* removals exhibited a 2-log difference between two pilot plants operated to produce similar low effluent turbidity values (< 0.1 ntu) and particle counts (< 20/mL). Removals in one location were ~ 5 log_{10} units, whereas those in the other location were ~ 3 log_{10} units. Coagulation regimes at the two plants differed significantly, but the reasons for the 2-log variation are not completely understood.
- At the end of a filter run, the authors observed a substantial deterioration (several log_{10} units) in oocyst removal capability, even in the early stages of breakthrough when filter effluent particle counts had just begun to rise. At this stage, turbidity had not always increased.

This period appeared to be a particularly vulnerable one for filter operation.

- Suboptimal coagulation also substantially reduced *Cryptosporidium* oocyst removals (again by an average of several $\log_{10}$ units), even at turbidity levels that were < 0.3 ntu.
- Under the conditions of this study, a hydraulic step (sudden increase in loading) had little effect on filter effluent oocyst concentrations, except in one out of the six experiments performed. These differing results occurred despite the fact that the same percentage increase in flow was always imposed. However, turbidity and particle counts did increase in some experiments. It was expected that the hydraulic step would have a greater effect on oocyst concentrations. The reasons for the observed variability are not currently understood. Therefore, hydraulic step effects should be investigated further.
- Compared with suboptimal coagulation or breakthrough, only minimal or moderate deterioration (0.5 $\log_{10}$ units or less) of *Cryptosporidium* removal was observed during filter ripening under the conditions of these experiments.
- Various surrogate parameters (i.e., turbidity, particle counts, and *B. subtilis* spores) provided only qualitative indications of the filters' ability to remove *C. parvum* oocysts under the various conditions tested. However, for a given plant or filter, increases in turbidity or particularly particle counts during a filter cycle or as a result of an operational event may signal substantial deterioration in *Cryptosporidium* removal capability. This was evident, for example, in the early breakthrough experiments at Ottawa.

On the basis of the findings of this study, the authors have also developed specific guidance for water providers.

- To avoid deterioration of pathogen removals attributable to suboptimal coagulation conditions, utilities should carefully consider the effects of reducing coagulant dosage. Utilities should not accept filter effluent turbidity levels of 0.2–0.3 ntu.
- To avoid breakthrough, plants should specify a maximum head loss and run time for washing filters and consider using particle counters to monitor for early breakthrough.
- Water providers need to minimize the effect of ripening. Strategies could include filter-to-waste, recycling filter effluent during ripening, storing filter effluent produced during ripening for backwash water (if facilities are available), or adding coagulants to backwash water or filter influent during ripening.
- To avoid the effect of a hydraulic step (sudden increase in loading), utilities should minimize the magnitude and rate of filter flow changes.

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FOOTNOTES

[1]Microsoft Excel 97, Version SR-2, Microsoft Corp., Redmond, Wash.
[2]Waterborne Inc., New Orleans, La.
[3]Petroff-Hausser Bacterial Counting Chamber, Hausser Scientific Corp., Horsham, Pa.
[4]CH Diagnostic & Consulting Services Inc., Loveland, Colo.
[5]ATCC 6051, obtained from American Type Culture Collection, Rockville, Md.
[6]66278, Pall Gelman Corp., Ann Arbor, Mich.
[7]Duke Scientific Corp., Palo Alto, Calif.
[8]At MWDSC, PCX particle counter, Met One, Grants Pass, Ore.; at Ottawa, IBR particle counter, IBR, Grass Lake, Mich.
[9]Hach 1720C, Hach Co., Loveland, Colo.
[10]Model 7997/201, ABB, Calgary, Alta.
[11]Hach 2100P, Hach Co., Loveland, Colo.

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BY MONICA B. EMELKO,
PETER M. HUCK,
AND IAN P. DOUGLAS

Pilot-scale studies were performed to evaluate *Cryptosporidium parvum* oocyst removal by a dual-media filter during optimized, end-of-run, and breakthrough operating conditions. Oocyst-sized polystyrene microspheres were also evaluated as surrogates for *C. parvum* removal by filtration. At optimal conditions, the pilot-scale filter consistently achieved ~5-log removal of *C. parvum* and microspheres. During end-of-run operation when filter effluent turbidity levels were <0.1 ntu, median oocyst removals deteriorated to ~3 log. During early (0.1–0.3 ntu) and late (>0.3 ntu) breakthrough, filtration oocyst removals deteriorated to ~2.1 and ~1.4 log, respectively. Microsphere removals by filtration were similar to oocyst removals during both stable and challenged operating periods, suggesting that microspheres are useful surrogates for investigating *C. parvum* removal.

Cryptosporidium and microsphere removal during late in-cycle filtration

Water samples are processed for *Cryptosporidium* analysis.

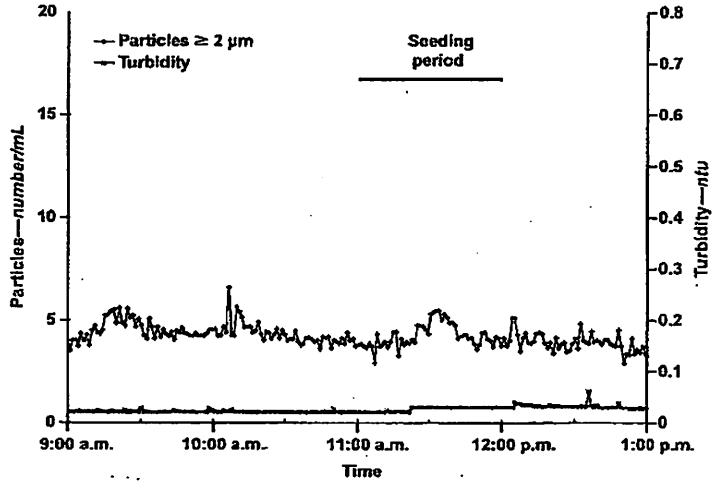
Several types of surrogates for viable *Cryptosporidium parvum* oocysts have been evaluated, including surrogates for occurrence, disinfection, and removal. Parameters that have been investigated as potential surrogates for cyst and oocyst removal by drinking water treatment processes have included turbidity, particle counts, heterotrophic plate counts, aerobic spores (typically *Bacillus subtilis*), ultraviolet absorbance at 254 nm, dissolved organic carbon, and polystyrene microspheres. Many of these parameters, such as turbidity and particle counts are reliable indicators of treatment performance, but they do not aid in quantitatively assessing oocyst removal by water treatment processes (Huck et al, 2002; Huck et al, 2001; Emelko, 2001; Hall et al, 1995; Nieminski & Ongerth, 1995; Ongerth & Pecoraro, 1995). Oocyst-sized fluorescent polystyrene microspheres have shown promise as surrogates for oocyst removal by filtration (Emelko et al, 1999; Swertfeger et al, 1999); however, further information is necessary to determine the range of conditions during which microsphere removal is a reliable surrogate for oocyst removal.

Filtration is an inherently dynamic process. Several studies have indicated that C. *parvum* removal by filtration deteriorates during vulnerable periods of operation such as suboptimal coagulation (Huck et al, 2002; Huck et al, 2001; Emelko et al, 1999; Patania et al, 1995). The Interim Enhanced Surface Water Treatment Rule (IESWTR) requires that combined filter effluent turbidity must be ≤0.3 ntu in at least 95% of the measurements taken each month (USEPA, 1998). The Long-term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR) may offer 0.5-log credit for treatment systems that maintain 95th percentile combined filter effluent turbidity levels <0.15 ntu (USEPA, 2000). Limited infor-

TABLE 1 Summary of experimental conditions

Experimental Condition	Description
Stable operation	Period of consistent filter effluent turbidity, <30 h of filter operation, filter effluent turbidity levels: ~0.05 ntu consistently
End-of-run	Period at the end of a filter cycle during which subtle changes in filter effluent turbidity are noticed, filter effluent turbidity levels: <0.1–0.1 ntu
Early breakthrough	Period at the end of a filter cycle during which increasing filter effluent turbidity levels are observed, filter effluent turbidity levels: 0.1–0.3 ntu
Late breakthrough	Period at the end of a filter cycle during which increasing filter effluent turbidity levels are observed, filter effluent turbidity levels: >0.3 ntu

FIGURE 1 Filter effluent turbidity and particle concentration ≥2 µm during a stable filter operation experiment



mation is available regarding pathogen passage through filters during end-of-run and early breakthrough filtration when filter effluent turbidity levels are increasing but remain <0.15 and 0.3 ntu, respectively (as specified by the LT2ESWTR and IESWTR, respectively).

One study demonstrated that turbidity breakthrough at the end of a filter cycle (when filter effluent turbidity was >0.4 ntu) can be accompanied by considerable passage of *Giardia* cysts through a filter (Logsdon et al, 1981). A considerable increase in cyst passage was observed during early breakthrough conditions when filter effluent turbidity was just >0.2 ntu (Logsdon et al, 1981). Another study also investigated *Giardia* passage through filters during breakthrough when effluent turbidity levels increased from 0.1 to 0.2 ntu or higher. Those researchers found that *Giardia* removal was ~0.5 log lower during breakthrough than during stable operation (Patania et al, 1995). These data suggested that increased *C. parvum* passage could also be expected during breakthrough, especially at filter effluent turbidity levels exceeding 0.2 ntu.

Pilot-scale investigations of *C. parvum* removal by filtration during turbidity breakthrough when filter effluent turbidity levels increased from 0.1 to 0.2 ntu or higher did not yield substantial differences between oocyst removals during stable operation and breakthrough (Patania et al, 1995). In replicate experiments, oocysts were detected in almost all of the samples collected during the stable operation and breakthrough experiments at the particular pilot plant where turbidity breakthrough was investigated (Patania et al, 1995). Similar results were obtained during two full-scale investigations, which showed little, if any, deterioration in oocyst removals during filter breakthrough at either of the plants investigated (Baudin & Laîné, 1998). Those authors indicated that oocyst removal during breakthrough at both plants depended on the filtration rate. Fluctuating filter influent oocyst concentrations during the stable operation experiment, unspecified filter effluent turbidity levels during the breakthrough experiments, and insufficient oocyst recovery information made it difficult to draw inferences from the oocyst removal data collected during these breakthrough and stable operation experiments (Baudin & Laîné, 1998).

The removal of *C. parvum* oocysts and oocyst-sized fluorescent polystyrene microspheres during end-of-run, early breakthrough, and late breakthrough filtration (as defined in Table 1) relative to optimized filtration was investigated during the research reported in this article. The stable experiments were performed to determine the maximum removals that could be obtained by pilot-scale filtration under optimal conditions (filter effluent turbidity levels consistently ~0.05 ntu). They also provided a baseline against which the other operating conditions were compared. Included in these baseline data are *C. parvum* removal data from stable operation experiments that are reported elsewhere (Huck et al, 2002; Huck et al, 2001). End-of-run operation describes the period from which subtle changes in the baseline filter effluent turbidity (~0.05 ntu) and particle counts were noticed and filter effluent turbidity increased to ~0.1 ntu. The next part of the filter

cycle was early breakthrough filtration during the period when filter effluent turbidity levels were increasing from ~0.1 to ~0.3 ntu. The last investigated portion of the filter cycle was late breakthrough, during which filter effluent turbidity levels continued to increase from ~0.3 ntu. With the exception of late breakthrough, all of the experimental conditions occurred during periods of filter operation that were in compliance with the IESWTR. The current research is from a study (Emelko, 2001) focused on defining oocyst removals by filtration during vulnerable periods and relating them to removals during optimal treatment.

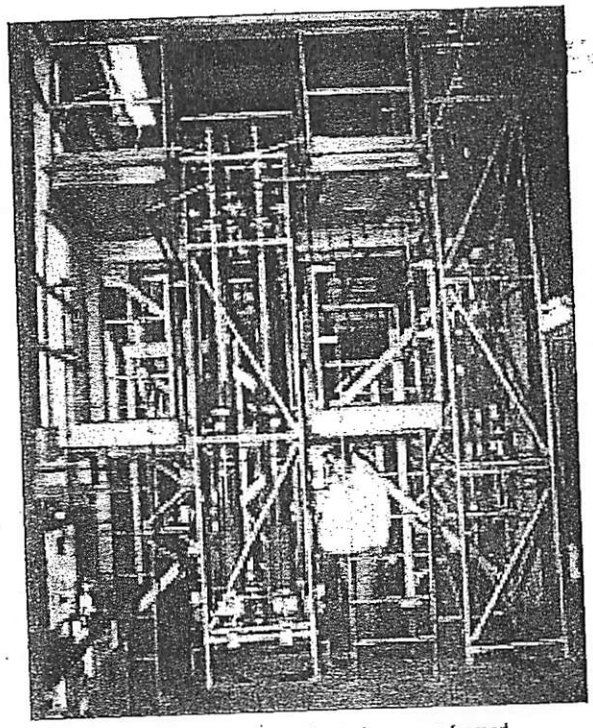
MATERIALS AND METHODS

Pilot-scale investigations were performed at the Britannia Pilot Plant in Ottawa, Ont. The pilot plant was conventionally operated with in-line coagulant injection, three-stage mechanical flocculation (velocity gradient [G] of 60, 40, and 20 s^{-1} in stages 1, 2, and 3, respectively), and plate settling. The raw water was from the Ottawa River and required a relatively high coagulant dose (~40 mg/L alum and 2 mg/L activated silica) for combined total organic carbon (5–7 mg/L) and particle removal (~3 ntu, ~5,000 particles ≥2µm/mL). Chlorine (2 mg/L) was added at rapid mix as a preoxidant.

One of the pilot-scale, dual-media filters of 152 mm (6 in.) diameter was seeded with jar-coagulated suspensions of 10^8 formalin-inactivated *C. parvum* oocysts and 10^8 carboxylated polystyrene microspheres. The filter contained media depths and sizes typical of many existing treatment plants. The design included 457 mm (18 in.) of anthracite (effective size [ES] = 1.07 mm [0.042 in.], uniformity coefficient [UC] = 1.35) and 279 mm (11 in.) of sand (ES = 0.515 mm [0.02 in.], UC = 1.32). The filter was operated in a constant rate mode at 6.6 m/h (2.7 gpm/sq ft). The backwashing regime consisted of chlorinated water and air-scour applied in a collapse-pulsing mode (Amitharajah et al, 1991).

The optimized coagulation conditions were selected to meet the 0.1-ntu turbidity goal of the Partnership for Safe Water, a voluntary treatment optimization program sponsored by the US Environmental Protection Agency and AWWA. The nonoptimal conditions targeted turbidity levels at the upper range of compliance with the IESWTR requirements of 0.3 ntu. The pilot-scale studies were performed to evaluate the oocyst removal capacity of a dual-media filter during optimized (period of consistent filter effluent turbidity of ~0.05 ntu), end-of-run (period at the end of filter cycle during which filter effluent turbidity increases from <0.1 to 0.1 ntu), early turbidity and particle breakthrough (period at the end of filter cycle during which filter effluent turbidity increases from 0.1 to 0.3 ntu), and late turbidity and particle breakthrough (period at the end of filter cycle during which filter effluent turbidity is >0.3 ntu) operation.

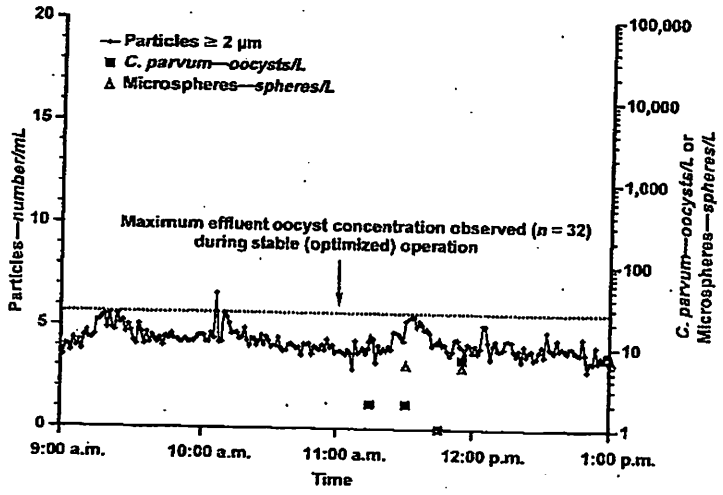
Seeding protocol. Both formalin-inactivated oocysts (mean concentration of 6.5×10^5 oocysts/L at filter influent) and oocyst-sized fluorescent polystyrene microspheres (mean concentration of 6.1×10^5 microspheres/L at filter influent, 4.675-µm diameter[1]), were jar-coagulated in a 2-L beaker. The coagulant dosages and rapid-mixing/flocculation times (1.2 s/30 min) were the same as those used in the pilot plant. The microspheres and oocysts were jar-coagulated in the same container and were therefore concurrently added to the filter influent. A peristaltic pump[2] was used to add the feedstock to the pilot-plant filter influent water. The seed suspensions were introduced into the filter influent water ~75 cm (2.5 ft) above the filter media. To facilitate filter influent sampling while minimizing losses to the sampling device, a second peristaltic pump[2] was continuously operated to recirculate filter influent water from ~5 cm (2 in.) above the surface of the filter media to the top of the water column within the filter.



The pilot-scale investigations in this study were performed at a pilot plant that was conventionally operated with in-line coagulant injection, three-stage mechanical flocculation, and plate settling.

Sample collection. Samples for microorganism and microsphere analyses were collected at the filter influent and effluent locations. The filter influent location was 5 cm (2 in.) above the surface of the filter media; the effluent was collected at the column exit immediately after passage through the support gravel (upstream of the turbidimeter and particle counter). Prior to the seeding experiments, 1-L negative controls were collected at the filter influent and effluent locations. The influent and effluent samples were collected in 250-mL and 1-L glass bottles, respectively. All sampling containers were washed, auto-

FIGURE 2 Filter effluent particle (≥2 µm), *C. parvum*, and microsphere concentrations during a stable filter operation experiment



claved, and rinsed with a buffered detergent solution (1× phosphate-buffered saline [PBS] with final concentrations of 0.1% sodium dodecyl sulfate, 0.1% polyoxyethylene sorbitan monooleate,[3] and 0.01% silicone polymer foam depressor,[4] and final pH of 7.4) prior to use.

The pilot-scale experiments evaluating optimal operation were performed during the early to mid-portion of the filter cycle after at least 4 h of filter operation. The end-of-run, early breakthrough, and late breakthrough experiments were conducted after periods of stable operation during which filter effluent turbidity levels were continuously <0.1 ntu. Filter influent and effluent samples were collected at 15, 30, 45, and 55 min after the start of seeding.

***C. parvum* analysis.** The *C. parvum* oocysts used during the seeding experiments were obtained from a commercial laboratory,[5] were bovine in origin, and were provided in a clean, purified form. For each experiment, 10^8 oocysts were obtained. They were inactivated with 5% formalin (final concentration) in 1× PBS with 0.01% polyoxyethylene sorbitan monolaureate[3] to prevent oocyst clumping. All microorganism stocks were refrigerated at 4°C in the dark until use.

Prior to *C. parvum* seeding, the stock suspension was vortexed, and a small portion of the suspension (<100 µL total) was removed to enumerate the oocyst concentration. The stock concentration was determined by averaging triplicate counts with a hemocytometer[6] and light microscopy.[7] The entire grid (1 mm^2 [0.001 sq in.]) was used for oocyst enumeration.

C. parvum oocysts were measured in the feedstock suspensions and the filter influent and effluent samples. Filter influents were analyzed in 10-, 5-, and 2.5-mL volumes. Filter effluents were analyzed in volumes ranging from 5 mL to 1 L, depending on the operating condition studied. Sample volumes were chosen to yield between 10 and 2,000 oocysts.

All of the samples were filtered through 25-mm, 0.40-µm polycarbonate membranes.[8] The filter membranes were placed on top of 25-mm, 8.0-µm nitrocellulose support membranes[9] placed on a manifold[10] and maintained at a vacuum of 125 mm (5 in.) of mercury. Weights held the membranes in place. Two millilitres of 1% bovine serum albumen (BSA) were passed through the filter membranes. Samples were then directly filtered on the manifold. The glassware that had contained the samples was then rinsed with the buffered detergent solution. The detergent rinse was followed by an additional 2 mL of BSA that was also filtered through the membranes; this was followed by a standard immunofluorescence assay.[11] If necessary, the membranes were kept wet with 1× PBS and covered until sample mounting on slides. Presumptive microscopic analysis for *C. parvum* enumeration was performed at 400× magnification at the University of Waterloo.[7] Recovery data from the filter influent and effluent water matrixes yielded a mean oocyst recovery of 75% and a relative standard deviation of 16%.

Microsphere analysis. Oocyst-sized fluorescent polystyrene microspheres[1] were used as nonbiological surrogate indicators for *C. parvum* removal. The microspheres had an average diameter of 4.675 ± 0.208 µm and a density of 1.045 g/mL. The dye is a proprietary chemical that is hydrophobic (to prevent dye leaching from the particles into the aqueous phase) and has maximum excitation at 458 nm and maximum emission at 540 nm, similar to fluorescein isothiocyanate (FITC), which is used for *C. parvum* analysis. Material provided by the manufacturer indicated that the microspheres did not contain any hazardous components.

The manufacturer provided the polystyrene microspheres in suspensions of 2.5% aqueous solids in deionized water. Neither biocides nor stabilizers were added to the suspensions. The microspheres were stored at 4°C until use. The weight-to-volume packaging allowed for the calculation of the particle concentration by a method provided by the manufacturer. The concentration of a stock suspension of 4.675-µm microspheres was 4.5×10^8 spheres/mL.

Microspheres were concentrated and enumerated by the same filtration method used for *C. parvum* (described earlier). The microspheres were readily distinguishable from the FITC-stained oocysts. Although they were approximately the same diameter, the microspheres appeared larger than the oocysts because of the halo effect associated with the strong intensity of the dye, which

permitted for microsphere enumeration at 100× magnification. Microspheres were enumerated concurrently with *C. parvum* oocysts at 400× magnification (FITC-stained oocysts did not fluoresce with enough intensity for enumeration at 100× magnification). Experiments previously reported (Emelko et al, 1999) indicated >90% recovery of microspheres using the concentration and enumeration method described earlier. It is hypothesized that the >90% recoveries originally reported (from seven replicate samples in a recovery study) were due to retention of microspheres on the micropipette tip used to dose the suspension for the recovery study. Given the very small volumes of stock microsphere suspensions (<200 µL) necessary for the seeding investigations, small droplets of the stock suspensions could affect recovery study outcomes. During the current investigation, three recovery experiments each included five high-microsphere concentrations (typical of filter influent samples) and 10 low-microsphere concentrations (typical of filter effluents) for a total of 45 samples. Although the microsphere recovery data demonstrated slightly higher variation than oocyst recovery data, mean microsphere recoveries were 75%.

Particle counts and turbidity. A standard protocol was used to verify the calibration of the particle counters using commercially available, calibrated, monodisperse polymer microspheres.[12] Each particle-counting instrument was calibrated by the manufacturer. The particle counters[13] measured total particles from 2 to 150 µm, with the data reported as total particles ≥2 µm. Turbidity was monitored at plant and filter influent and filter effluent locations using online turbidimeters[14] that were calibrated using dilute formazin solutions. An additional turbidimeter[15] was also used at the filter effluent location.

RESULTS

One experiment evaluating stable (i.e., optimized) filtration conditions was performed; it included concurrent seeding of polystyrene microspheres and *C. parvum*. Two experiments investigated end-of-run operation, three investigated early breakthrough filtration, and two were performed during late breakthrough filtration. These results are discussed together with seven additional stable operation experiments that were performed without polystyrene microspheres and from which *C. parvum* removals were reported elsewhere (Huck et al, 2002; Huck et al, 2001).

As shown in Figure 1, filter effluent turbidity and particle concentrations ≥2µm were consistently low (~0.04 ntu and <6 particles/mL, respectively) during the stable operation experiment investigating oocyst and microsphere removals; this type of performance was observed during all of the stable operation experiments. The stable experiments were performed to determine the best removals that could be obtained under optimal conditions at the Ottawa pilot plant; they also provided a baseline against which the other operating conditions were compared. Eight experiments (32 samples) of *C. parvum* removal are discussed; as indicated previously, one of these experiments (four samples) also investigated microsphere removal.

C. parvum removals by the pilot filter during stable (optimized) operation ranged from 4.7 to 5.8 log, with a median oocyst removal of 5.6 log (32 paired samples). Filter effluent particle (≥2µm), oocyst, and microsphere concentrations during the stable operation experiment are provided in Figure 2. Microsphere removals during stable operation ranged from 4.7 to 5.1 log, with a median microsphere removal of 4.9 log. The filter influent oocyst and microsphere concentrations during the stable operation experiment were similar, 4.6×10^5 oocysts/L and 6.5×10^5 microspheres/L on average. Overall, *C. parvum* concentrations in the filter effluent were typically <10 oocysts/L during stable operation, with several nondetects during the experiments performed with oocysts only.

Two experiments (eight samples total) investigating *C. parvum* and microsphere removal during end-of-run filtration were performed. The filter effluent turbidity and particle concentration ≥2 µm during an end-of-run experiment are provided in Figure 3. The filter effluent turbidity was low (~0.04 ntu) at the start of these experiments, increased to 0.13 ntu by the end of the seeding period in the first experiment, and was 0.06 ntu at the end of the second experiment.

FIGURE 3 Filter effluent turbidity and particle concentration ≥2 µm during an end-of-run experiment

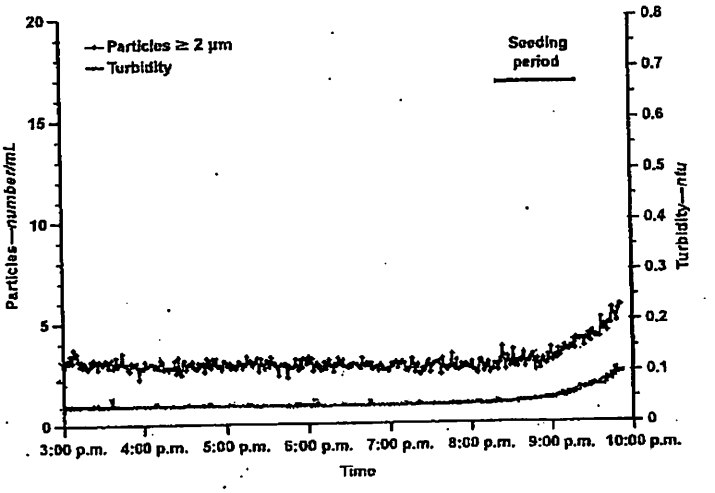


FIGURE 4 Filter effluent particle (≥2 µm), *C. parvum*, and microsphere concentrations during an end-of-run experiment

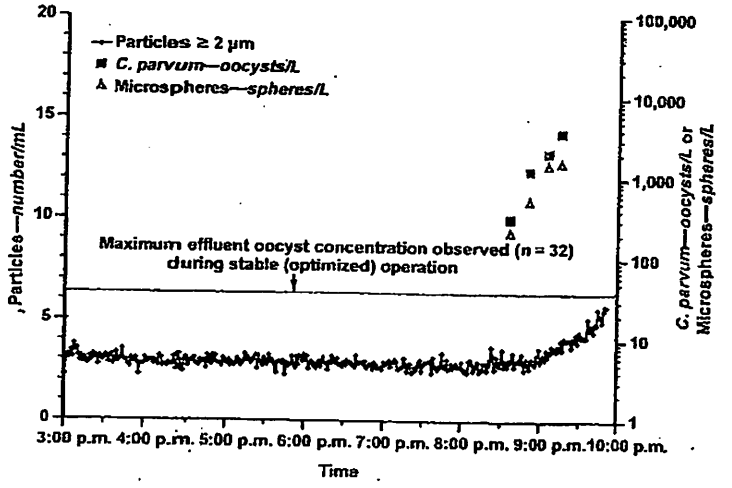
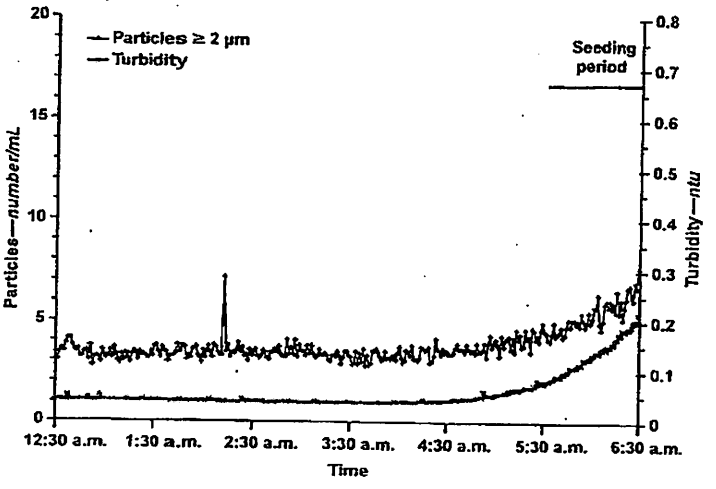


FIGURE 5 Filter effluent turbidity and particle concentration ≥2 µm during an early breakthrough experiment



Although the filter effluent turbidity levels and particle concentrations increased only slightly during the end-of-run experiments, they were accompanied by considerably elevated filter effluent *C. parvum* and microsphere concentrations relative to those obtained during stable operation. Filter effluent particle (≥2 µm), oocyst, and microsphere concentrations during an end-of-run experiment are given in Figure 4. *C. parvum* removals by the pilot filter during end-of-run filtration ranged from 1.8 to 3.3 log, with a median oocyst removal of 2.4 log (eight samples). Microsphere removals during end-of-run ranged from 1.8 to 3.1 log, with a median microsphere removal of 2.4 log. The filter influent oocyst and microsphere concentrations during the end-of-run experiments were similar, with mean concentrations of 6.8×10^5 oocysts/L and 5.6×10^5 microspheres/L. Both *C. parvum* and microspheres were found in all of the filter effluent samples during the end-of-run experiments.

Three experiments (12 samples) investigating *C. parvum* and microsphere removal during early breakthrough were performed; the seeding period and filter effluent turbidity and particle concentrations ≥2µm during one of these experiments are provided in Figure 5. The filter effluent turbidity was low (0.04–0.08 ntu) at the start of these experiments and increased to ~0.2 ntu by the end of the experiments. The increased filter effluent turbidity levels and particle concentrations during early breakthrough at Ottawa were also accompanied by increased filter effluent *C. parvum* and microsphere concentrations relative to those obtained during stable operation.

Typical filter effluent oocyst and microsphere data for an early breakthrough experiment are given in Figure 6. *C. parvum* removals by the pilot filter ranged from 1.7 to 2.8 log during early breakthrough, with a median oocyst removal of 2.1 log (12 samples). Microsphere removals during early breakthrough also ranged from 1.7 to 2.8 log, with a median microsphere removal of 2.1 log. The filter influent oocyst and microsphere concentrations during the early breakthrough experiment were similar, with mean concentrations of 6.6×10^5 oocysts/L and 5.7×10^5 microspheres/L. Both *C. parvum* and microspheres were found in all the filter effluent samples collected during the early breakthrough experiments.

The seeding period and filter effluent turbidity, and oocyst and microsphere concentrations during one of the late breakthrough experiments are shown in Figure 7. Two experiments (eight samples) investigating *C. parvum* and microsphere removal during late breakthrough were performed. The filter effluent turbidity was consistently 0.25–0.3 ntu at the start of these experiments. The elevated filter effluent turbidity levels during late breakthrough were accompanied by high filter effluent *C. parvum* and

microsphere concentrations relative to those obtained during the stable operation experiments. *C. parvum* removals by the pilot filter during the late breakthrough experiments ranged from 1.3 to 1.8 log, with a median oocyst removal of 1.4 log (eight samples). Microsphere removals during late breakthrough ranged from 1.3 to 2.0 log, with a median microsphere removal of 1.5 log. The filter influent oocyst and microsphere concentrations during these experiments were similar, with mean concentrations of 6.9×10^5 oocysts/L and 6.8×10^5 microspheres/L. Both *C. parvum* and microspheres were found in all of the filter effluent samples during the late breakthrough experiments.

The *C. parvum* and polystyrene microsphere removal data are summarized in a box-and-whisker plot (Figure 8). These data clearly indicate a substantial deterioration in both oocyst and microsphere removals during end-of-run, early breakthrough, and late breakthrough filtration; moreover, overall oocyst and microsphere removals generally continued to decrease as filter effluent turbidity levels and particle concentrations increased during these successive operating periods.

The box-and-whisker plot also indicates a relatively good correlation between *C. parvum* oocyst and polystyrene microsphere removals during the variety of operating conditions investigated (Figure 8). The relationship between oocyst and microsphere removals by the pilot filter was highly linear, as indicated in Figure 9, with a coefficient of determination (R^2) of 0.96. There are considerably fewer data points in the >4-log removal range that corresponds to the stable operation investigations. Although the data in Figure 9 clearly indicate a linear relationship between *C. parvum* and oocyst-sized microsphere removals in the 1.0–3.5-log removal range, more data are necessary to confidently extend this relationship into the 3.5–5.5-log removal range. Although the stable operation oocyst and microsphere removals were not as similar as those obtained during the other operating conditions, the data in Figure 8 and Figure 9 suggest that polystyrene microsphere removals were good and often conservative indicators of *C. parvum* removals by filtration. Further investigations are necessary to determine whether this relationship holds during stable operation and other nonoptimal operating periods such as suboptimal coagulation.

FIGURE 6 Filter effluent particle (≥2 µm), *C. parvum*, and microsphere concentrations during an early breakthrough experiment

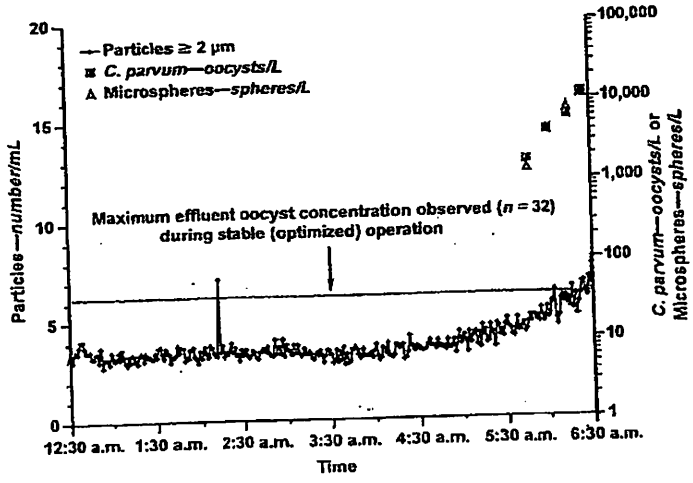
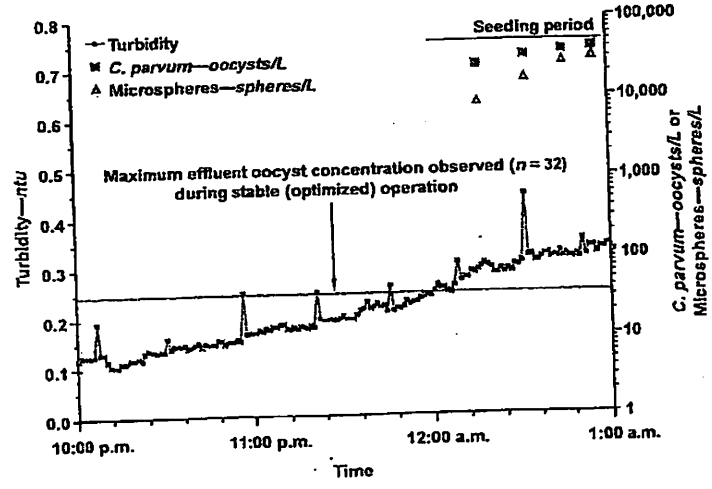


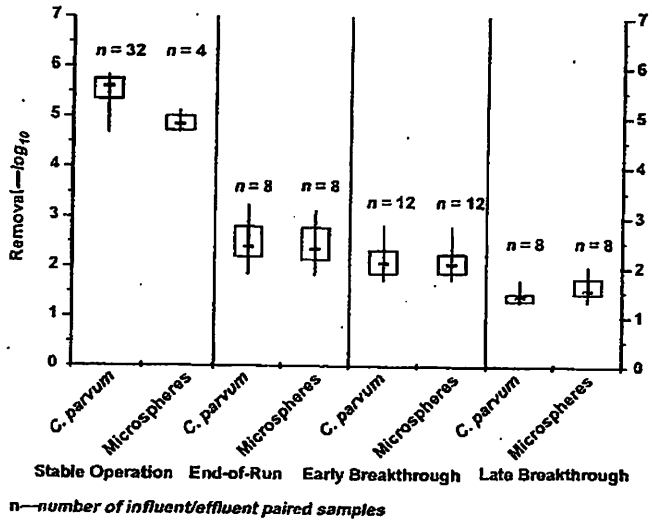
FIGURE 7 Filter effluent turbidity, seeding period, *C. parvum*, and microsphere concentrations during a late breakthrough experiment



DISCUSSION

Considerable deterioration in *C. parvum* and polystyrene microsphere removal during end-of-run filtration when filter effluent turbidity levels were increasing but still <0.1 ntu was not expected given other data that have been provided in the literature (Baudin and Laîné, 1998; Patania et al, 1995). Nonetheless, the data collected dur-

FIGURE 8 Box-and-whisker plot of *C. parvum* and microsphere removal by the pilot-scale dual-media filter



ing this research indicated that end-of-run, early breakthrough, and late breakthrough filtration all represent operating periods during which *C. parvum* removals can be substantially compromised relative to those obtained during optimized filtration (Figure 8). This result is in agreement with the late breakthrough filtration performance deterioration reported by Huck et al (2002; 2001). In the current investigation, the pilot-scale dual-media filter consistently achieved ~5-log removal of *C. parvum* oocysts during stable (optimized) filtration; similar levels of oocyst-sized polystyrene microspheres were observed during stable operation. During end-of-run operation when filter effluent turbidity levels demonstrated the first signs of increasing (but still were <0.1 ntu), *C. parvum* removal deteriorated to ~3 log. Oocyst and microsphere removals decreased to even lower levels during early breakthrough and late breakthrough filtration. The deterioration in removals of incoming *C. parvum* and oocyst-sized microspheres during end-of-run and breakthrough filter operation relative to stable operation is quite obvious in Figure 8. A relative deterioration between removals during end-of-run and early or late breakthrough is less obvious. More experimentation would help to elucidate whether these differences are significant.

The high *C. parvum* and microsphere concentrations that were found in the filter effluents even after only 15 min of seeding suggested that the passage of oocysts through the filter during the end-of-run, early breakthrough, and late breakthrough filtration periods is largely a function of nonattachment rather than of detachment. This conclusion, though far from incontrovertible, is in general agreement with other studies that suggest nonattachment is an important mechanism of particle passage through filters during breakthrough operation (Moran et al, 1993; Ginn et al, 1992). The current experiments, however, were designed to assess the removals of microorganisms that were introduced to the filter from the influent water late in the filter cycle. The experiments were not designed to investigate detachment during end-of-run and breakthrough filtration.

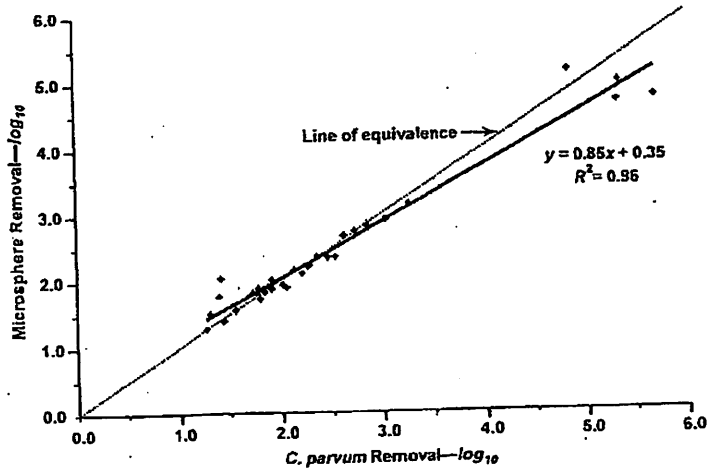
The end-of-run and early breakthrough filtration data clearly indicated a substantial deterioration in *C. parvum* removal by filtration during operating conditions that were in compliance with the 0.3-ntu filter effluent turbidity requirement of the IESWTR. From an operational perspective, these data might challenge the appropriateness of an upper turbidity limit of 0.3 ntu for all points in the filter cycle. This work suggests merit in placing filters out of service at an earlier point in the filter cycle (perhaps when effluent turbidity levels are still <0.1 ntu) to ensure maximum pathogen removal. An important question not answered by the current investigation is when the deterioration in *C. parvum* removal (relative to stable operation) "begins" during a filter cycle. Is it an ongoing, slow deterioration, or does it happen somewhat abruptly toward the end of a filter cycle? An equally important, related question is whether filter effluent turbidity and particle concentration measurements indicate when this deterioration in *C. parvum* removal commences.

The substantial reduction in *C. parvum* removal during the end-of-run and breakthrough experiments relative to the optimized filtration experiments should be considered in the context of the experimental conditions. Because filter influent *C. parvum* concentrations are not typically in the range of the 10^5 oocysts/L used during these experiments, the removal data collected during this investigation should not be used to quantitatively predict differences in oocyst removals at various points in the filter cycle in full-scale plants. However, they do indicate the potential for substantial deterioration in the removal of incoming *C. parvum* oocysts as early as the end-of-run period.

The largest deterioration in oocyst and microsphere removals was expected during the later portions of the filter cycle when filter effluent turbidity levels were high (~0.3 ntu). The early and late breakthrough findings were in general agreement with the findings of other researchers that showed that turbidity breakthrough at the end of a filter cycle could be accompanied by considerable passage of *Giardia* cysts (Logsdon et al, 1981). The early breakthrough

results, however, were different from those obtained during other investigations of *Giardia* and *C. parvum* passage through filters during breakthrough when effluent turbidity levels increased from 0.1 to 0.2 ntu or higher. Patania et al (1995) found that although *Giardia* removal was ~0.5 log lower during breakthrough relative to stable operation, no difference between *C. parvum* removals during stable operation and breakthrough was observed. It is possible that other factors such as chemical pretreatment, which has been demonstrated as critical for optimizing *C. parvum* removal by filtration (Huck et al, 2002; Huck et al, 2001; Patania et al, 1995), may affect the degree of pathogen passage that occurs during early breakthrough filtration.

FIGURE 9 Relationship between *C. parvum* and microsphere removal by the pilot-scale dual-media filter



Commensurate with the findings of several other studies (Nieminski & Ongerth, 1995; Patania et al, 1995), the elevated filter effluent *C. parvum* concentrations during operation late in the filter cycle (i.e., end-of-run, early breakthrough, and late breakthrough) were generally associated with increasing filter effluent total particle counts ≥2 µm and turbidity. This relationship does not hold for all operating conditions, however. As well, the current investigation supported the general conclusions of previous studies that suggested that oocyst-sized polystyrene microsphere removals may be good surrogates for *C. parvum* removal by filtration (Emelko et al, 1999; Swertfeger et al, 1999). A good linear relationship between oocyst and microsphere removals by filtration was provided in Figure 9. From this figure, it is clear that the relationship between oocyst and microsphere removals by filtration is weakest at the highest removals that occurred during stable (optimized) filtration. Only limited *C. parvum* and microsphere data in the 3.5–5.5-log removal range were available. Only one stable operation experiment could be performed with microspheres and should be repeated to better discern whether this apparent deviation from an otherwise highly linear relationship is due to experimental drift. The slightly more variable microsphere recovery also might have affected these results.

As has been discussed previously, the microsphere findings are particularly important because no reliable surrogates for the removal of *C. parvum* during water treatment exist at this time. The microspheres offer several advantages for use over oocysts in treatment process evaluations such as those reported in this study. The microspheres cost substantially less than oocysts, do not require antibody staining, do not pose the public health threats of *C. parvum* (although they could not necessarily be introduced into full-scale plants), are resilient during treatment, and may possibly lend themselves to automated enumeration. As shown earlier, the microspheres also appear to be removed at levels that are comparable to oocyst removals (or slightly lower in the case of stable operation), thereby suggesting that they are generally conservative surrogates that can be used for investigating *C. parvum* removals in treatment process evaluations.

CONCLUSIONS

1. Microsphere removals by filtration were comparable to oocyst removals during both stable and challenged operating periods, suggesting that microspheres may be useful surrogates for investigating *C. parvum* removal.

2. At optimal conditions, the pilot-scale filter consistently achieved >4.5-log removal of *C. parvum* and microspheres. These results were similar to previously reported *C. parvum* removal data (Huck et al, 2002; Huck et al, 2001).

3. During end-of-run operation when filter effluent turbidity levels were <0.1 ntu, median oocyst removals deteriorated to ~3 log.

4. Relative to stable operation, substantial deterioration in *C. parvum* removal can occur during early (operating conditions that were in compliance with the 0.3-ntu filter effluent turbidity requirement of the IESWTR) and late breakthrough filtration. During these periods, observed oocyst removals were 2.1 and 1.4 log, respectively. The early breakthrough data demonstrated that oocyst removals of <2 log could be obtained when in compliance with the 0.3-ntu filter effluent turbidity requirement of the IESWTR. These findings suggested that placing filters out of service prior to reaching a 0.3-ntu (or even lower) filter effluent turbidity is one opera-

tional strategy for maximizing *C. parvum* and potentially other pathogen removal by filtration.

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FOOTNOTES

[1]Fluoresbrite™ carboxylated YG microspheres, Polysciences Inc., Warrington, Pa.
[2]Masterflex Standard Drive and Easy Load II Pump Head With PharMed™ Precision Tubing, Labcor, Concord, Ont.
[3]Tween 80, Tween 20, J.T. Baker Chemical Co., Philadelphia, Pa.
[4]Sigma Antifoam A, Sigma-Aldrich Corp., St. Louis, Mo.
[5]University of Arizona, Dept. of Veterinary Science, Tucson, Ariz.
[6]Petroff-Hausser Bacterial Counting Chamber, Hausser Scientific Corp., Horsham, Pa.
[7]Zeiss Axioskop 2, Empix Imaging, Mississauga, Ont.
[8]Nuclepore Polycarbonate Membranes, Corning, Acton, Mass.
[9]MF Millipore Membrane Filters, Millipore Canada Ltd., Nepean, Ont.
[10]320 NM Filter Assembly, Hoefer Scientific, San Francisco, Calif.
[11]Hydrofluor™ Combo *Cryptosporidium* and *Giardia* kit, Strategic Diagnostics, Newark, Del.
[12]Duke Scientific Corp., Palo Alto, Calif.
[13]IBR Water Particle Counting System Model PWCSD, Inter Basic Resources Inc., Grass Lake, Mich.
[14]Hach Model 1720C, Hach Co., Loveland, Colo.
[15]ABB Model 7997/201, ABB, Calgary, Alta.
[16]To whom correspondence should be addressed

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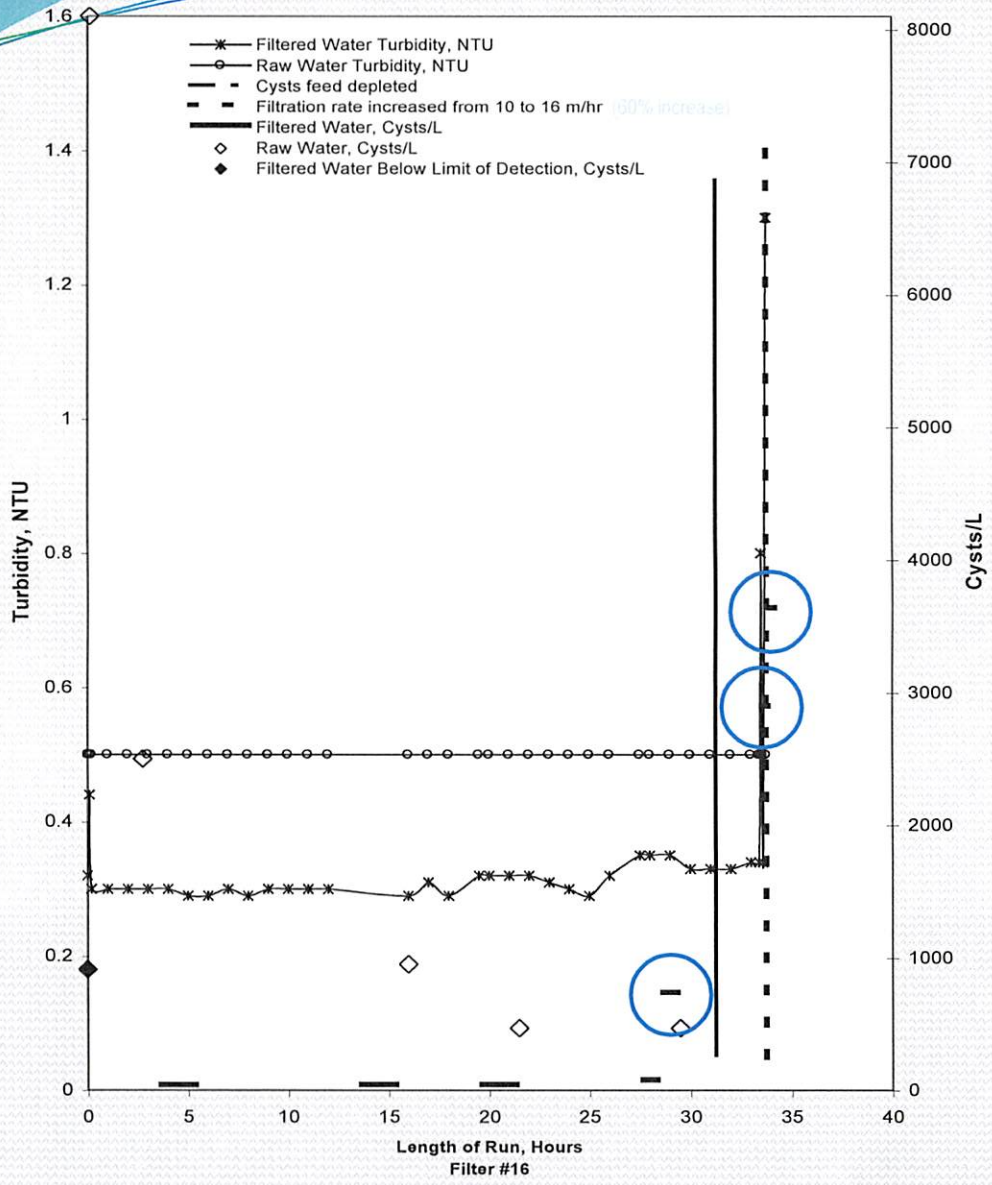


Turbidity breakthrough at the end of a filter run discharges cysts stored during the entire run. (Source: "Filter Operations and Maintenance Guidance Manual" [2002] adapted from Logsden et. al. 1981)

7. IMPORTANCE OF TURBIDITY

7.1 Overview

Section 2 of this guidance manual is included to present an overview on the definition and sources of turbidity. Understanding turbidity, its causes and sources, and the significance to human health will provide the background on which the new turbidity standards are based.

7.2 Turbidity: Definition, Causes, and History as a Water Quality Parameter

Turbidity is a principal physical characteristic of water and is an expression of the optical property that causes light to be scattered and absorbed by particles and molecules rather than transmitted in straight lines through a water sample. It is caused by suspended matter or impurities that interfere with the clarity of the water. These impurities may include clay, silt, finely divided inorganic and organic matter, soluble colored organic compounds, and plankton and other microscopic organisms. Typical sources of turbidity in drinking water include the following (see Figure 7-1):

- Waste discharges;
- Runoff from watersheds, especially those that are disturbed or eroding;
- Algae or aquatic weeds and products of their breakdown in water reservoirs, rivers, or lakes;
- Humic acids and other organic compounds resulting from decay of plants, leaves, etc. in water sources; and
- High iron concentrations which give waters a rust-red coloration (mainly in ground water and ground water under the direct influence of surface water).
- Air bubbles and particles from the treatment process (e.g., hydroxides, lime softening)

Simply stated, turbidity is the measure of relative clarity of a liquid. Clarity is important when producing drinking water for human consumption and in many manufacturing uses. Once considered as a mostly aesthetic characteristic of drinking water, significant evidence exists that controlling turbidity is a competent safeguard against pathogens in drinking water.

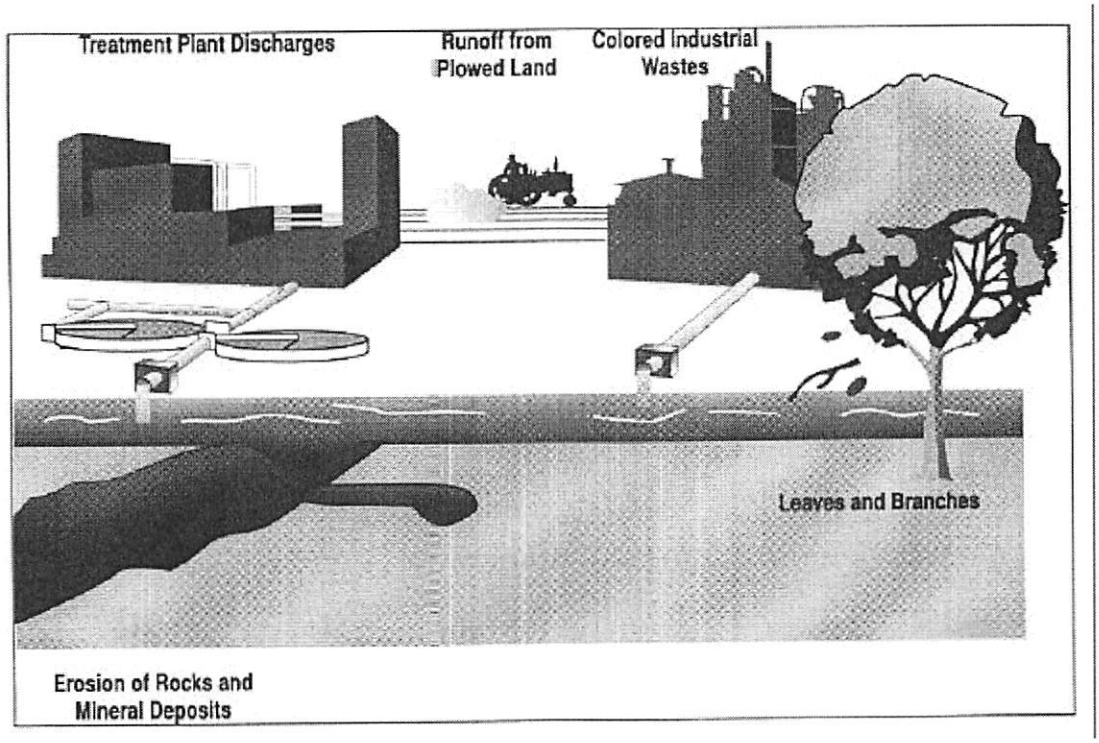
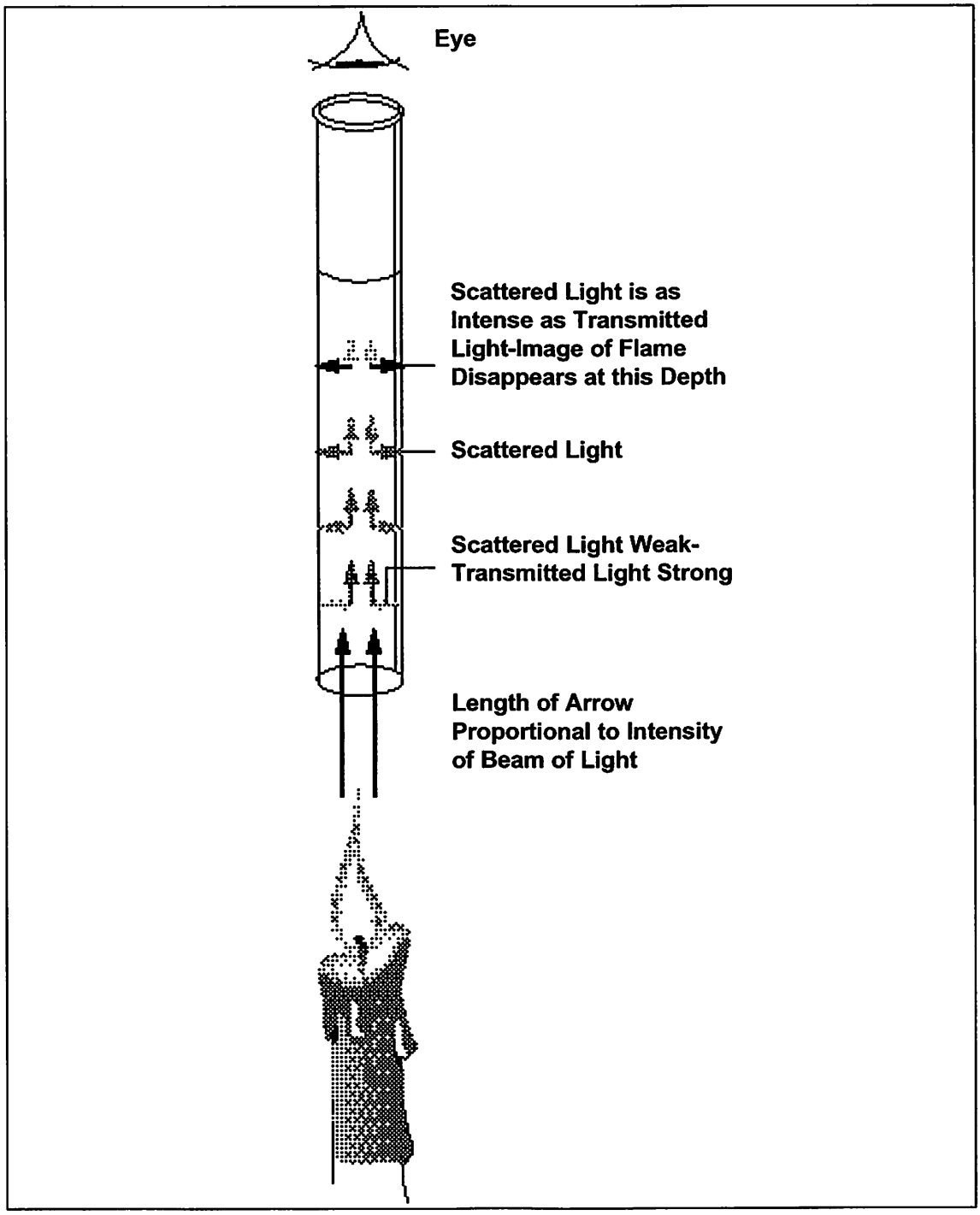


Figure 7-1. Typical Sources of Turbidity in Drinking Water

The first practical attempts to quantify turbidity date to 1900 when Whipple and Jackson developed a standard suspension fluid using 1,000 parts per million (ppm) of diatomaceous earth in distilled water (Sadar, 1996). Dilution of this reference suspension resulted in a series of standard suspensions, which were then used to derive a ppm-silica scale for calibrating turbidimeters.

The standard method for determination of turbidity is based on the Jackson candle turbidimeter, an application of Whipple and Jackson's ppm-silica scale (Sadar, 1996). The Jackson candle turbidimeter consists of a special candle and a flat-bottomed glass tube (Figure 7-2), and was calibrated by Jackson in graduations equivalent to ppm of suspended silica turbidity. A water sample is poured into the tube until the visual image of the candle flame, as viewed from the top of the tube, is diffused to a uniform glow. When the intensity of the scattered light equals that of the transmitted light, the image disappears; the depth of the sample in the tube is read against the ppm-silica scale, and turbidity was measured in Jackson turbidity units (JTU). Standards were prepared from materials found in nature, such as Fuller's earth, kaolin, and bed sediment, making consistency in formulation difficult to achieve.



Source: Sadar, 1996.

Figure 7-2. Jackson Candle Turbidimeter

In 1926, Kingsbury and Clark discovered formazin, which is formulated completely of traceable raw materials and drastically improved the consistency in standards formulation. Formazin is a suitable suspension for turbidity standards when prepared accurately by weighing and dissolving 5.00 grams of hydrazine sulfate and 50.0 grams of hexamethylenetetramine in one liter of distilled water. The solution develops a white hue after standing at 25°C for 48 hours. A new unit of turbidity measurement was adopted called formazin turbidity units (FTU).

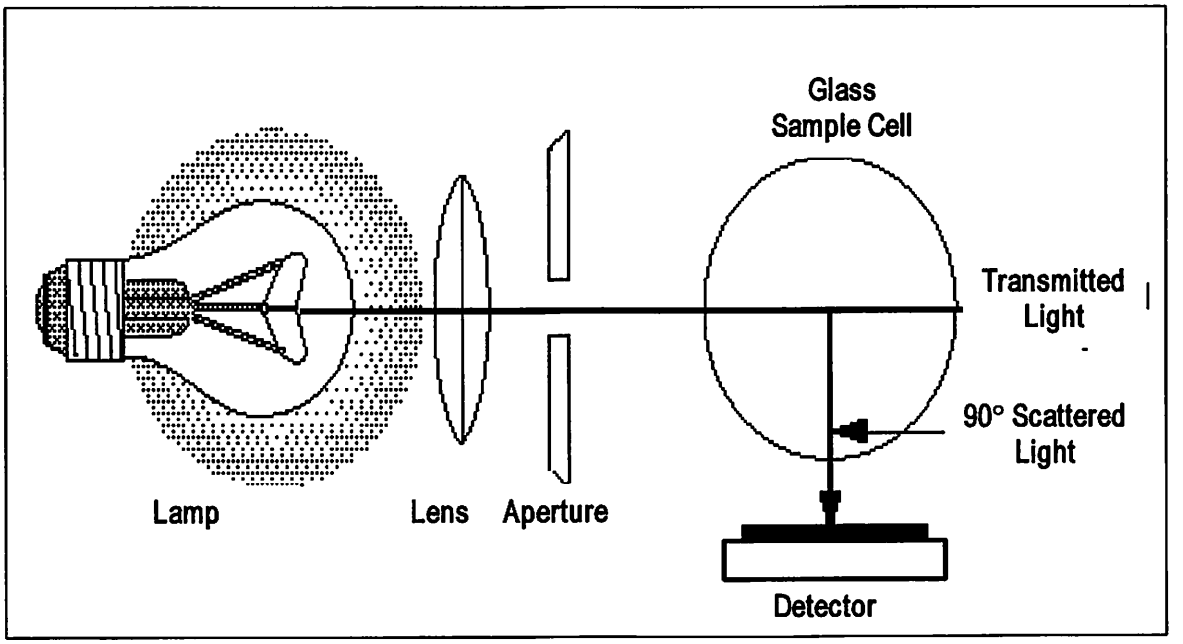
Even though the consistency of formazin improved the accuracy of the Jackson Candle Turbidimeter, it was still limited in its ability to measure extremely high or low turbidity. More precise measurements of very low turbidity were needed to define turbidity in samples containing fine solids. The Jackson Candle Turbidimeter is impractical for this because the lowest turbidity value on this instrument is 25 JTU. The method is also cumbersome and too dependent on human judgement to determine the exact extinction point.

Indirect secondary methods were developed to estimate turbidity. Several visual extinction turbidimeters were developed with improved light sources and comparison techniques, but all were still dependent of human judgement. Photoelectric detectors became popular since they are sensitive to very small changes in light intensity. These methods provided much better precision under certain conditions, but were still limited in ability to measure extremely high or low turbidities.

Finally, turbidity measurement standards changed in the 1970's when the nephelometric turbidimeter, or nephelometer, was developed which determines turbidity by the light scattered at an angle of 90° from the incident beam (Figure 7-3). A 90° detection angle is considered to be the least sensitive to variations in particle size. Nephelometry has been adopted by *Standard Methods* as the preferred means for measuring turbidity because of the method's sensitivity, precision, and applicability over a wide range of particle size and concentration. The nephelometric method is calibrated using suspensions of formazin polymer such that a value of 40 nephelometric units (NTU) is approximately equal to 40 JTU (AWWARF, 1998). The preferred expression of turbidity is NTU.

7.3 Turbidity's Significance to Human Health

Excessive turbidity, or cloudiness, in drinking water is aesthetically unappealing, and may also represent a health concern. Turbidity can provide food and shelter for pathogens. If not removed, turbidity can promote regrowth of pathogens in the distribution system, leading to waterborne disease outbreaks, which have caused significant cases of gastroenteritis throughout the United States and the world. Although turbidity is not a direct indicator of health risk, numerous studies show a strong relationship between removal of turbidity and removal of protozoa.



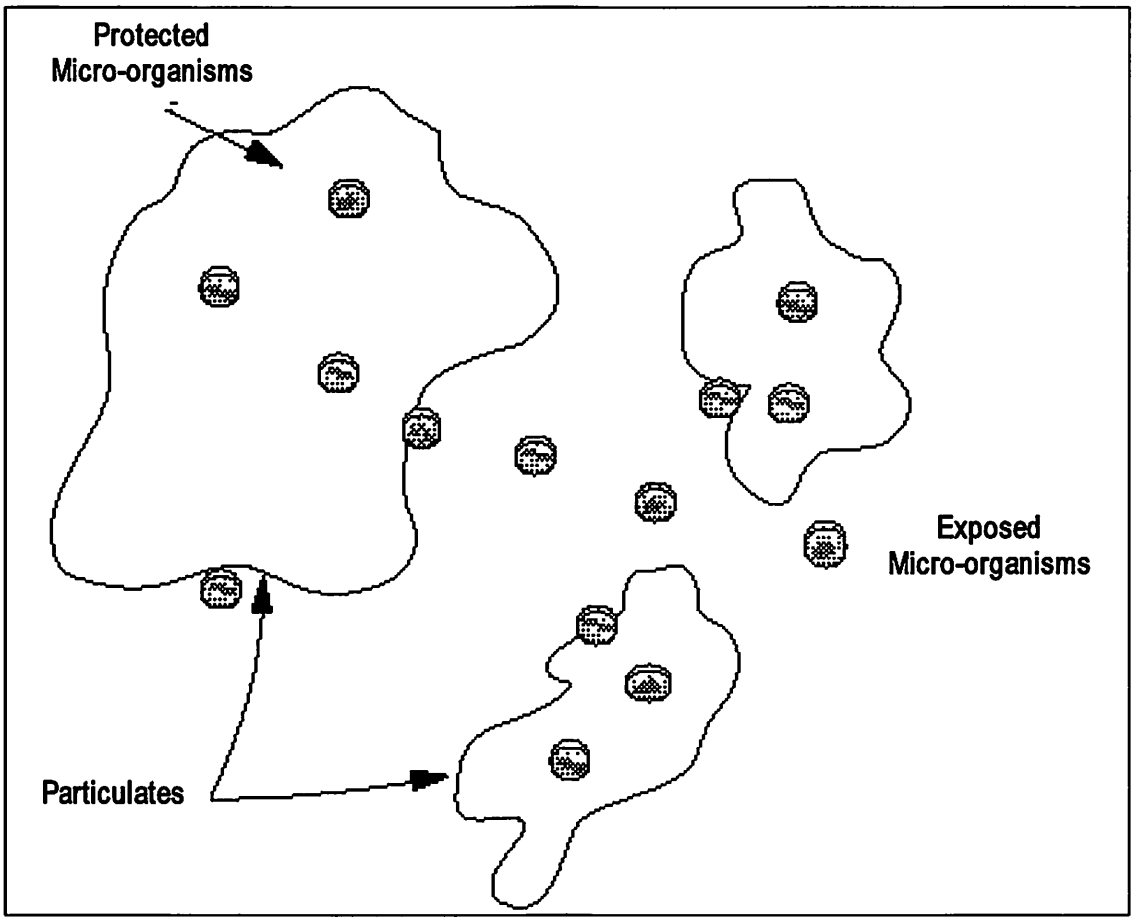
Source: Sadar, 1996; photo revised by SAIC, 1998.

Figure 7-3. Nephelometric Turbidimeter

The particles of turbidity provide "shelter" for microbes by reducing their exposure to attack by disinfectants (Figure 7-4). Microbial attachment to particulate material or inert substances in water systems has been documented by several investigators (Marshall, 1976; Olson et al., 1981; Herson et al., 1984) and has been considered to aid in microbe survival (NAS, 1980). Fortunately, traditional water treatment processes have the ability to effectively remove turbidity when operated properly.

7.3.1 Waterborne Disease Outbreaks

Notwithstanding the advances made in water treatment technology, waterborne pathogens have caused significant disease outbreaks in the United States and continue to pose a significant problem. Even in developed countries, protozoa have been identified as the cause of half of the recognized waterborne outbreaks (Rose et al., 1991). The most frequently reported waterborne disease in the United States is acute gastrointestinal illness, or gastroenteritis (Huben, 1991). The symptoms for this disease include fever, headache, gastrointestinal discomfort, vomiting, and diarrhea. Gastroenteritis is usually self-limiting, with symptoms lasting one to two weeks in most cases. However, if the immune system is suppressed, as with the young, elderly and those suffering from HIV or AIDS, the condition can be very serious and even life threatening. The causes are usually difficult to identify but can be traced to various viruses, bacteria, or protozoa.



Source: LeChevallier and Norton, 1991.

Figure 7-4. Particles of Turbidity May Provide Protection for Microorganisms

Giardia and *Cryptosporidium* are the two most studied organisms known to cause waterborne illnesses. These two protozoa are believed to be ubiquitous in source water, are known to occur in drinking water systems, have been responsible for the majority of waterborne outbreaks, and treatments to remove and/or inactivate them are known to be effective for a wide range of waterborne parasites (LeChevallier and Norton, in Craun, 1993). *Giardia* and *Cryptosporidium* have caused over 400,000 persons in the United States to become ill since 1991, mostly due to a 1993 outbreak in Milwaukee, Wisconsin.

Giardia and viruses are addressed under the 1989 SWTR. Systems using surface water must provide adequate treatment to remove and/or inactivate at least 3-log (99.9%) of the *Giardia lamblia* cysts and at least 4-log (99.99%) of the enteric viruses. However, *Cryptosporidium* was not addressed in the SWTR due to lack of occurrence and health effects data. In the mid-1980's, the United States experienced its first recognized waterborne disease outbreak of cryptosporidiosis (D'Antonio et al., 1985). It was soon discovered that the presence of *Cryptosporidium* in drinking water, even in very low

concentrations, could be a significant health hazard (Gregory, 1994). In 1993, a major outbreak of cryptosporidiosis occurred even though the system was in full compliance with the SWTR. Several outbreaks caused by this pathogen have been reported (Smith et al., 1988; Hayes at al., 1989; Levine and Craun, 1990; Moore et al., 1993; Craun, 1993). The ESWTR's primary focus is to establish treatment requirements to further address public health risks from pathogen occurrence, and in particular, *Cryptosporidium.*

Table 7-1 displays several instances of past outbreaks of cryptosporidiosis in systems using surface water as a source, along with general information about the plant and turbidity monitoring. In three out of four of the cases displayed in the table (Milwaukee, Jackson County, and Carrollton), turbidity over 1.0 NTU was occurring in finished water during the outbreaks.

Table 7-1. Cryptosporidium Outbreaks vs. Finished Water Turbidity

Location of Outbreak	Year	General Plant Information	Turbidity Information
Las Vegas, Nevada (CDC, 1996)	1993-1994	No apparent deficiencies or problems with this community system; SWTR compliant; system performed pre-chlorination, filtration (sand and carbon), and filtration of lake water; outbreak affected mostly persons infected with the human immunodeficiency virus (HIV)	The raw water averaged 0.14 NTU between January 1993 and June 1995, with a high of 0.3 NTU; the maximum turbidity of finished water during this time was 0.17 NTU.
Milwaukee, Wisconsin (CDC, 1996, Logsdon, 1996)	1993	Community system; SWTR compliant; however, deterioration in source (lake) raw-water quality and decreased effectiveness of the coagulation-filtration process	Dramatic temporary increase in finished water turbidity levels; reported values were as high as 2.7 NTU. (Turbidity had never exceeded 0.4 NTU in the previous 10 years.)
Jackson County, Oregon (USEPA, 1997)	1992	Poor plant performance (excessive levels of algae and debris); no pre-chlorination before filtration	Earlier in the year when outbreak occurred, filtered water had averaged 1 NTU or greater.
Carrollton, Georgia (USEPA, 1997, Logsdon, 1996)	1987	Conventional filtration plant; sewage overflowed into water treatment intake, followed by operational irregularities in treatment; filters were placed back into service without being backwashed.	Filtered water turbidity from one filter reached 3 NTU about three hours after it was returned to service without being washed.

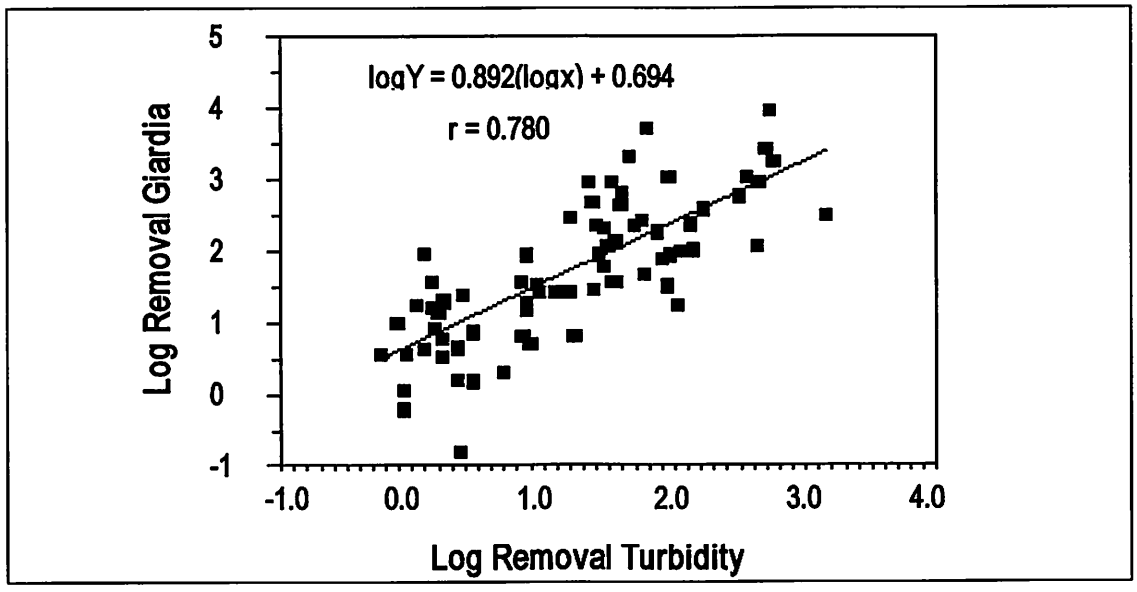
7.3.2 The Relationship Between Turbidity Removal and Pathogen Removal

Low filtered water turbidity can be correlated with low bacterial counts and low incidences of viral disease. Positive correlations between removal (the difference between raw and plant effluent water samples) of pathogens and turbidity have also been observed in several studies. In fact, in every study to date where pathogens and turbidity occur in the source water, pathogen removal coincides with turbidity/particle removal (Fox, 1995).

As an example, data gathered by LeChevallier and Norton (in Craun, 1993) from three drinking water treatment plants using different watersheds indicated that for every log removal of turbidity, 0.89 log removal was achieved for the parasites *Cryptosporidium*

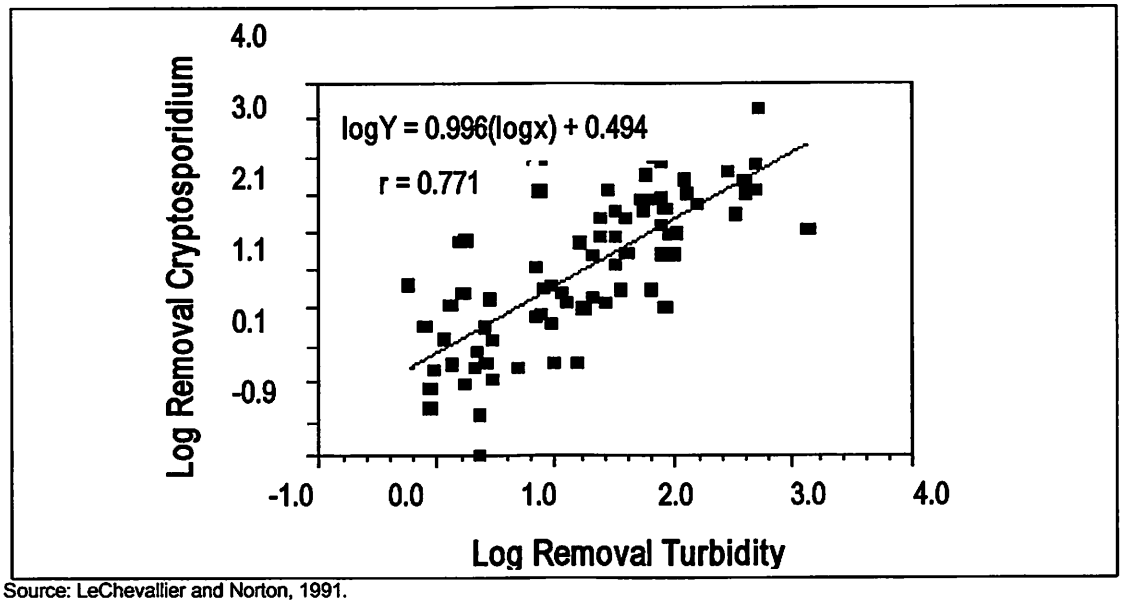
and *Giardia* (Figures 7-5 and 7-6). Of course, this exact relationship does not hold for all treatment plants. Table 7-2 lists several other studies in addition to LeChevallier and Norton's, and their conclusions on the relationship of turbidity to protozoan removal.

All studies in Table 7-2 show turbidity as a useful predictor of parasite removal efficiency. This evidence suggests that although a very low turbidity value does not completely ensure that particles are absent, it is an excellent measure of plant optimization to ensure maximum public health protection.



Source: LeChevallier and Norton, 1991.

Figure 7-5. Relationship Between Removal of *Giardia* and Turbidity



Source: LeChevallier and Norton, 1991.

Figure 7-6. Relationship Between Removal of *Cryptosporidium* and Turbidity

Table 7-2. Studies on the Relationship between Turbidity Removal and Protozoa Removal

Reference/Study	Discovery/Conclusion on Turbidity
Patania et al., 1995*	Four systems using rapid granular filtration, when treatment conditions were optimized for turbidity and particle removal, achieved a median turbidity removal of 1.4 log and median particle removal of 2 log. The median cyst and oocyst removal was 4.2 log. A filter effluent turbidity of less than 0.1 NTU or less resulted in the most effective cyst removal, by up to 1.0 log greater than when filter effluent turbidities were greater than 0.1 NTU (within the 0.1 to 0.3 NTU range).
Nieminski and Ongerth, 1995*	Pilot plant study: Source water turbidity averaged 4 NTU (maximum = 23 NTU), achieving filtered water turbidities of 0.1-0.2 NTU. *Cryptosporidium* removals averaged 3.0 log for conventional treatment and 3.0 log for direct filtration, while *Giardia* removals averaged 3.4 log for conventional treatment and 3.3 log for direct filtration. Full scale plant study: Source water had turbidities typically between 2.5 and 11 NTU (with a peak level of 28 NTU), achieving filtered water turbidities of 0.1-0.2 NTU. *Cryptosporidium* removals averaged 2.25 log for conventional treatment and 2.8 log for direct filtration, while *Giardia* removals averaged 3.3 log for conventional treatment and 3.9 log for direct filtration.
Ongerth and Pecoraro, 1995*	Using very low-turbidity source waters (0.35 to 0.58 NTU), 3 log removal for both cysts were obtained, with optimal coagulation. (With intentionally suboptimal coagulation, the removals were only 1.5 log for *Cryptosporidium* and 1.3 log for *Giardia*.)
LeChavallier and Norton (in Craun, 1993)	Data gathered from three drinking water treatment plants using different watersheds indicated that for every log removal of turbidity, 0.89 log removal was achieved for *Cryptosporidium* and *Giardia*.
Nieminski, 1992	A high correlation (r^2=0.91) exists between overall turbidity removal and both *Giardia* and *Cryptosporidium* removal through conventional water treatment.
Ongerth, 1990	*Giardia* cyst removal by filtration of well-conditioned water results in 90% or better turbidity reduction, which produces effective cyst removal of 2-log (99%) or more.
LeChavallier et al., 1991*	In a study of 66 surface water treatment plants using conventional treatment, most of the utilities achieved between 2 and 2.5 log removals for both *Cryptosporidium* and *Giardia*, and a significant correlation (p=0.01) between removal of turbidity and *Cryptosporidium* existed.
LeChavallier and Norton, 1992*	In source water turbidities ranging from 1 to 120 NTU, removal achieved a median of 2.5 log for *Cryptosporidium* and *Giardia* at varying stages of treatment optimization. The probability of detecting cysts and oocysts in finished water supplies depended on the number of organisms in the raw water; turbidity was a useful predictor of *Giardia* and *Cryptosporidium* removal.
Foundation for Water Research, 1994*	Raw water turbidity ranged from 1 to 30 NTU, and *Cryptosporidium* removal was between 2 and 3 log. Investigators concluded that any measure which reduces filter effluent turbidity should reduce risk from *Cryptosporidium*.
Hall et al., 1994	Any measure which reduces filtrate turbidity will reduce the risk from *Cryptosporidium*; a sudden increase in the clarified water turbidity may indicate the onset of operational problems with a consequent risk from cryptosporidiosis.
Gregory, 1994	Maintaining the overall level of particulate impurities (turbidity) in a treated water as low as possible may be an effective safeguard against the presence of oocysts and pathogens.
Anderson et al., 1996	In a pilot plant study, the removal of particles > 2 m was significantly related to turbidity reduction r=0.97 (p<0.0001); the removal of *Cryptosporidium* oocysts may be related to the removal of *Giardia*, r=0.79 (p<0.14); the reduction of turbidity may be related to the removal of *Giardia* cysts, r=0.67 (p<0.13) and *Cryptosporidium* oocysts (p<0.08)

* as discussed in EPA's Notice of Data Availability (USEPA, 1997)

7.4 References

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7. IMPORTANCE OF TURBIDITY 7-1

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Table 7-1. Cryptosporidium Outbreaks vs. Finished Water Turbidity 7-7
Table 7-2. Studies on the Relationship between Turbidity Removal and Protozoa Removal 7-9

1. Does your state require surface water filtration plants to continuously monitor and record their combined filter effluent turbidity?

- Answered: 30
- Skipped: 0

Answer Choices	Responses
Yes	66.67% 20
No	33.33% 10
Total	30

Comments(13)

Yes for membranes. No for all others. For conventional, direct, and DE: required at least every 4 hours; or, once/day for systems serving 500 or fewer persons if approved by the director. For slow sand: every 4 hrs can be reduced to once/day if approved by the director. In lieu of CFE, could monitor IFEs and record average.

1/24/2014 10:22 AM View respondent's answers

Surface water sytems serving 500 or fewer people may grab sample once per day if approved by the State. Slow sand filtration systems may grab sanple once per day if approved by the State.

1/21/2014 11:01 AM View respondent's answers

We only require systems to conduct continuous monitoring of turbidity in the combined filter effluent if they serve fewer than 10,000 people, have only two or fewer filters and choose to monitor turbidity in the combined filter effluent rather than monitor turbidity at individual filters.

1/16/2014 5:51 PM View respondent's answers

Minimum required is 1 reading each 4 hours of operation.

1/10/2014 12:55 PM View respondent's answers

No, we require one grab sample every four hours for combined filter effluent turbidity.

1/9/2014 12:52 PM View respondent's answers

Alabama requires each filter to be monitored and recorded on a continuous basis. Compliance is determined on each individual filter. One filter may cause a violation, even if the combined filter effluent still meets federal standards. Alabama has no CFE limits, all limits are IFE.

1/9/2014 11:37 AM View respondent's answers

Community - The majority of MN Community Surface Water Systems are monitoring CFE continuously; taking grab sample every 4 hours is acceptable. MDH has no plan to require continuous CFE monitoring. NonCommunity - Not for population <500

1/9/2014 7:49 AM View respondent's answers

Systems using conventional or direct filtration must continually monitor individual filter effluent turbidity and record individual filter effluent turbidity every 15 minutes. For conventional and direct filtration systems with only one filter, the combined filter effluent turbidity, by default, must be continuously monitored and recorded every 15 minutes.

1/8/2014 7:48 PM View respondent's answers

At least 15 minute monitoring must be recorded. Systems that serve less than 500 pop can do daily monitoring if requested.

1/8/2014 1:20 PM View respondent's answers

Almost all system have continuous monitoring; however, the Reg.s allow collecting grab samples at 4 hour increments and doing a bench test.

1/8/2014 9:45 AM View respondent's answers

310 CMr 22.20F (6)(a)

1/7/2014 3:00 PM View respondent's answers

Individual filters are continuously monitored.

1/7/2014 1:06 PM View respondent's answers

Our State Regulations require continuous monitoring of CFE but these regs don't explicity state how the reporting should be done (ie do they just report on the four hour mark or report the number of 15 minute intervals in a month) so we have systems that report inconsistently.

1/7/2014 10:58 AM View respondent's answers

2. Does your state require surface water filtration plants using Slow Sand, Diatomaceous Earth, or alternative filtration to continuously monitor and record their individual filter effluent turbidity?

- Answered: 30
- Skipped: 0

Answer Choices--	Responses--	
Yes	46.67% 14	
No	53.33% 16	
Total		30
Comments(14)		

1/10/2014 12:55 PM View respondent's answers

No, we require one grab sample every four hours for individual filter effluent turbidity for systems that use Slow Sand or Diatomaceous Earth. Individual filter turbidity monitoring for systems that use alternative filtration is set on a system-specific basis but cannot be less than one grab sample every four hours.

1/9/2014 12:52 PM View respondent's answers

Alabma only has conventional (high rate) filtration and membrane filtration. Slow sand and others are not allowed on surface water sources.

1/9/2014 11:37 AM View respondent's answers

Community - Minnesota does not have systems using slow sand or diatomaceous earth filters. Alternative filtration systems (using UF) are required to continuously monitor and record effluent turbidity of each UF Train/Skit. Noncommunity - Not for population <500

1/9/2014 7:49 AM View respondent's answers

Systems using membrane filtration must conduct continuous individual filter effluent monitoring at least every 15 minutes on each individual unit, if not conducting continuous direct integrity testing of the membrane units.

1/8/2014 7:48 PM View respondent's answers

We recommend. Bags and Cartridges typically only monitor with grab samples.

1/8/2014 6:19 PM View respondent's answers

Slow sand and alternative filtration may reduce sampling frequency with State approval.

1/8/2014 3:20 PM View respondent's answers

It is a case by case decision but for membranes we require each bank have a monitor via permit condition, not in regulation.

1/8/2014 1:20 PM View respondent's answers

310 CMr 22.20D (4)(b)2

1/7/2014 3:00 PM View respondent's answers

Currently we require IFE turbidity monitoring for membrane filtration plants

1/7/2014 1:42 PM View respondent's answers

We don't have any functing slow sand filters it the state.

1/7/2014 1:39 PM View respondent's answers

Two trains or less not required to do IFE monitoring

1/7/2014 11:03 AM View respondent's answers

We several plants that use membrane filtration.

1/7/2014 10:58 AM View respondent's answers

3. If you answered yes to question 2, do you require these plants to report individual filter trigger level exceedances and conduct any followup actions?

- Answered: 14
- Skipped: 16

Answer Choices–	Responses–
Yes	92.86% 13
No	7.14% 1
Total	14

Comments(5)

All surface water treatment plants are required to report the highest daily turbidity from each filtration unit on their monthly operational report. Membranes have a turbidity limit of 0.15 NTU. Please see ADEM Admin. Code r. 335-7-10-.06(10) for details. Regulations can be downloaded from www.adem.alabama.gov under regulations and then click on Division 7.

1/9/2014 11:37 AM View respondent's answers

Community - for conventional, direct filtration and low-pressure membrane filtration systems Noncommunity - , for conventional/direct filtration.

1/9/2014 7:49 AM View respondent's answers

-na-

1/8/2014 6:19 PM View respondent's answers

Exceedance report similar to conv or direct but via permit so case by case.

1/8/2014 1:20 PM View respondent's answers

NA

1/7/2014 3:00 PM View respondent's answers

4. Does your state require surface water treatment plants to be attended during operation?

- Answered: 30
- Skipped: 0

Answer Choices–	Responses–
Yes	40% 12
No	60% 18

Answer Choices	Responses
Total	30
Comments(14)	

Operators must be in contact with the plant via alarms/dialers while the plant is in operation if the operators are not at the plant.

1/23/2014 3:35 PM View respondent's answers

GWUDI plants may be operated remotely if the plant has monitoring equipment and alarms or automatic shutdown capability in place

1/21/2014 11:01 AM View respondent's answers

it is strongly recommended that plants be attended during operation

1/10/2014 3:03 PM View respondent's answers

However, public water supply systems must have the appropriate level of operator certification and the facility must be under their control irrespective of whether or not the facility is physically attended.

1/10/2014 12:55 PM View respondent's answers

We have no specific prohibition against unattended surface water plants and have adopted the Ten States Standards Policy Statement for these types of systems.

1/9/2014 12:52 PM View respondent's answers

But not continuously. They need to be on site at least once per day. However, of the 23 community surface water systems at least 20 of them have personnel on site while the plant is in operation.

1/9/2014 7:49 AM View respondent's answers

Systems using conventional or direct filtration must have a high turbidity alarm with an auto dial or auto plant shutdown, if the plant operates with no operator present.

1/8/2014 7:48 PM View respondent's answers

We have no specified requirements in our State Sanitary Code but we do have a general due care and diligence for the operation of a treatment plant requirement.

1/8/2014 3:20 PM View respondent's answers

But can be remotely attended in certain situations where there is 24-hour manned video and SCADA surveillance of all operations.

1/8/2014 11:25 AM View respondent's answers

However, we acknowledge that some small systems may not have continuous attendance. We also recognize that this problematic.

1/8/2014 9:45 AM View respondent's answers

If remote SCADA is in place, then physical presence is not required during night operation.

1/7/2014 3:00 PM View respondent's answers

401 KAR 8:030 has the following language for surface water treatment plants "...in direct responsible charge of the plant and shall be present at the water treatment plant or performing

system-related duties"; 401 KAR 8:030 further defines "system-related duties" (e) System-related duties shall be for: 1. Class IIA, Class IIIA, and Class IVA water systems, duties related to the operation and maintenance of the water treatment plant; or 2. Class IA-D water systems, duties related to the operation and maintenance of the water treatment plant and distribution system.

1/7/2014 1:42 PM View respondent's answers

Must be attended unless process alarms with auto-dial and/or auto-plant shutdown on pH, turbidity and disinfectant are in place and operational.

1/7/2014 1:06 PM View respondent's answers

Minimum 1/day inspection

1/7/2014 11:03 AM View respondent's answers

5. If you answered yes to question 4, do you allow water systems to apply for an exception?

- Answered: 12
- Skipped: 18

Answer Choices–	Responses–
Yes	58.33% 7
No	41.67% 5
Total	12
Comments(9)	

GWUDI systems may be operated remotely. Non-Community surface supplies may apply for exemption from operator in attendance rules.

1/21/2014 11:01 AM View respondent's answers

The exception is for surface systems which serve less than 10,000 persons and which utilize automated operation systems which monitor system operation, record all required readings, notify the operator in the event of a system upset or failure, and allow the operator to remotely control or shut down the system.

1/10/2014 4:03 PM View respondent's answers

-na-

1/8/2014 6:19 PM View respondent's answers

We allow some MF plants treating a high quality raw water source to operate for short periods of time unattended if the proper controls are in place to alarm staff or shut down the plant in the event of a treatment failure.

1/8/2014 2:05 PM View respondent's answers

See above.

1/8/2014 11:25 AM View respondent's answers

However, some large utilities do follow the Recommended Standards Procedure for Automated/Unattended Operation of Surface Water Treatment Plants Policy

1/8/2014 9:45 AM View respondent's answers

SCADA capability--night operation only

1/7/2014 3:00 PM View respondent's answers

401 KAR 8:030 has language regarding "alternate staffing plans" 6. A public water system may propose an alternate staffing plan to the staffing requirement established in this paragraph. a. The proposal shall be submitted to the cabinet and shall thoroughly explain the alternate proposal. b. The proposal shall demonstrate: (i) A necessity for the water system to vary from the requirement in this paragraph; and (ii) An equal level of protection of human health and the environment. c. The cabinet shall not approve an alternate proposal that does not propose that a duly certified operator in direct responsible charge operate a water treatment plant, in accordance with KRS 223.210. Since February 2010, KY DOW has approved alternate staffing plans for 20 operators.

1/7/2014 1:42 PM View respondent's answers

Membrane Filtration systems are the exception - these do not require operator attendance at all times.

1/7/2014 11:21 AM View respondent's answers

6. What state do you represent?

- Answered: 30
- Skipped: 0

Connecticut

1/24/2014 1:24 PM View respondent's answers

Rhode Island

1/24/2014 10:22 AM View respondent's answers

Nebraska

1/23/2014 3:35 PM View respondent's answers

Tennessee

1/21/2014 11:01 AM View respondent's answers

WV

1/20/2014 8:17 AM View respondent's answers

New Mexico

1/16/2014 5:51 PM View respondent's answers

Maine

1/15/2014 1:24 PM View respondent's answers

Louisiana

ASDWA Survey

1/10/2014 4:03 PM View respondent's answers

Idaho

1/10/2014 3:03 PM View respondent's answers

Kansas

1/10/2014 12:55 PM View respondent's answers

Montana

1/9/2014 12:52 PM View respondent's answers

Alabama

1/9/2014 11:37 AM View respondent's answers

Minnesota

1/9/2014 7:49 AM View respondent's answers

Oregon

1/8/2014 7:48 PM View respondent's answers

Alaska

1/8/2014 6:19 PM View respondent's answers

Colorado

1/8/2014 3:46 PM View respondent's answers

New York

1/8/2014 3:20 PM View respondent's answers

Michigan

1/8/2014 2:05 PM View respondent's answers

California

1/8/2014 1:20 PM View respondent's answers

Missouri

1/8/2014 12:06 PM View respondent's answers

Iowa

1/8/2014 11:25 AM View respondent's answers

Vermont

1/8/2014 10:17 AM View respondent's answers

Illinois

1/8/2014 9:45 AM View respondent's answers

Massachusetts

1/7/2014 3:00 PM View respondent's answers

Kentucky

1/7/2014 1:42 PM View respondent's answers

Utah

1/7/2014 1:39 PM View respondent's answers

Arkansas

1/7/2014 1:06 PM View respondent's answers

Virginia

1/7/2014 11:21 AM View respondent's answers

New Hampshire

1/7/2014 11:03 AM View respondent's answers

New Jersey

1/7/2014 10:58 AM View respondent's answers

7. What is your contact information?

- Answered: 30
- Skipped: 0

Tom Chyra Thomas.chyra@ct.gov 860-509-7333

1/24/2014 1:24 PM View respondent's answers

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1/24/2014 10:22 AM View respondent's answers

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1/23/2014 3:35 PM View respondent's answers

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1/21/2014 11:01 AM View respondent's answers

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1/20/2014 8:17 AM View respondent's answers

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1/16/2014 5:51 PM View respondent's answers

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1/15/2014 1:24 PM View respondent's answers

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1/10/2014 4:03 PM View respondent's answers

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1/10/2014 3:03 PM View respondent's answers

785-296-5516

1/10/2014 12:55 PM View respondent's answers

Rachel Clark, PE Montana Department of Environmental Quality Public Water and Subdivisions Bureau (406) 444-6722

1/9/2014 12:52 PM View respondent's answers

William McClimans (334) 271-7985 wdm@adem.state.al.us

1/9/2014 11:37 AM View respondent's answers

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James Nusrala, Regional Engineer, 971 673-0459, and james.b.nusrala@state.or.us

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Vanessa Wike, 907 269-7636

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3036923258

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maher.jaafari@dnr.mo.gov everett.baker@dnr.mo.gov

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Jennifer Bunton, 515-725-0298, jennifer.bunton@dnr.iowa.gov

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Thomas Brown Operations Secion Supervisor DrinkingWater and Groundwater Protection Division tom.brown@state.vt.us. 802-371-7610

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W. David McMillan, P.G. Manager, Division of Public Water Supplies Illinois EPA dave.mcmillan@illinois.gov; 217-524-8111

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Frank Niles One Winter St, Boston,MA 02108

ASDWA Survey

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Ken Bousfield, P.E. Director, Utah Division of Drinking Water 195 North 1950 West Salt Lake City, Utah 84116 801-536-4207 kbousfield@utah.gov

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Lance Jones lance.jones@arkansas.gov 501-661-2623

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Susan E Douglas, PE Director of Technical services Office of Drinking Water Virginia Department of Health susan.douglas@vdh.virginia.gov 804-864-7490

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Richard Skarinka, P.E. Engineering Section Manager NHDES Drinking Water and Groundwater Bureau P.O. Box 95, Concord NH 03302-0095 Richard.Skarinka@des.nh.gov (603) 271-2948

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Karen Fell 609-292-5550

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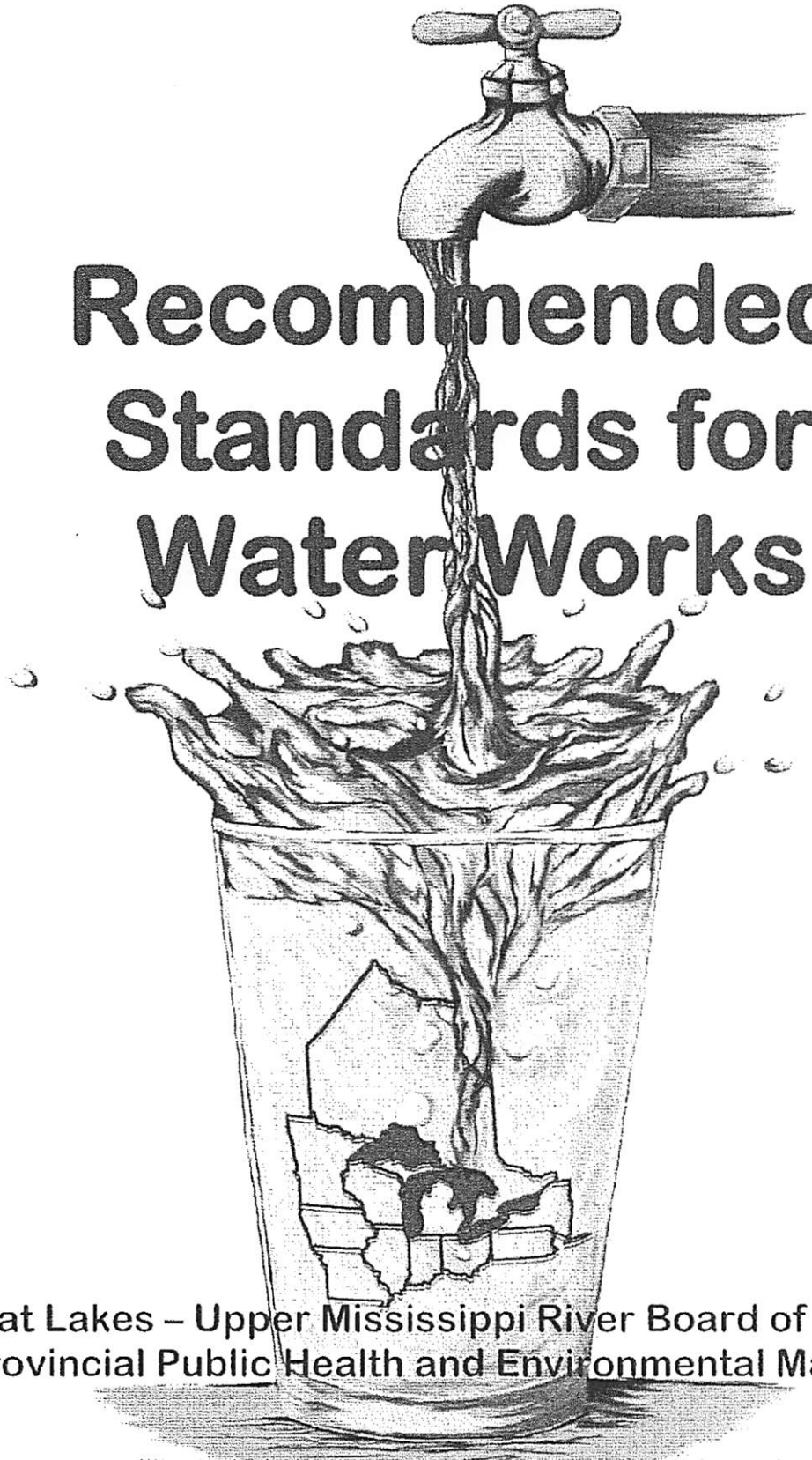
Recommended Standards for Water Works



Great Lakes – Upper Mississippi River Board of State and Provincial Public Health and Environmental Managers

Illinois Indiana Iowa Michigan Minnesota Missouri
New York Ohio Ontario Pennsylvania Wisconsin

POLICY STATEMENT ON
AUTOMATED/UNATTENDED OPERATION OF SURFACE WATER TREATMENT PLANTS

Recent advances in computer technology, equipment controls and Supervisory Control and Data Acquisition (SCADA) Systems have brought automated and off-site operation of surface water treatment plants into the realm of feasibility. Coincidentally, this comes at a time when renewed concern for microbiological contamination is driving optimization of surface water treatment plant facilities and operations and finished water treatment goals are being lowered to levels of <0.1 NTU turbidity and <20 total particle counts per milliliter.

Review authorities encourage any measures, including automation, which assist operators in improving plant operations and surveillance functions.

Automation of surface water treatment facilities to allow unattended operation and off-site control presents a number of management and technological challenges which must be overcome before an approval can be considered. Each facet of the plant facilities and operations must be fully evaluated to determine what on-line monitoring is appropriate, what alarm capabilities must be incorporated into the design and what staffing is necessary. Consideration must be given to the consequences and operational response to treatment challenges, equipment failure and loss of communications or power.

An engineering report shall be developed as the first step in the process leading to design of the automation system. The engineering report to be submitted to the reviewing authorities must cover all aspects of the treatment plant and automation system including the following information/criteria:

1. Identify all critical features in the pumping and treatment facilities that will be electronically monitored, have alarms and can be operated automatically or off-site via the control system. Include a description of automatic plant shut-down controls with alarms and conditions which would trigger shut-downs. Dual or secondary alarms may be necessary for certain critical functions.

2. Automated monitoring of all critical functions with major and minor alarm features must be provided. Automated plant shutdown is required on all major alarms. Automated startup of the plant is prohibited after shutdown due to a major alarm. The control system must have response and adjustment capability on all minor alarms. Built-in control system challenge test capability must be provided to verify operational status of major and minor alarms. The computer system must incorporate cyberspace security to protect the confidentiality and integrity of transmitted information and deter identity theft through such means as placing routers and "firewalls" at the entry point of a sub network to block access from outside attackers.

3. The plant control system must have the capability for manual operation of all treatment plant equipment and process functions.

4. A plant flow diagram which shows the location of all critical features, alarms and automated controls to be provided.

5. Description of off-site control station(s) that allow observation of plant operations, receiving alarms and having the ability to adjust and control operation of equipment and the treatment process.

6. A certified operator must be on "standby duty" status at all times with remote operational capability and located within a reasonable response time of the treatment plant.

7. A certified operator must do an on-site check at least once per day to verify proper operation and plant security.

8. Description of operator staffing and training planned or completed in both process control and the automation system.

9. Operations manual which gives operators step by step procedures for understanding and using the automated control system under all water quality conditions. Emergency operations during power or communications failures or other emergencies must be included. A backup battery shall be provided for the control system.

10. A plan for a 6 month or more demonstration period to prove the reliability of procedures, equipment and surveillance system. A certified operator must be on-duty during the demonstration period. The final plan must identify and address any problems and alarms that occurred during the demonstration period. Challenge testing of each critical component of the overall system must be included as part of the demonstration project.

11. Schedule for maintenance of equipment and critical parts replacement.

12. Sufficient finished water storage shall be provided to meet system demands and CT requirements whenever normal treatment production is interrupted as the result of automation system failure or plant shutdown.

13. Sufficient staffing must be provided to carry out daily on-site evaluations, operational functions and needed maintenance and calibration of all critical treatment components and monitoring equipment to ensure reliability of operations.

14. Plant staff must perform, as a minimum, weekly checks on the communication and control system to ensure reliability of operations. Challenge testing of such equipment should be part of normal maintenance routines.

15. Provisions must be made to ensure security of the treatment facilities at all times. Incorporation of appropriate intrusion alarms must be provided which are effectively communicated to the operator in charge.

Adopted April, 1997
Revised April, 2012

The West Virginia Legislative Rule Title 64 Bureau for Public Health Series 4 (64CSR4) specifies adequate operator coverage requirements. The additional exceptions allowable by this policy are for Class II – IV public water systems (PWS) only and are based on proven automation. This policy covers unattended operation with or without remote monitoring and does not allow for remote treatment changes. Systems operating unattended under previous approvals based on the 1993 version of DW-36 must work towards these requirements in cooperation with the Environmental Engineering Division (EED).

To evaluate requests for automated/unattended operations, a proposal must be submitted to the EED central office for review and approval. Equipment used or to be installed to meet the requirements of this procedure must comply with the PWS design standards (64CSR77). Functionality of the automated system must also be demonstrated to EED for final approval.

In considering any proposal, the criteria listed below are to be followed:

1. Identify all critical features in the pumping and treatment facilities that will be electronically monitored and/or have alarms. These critical features will include, but are not limited to:
   a. Water storage facility's high and low levels at the treatment plant and in the distribution system;
   b. Any instrumentation or equipment related to pH (if system is controlled by adding caustic), turbidity, chlorine residual, and required selective ions within specific ranges;
   c. Chlorine gas leaks and tank pressure changes;
   d. Distribution system pressure loss;
   e. Fire;
   f. Intrusion;
   g. Power failures;
   h. Critical pumps, motors and generator failures; and,
   i. Chemical feed tank volumes to prevent any over or underfeed situations.

2. Provide a plant flow diagram which shows the location of all critical features and automated controls.

3. Provide a description of all alarm features. These alarm features will include, but not be limited to:

   a. Alarm set points; and,

b. Automatic actions as a result of an alarm. For example, switch to back-up equipment, notify supervisor via auto-dialer, shutdown of individual equipment, and plant-wide shutdown.

4. Names, titles, and telephone numbers of individuals who will be notified in the event of an alarm/shutdown event.

5. Operation and maintenance manual available that includes description of treatment, control and pumping equipment, necessary maintenance and schedule, and a troubleshooting guide for typical problems.

6. Define the intended period(s) of unattended operations.

7. The plant must retain the capability for on-site operator intervention of all treatment plant equipment and process functions.

For surface and groundwater under the direct influence water treatment plants:

It is recommended that an operator be present at the plant at all times due to the variable nature of most surface water sources in West Virginia. However, if it is desirous to obtain an exception to operate the plant without an operator present at all times, it is mandatory that the following items be installed:

1. Dual turbidimeters and recorders on combined filter effluent. If either analyzer is outside of a specified range, automatic system shutdown shall occur. The systems shall also be equipped with provision to shutdown the plant when turbidity exceeds 70% of the applicable 95th percentile value, as per the chart below (systems may self-impose more stringent shutdown limits):

Filtration Technology	95th Percentile (NTU)	Shutdown Trigger (NTU)
Conventional	0.3	0.20
Direct	0.3	0.20
Diatomaceous Earth	1.0	0.70
Slow Sand	1.0	0.70
Membrane	0.15	0.10
Other Technologies	TBD	TBD

2. Dual chlorine residual analyzers and recorders on the high service pump effluent. The system shall be equipped with provisions to shut down the entire plant if either analyzer indicates the free chlorine demand increases above a predetermined level or if the free chlorine residual drops below the pre-determined set amount needed to maintain adequate disinfection (log removal) in the treatment plant and/or an active total chlorine residual in the extremes of the distribution system of 0.20 mg/L, as required by 64CSR3.

3. An alarm system/auto-dialer to immediately alert the responsible parties in the event of a system shutdown.

It will also be mandatory the system does not operate unattended for more than 8-hours in a given 24-hour period. Unattended startup of the plant is prohibited after shutdown. All laws, rules and regulations of the Department remain in effect.

For groundwater source water treatment plants:

It is mandatory the system is equipped with continuous chlorine analyzers, recorders, and controls as in number 2 above. A system auto-dialer (number 3 above) is also required. Maximum unattended timeframes will be determined by EED on a case-by-case basis.

In addition to the proposal, the following requirements apply to all systems:

1. To be considered for an exception, the system shall have demonstrated automated operation for a minimum of 12-months continuous operation with a properly certified operator present at all times. The system should be able to run without operational problems and without any monitoring or Maximum Contaminant Level (MCL) violations during this time and thereafter. The system must submit documentation of any deviations or occurrences [during the proposed period(s) of unattended operations as defined earlier] requiring operator intervention monthly with the system Monthly Operational Report (MOR). Any reasons for plant shutdown will be submitted to EED with the MOR, and will continue this practice after approval. This documentation will be required for each intended period of unattended operations. Any operation intervention during this period must be noted, regardless of the reason for this intervention. If no interventions or shutdowns are required for any operation period, this will need to be noted on the log that is submitted with the MOR.

2. Exceptions for automated operation will normally be valid until the next scheduled sanitary survey. Any system granted this exemption will continue to submit documentation of any deviation or occurrences that result in a system shutdown or require operation intervention with its MOR. The district office personnel will review and determine that all personnel, equipment, instrumentation and systems perform as originally approved. To be eligible for renewal, the system must be in full compliance with all regulatory requirements from the time of the original or renewed exception approval. At all times, all operators must be properly certified by the EED.

3. If the Chief Operator resigns or otherwise leaves the system, the system must immediately notify the EED. The exception for automated operation becomes null and void if the district office deems it necessary. The system may reapply with a written request to the EED when operations again meet specific criteria of this memorandum necessary for the consideration of an exception issuance.

4. The EED reserves the right to revoke an exception at any time it has been determined the automated system is not fully functional, or meeting operational, monitoring, reporting and/or MCL requirements. If an exception is revoked, reinstatement of exception would require the system to reapply for an exception for

automated operation and the district office staff would have to review operational procedures to insure that the system has rectified any and all problems resulting in revocation.

References	WV 64 CSR 3, Public Water Systems WV 64 CSR 4, Public Water Systems Operators WV 64 CSR 77, Public Water Systems Design Standards
History	Replaces original memo of April 12, 1993.
Attachments	DW-36 Checklist

DW-36 Checklist

This checklist was developed to assist systems with operator exception requests for automated public water systems.

Basic Information:

1. Is this an ☐ initial ☐ renewal or ☐ reinstatement request?

2. Date Proposal Received by EED Central Office: _____
EED Staff Reviewing Checklist: _____

3. Does the PWS understand they must retain the capability for on-site operator intervention of all treatment plant equipment and process functions? ☐ Yes ☐ No

4. PWSID#: WV_____ PWS Classification: ☐ II ☐ III ☐ IV
PWS Source Water: ☐ Purchased ☐ GW ☐ GWUDI ☐ SW
Date of last sanitary survey: _____
Frequency of sanitary surveys for this system: ☐ 3 years ☐ 5 years
District Office:
☐ Beckley ☐ Kearneysville ☐ Philippi ☐ St. Albans ☐ Wheeling
DO Contact Person: _____

Proposal Information:

1. What are the critical features in the pumping and treatment facilities that will be electronically monitored and/or have alarms?

_____
_____
_____
_____

2. Was a plant flow diagram which shows the location of all critical features and automated controls provided? ☐ Yes ☐ No Comments:

_____
_____

3. Were descriptions provided for all alarm features, including set points and automatic actions? ☐ Yes ☐ No Comments:

_____
_____

4. Were the names, titles, and telephone numbers of individuals who will be notified in the event of an alarm/shutdown event provided? ☐ Yes ☐ No

5. Is an operation and maintenance manual available that includes description of treatment, control and pumping equipment, necessary maintenance and schedule, and a troubleshooting guide for typical problems? □ Yes □ No

6. What are the intended period(s) of unattended operations?

_____

_____

For GWUDI or SW sources only:

1. Are there dual turbidimeters & recorders on combined filter effluent? □ Yes □ No
   a. Do these have automatic system shutdown if either analyzer is outside of a specified range? □ Yes □ No

2. Are there dual chlorine residual analyzers and recorders on the high service pump effluent? □ Yes □ No
   a. Do these have automatic system shutdown if either analyzer is outside of a specified range? □ Yes □ No

3. Does an alarm system/autodialer immediately alert the responsible parties in the event of a system shutdown? □ Yes □ No

4. Does the system understand they may not operate unattended for more than 8 hours in a given 24 hour period? □ Yes □ No

For GW sources only:

1. Are there dual chlorine residual analyzers and recorders on the high service pump effluent? □ Yes □ No
   a. Do these have automatic system shutdown if either analyzer is outside of a specified range? □ Yes □ No

2. Does an alarm system/autodialer immediately alert the responsible parties in the event of a system shutdown? □ Yes □ No

3. What is the maximum unattended timeframe determined by EED? _____

Demonstration Information:

1. Did the PWS demonstrate automated operation for a minimum of 12-months continuous operation with a properly certified operator present at all times? □ Yes □ No

2. Were there operational problems during this time? □ Yes □ No

If yes, describe:

3. Were there any monitoring or MCL violations during this time? ☐ Yes ☐ No
If yes, describe:

4. Did the system submit the following required documentation for unattended operations with their MOR:
   a. Any deviations or occurrences requiring operator intervention? ☐ Yes ☐ No
   b. Any reason(s) for plant shutdown? ☐ Yes ☐ No

Note: If no intervention or shutdown occurs during a period of unattended operation, it must still be noted in MOR.

Recommendation Information:

The following EED staff recommend ☐ approval or ☐ denial of the issuance of an operator exception for an automated public water system on the date noted:

DO Name Printed	Signature	Date

EED Name Printed	Signature	Date

Renewal Information:

1. Did the DO Contact Person review and determine all personnel, equipment, instrumentation and systems perform as originally approved? ☐ Yes ☐ No

2. Is the PWS in full compliance with all regulatory requirements from the time of the original exception? ☐ Yes ☐ No Attach any needed comments.

The following EED staff recommend ☐ approval or ☐ denial of the renewal of an operator exception for an automated public water system on the date noted:

DO Name Printed	Signature	Date

EED Name Printed	Signature	Date

Revocation/Reinstatement Information:

1. Does EED staff recommend revocation of an exception based on determination the automated system is not fully functional, or meeting operational, monitoring, reporting and/or MCL requirements? ☐ Yes ☐ No

2. Does EED staff recommend reinstatement of a revoked exception based on the system reapplication for an exception for automated operation and the district office staff review of operational procedures to insure that the system has rectified any and all problems resulting in revocation? ☐ Yes ☐ No

DO Name Printed	Signature	Date

EED Name Printed	Signature	Date

PLEASE COMPLETE FORM THOROUGHLY &
INCLUDE ANY SUPPORTING INFORMATION WITHIN OR ATTACHED

SUBMIT TO:

Office of Environmental Health Services
Environmental Engineering Division
ATTN: Certification & Training Program Manager
350 Capital Street Room 313
Charleston, WV 25301
Phone: (304) 558-2981
Fax: (304) 558-4322

Raco Mfg. & Engineering Co., Inc
1400 62nd St
Emeryville,CA,94608,US
Phone: 510-658-6713
Fax: 510-658-3153
Toll-free: 800-722-6999
Email: sales@racoman.com
Website: http://www.racoman.com

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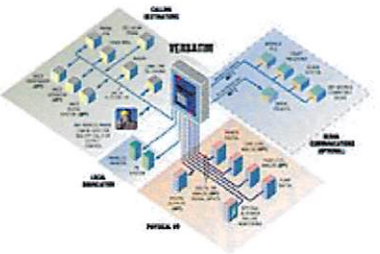

Results 1 - 5 of 5

Model Number	Digital Alarm Inputs	Optional Analog Alarm Inputs	Optional Digital Outputs	Optional PLC Addresses	PLC Protocols	Phone Numbers Dialed	Battery Backup Time	Warranty	List Price
300VSS-4C	4	1 4 8 16	4 8	32 64 96	DF1 & Modbus connection via RS-232 [optional]	16	20 hours	5 years	$2,095.00
301VSS-8C	8	1 4 8 16	4 8	32 64 96	DF1 & Modbus connection via RS-232 [optional]	16	20 hours	5 years	$2,350.00
302VSS-16C	16	1 4 8 16	4 8	32 64 96	DF1 & Modbus connection via RS-232 [optional]	16	20 hours	5 years	$3,250.00
303VSS-24C	24	1 4 8 16	4 8	32 64 96	DF1 & Modbus connection via RS-232 [optional]	16	20 hours	5 years	$3,895.00

304VSS-32C	32	1 4 8 16	4 8	32 64 96	DF1 & Modbus connection via RS-232 [optional]	16	20 hours	5 years	$4,650.00

Results 1 - 5 of 5

ALLIED CONTROL SERVICES, INC.

611 GARFIELD AVE. • P.O. BOX 234 • WEST POINT, PA 19486
Phone: 215-699-2855
Fax: 215-699-9030

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January 20, 2017

Mr. Kevin Anderson
Pennsylvania DEP
400 Market Street
10th Floor RCSOB
Harrisburg, PA 17105

Reference: Surface Water Treatment Plant Effluent Monitor/Alarming and Shut Down System

Dear Kevin,

Per your request, we offer the following proposal for the new SWTP Combined Filter Effluent Monitoring and Alarming System with SWTP shut down. The system includes costs for the monitor/controller and alarm dial-out system. It is assumed that the existing SWTP will have the required chlorine residual analyzer, turbidity analyzer and clear-well level transmitter. An estimated cost for the equipment installation is provided.

The controller/monitor will include adjustable alarm set-points with time delay for a relay output which can be wired to the plant for shut down of the filter system upon the following conditions:

High or Low Clear Well Level
High or Low CFE Chlorine Residual
High or Low CFE Turbidity

The monitor/controller can be configured to send a pre-shut down warning to allow operators the opportunity to go to the plant to try to resolve the problem before reaching the shut-down set-point. If the process value reaches the shut-down set-point, the filter plant shut-down command will occur and a shut-down alarm message will be sent to the plant operator by text message, email or voice message.

If the facility already has an alarm dialer with capacity for three additional alarm inputs, the alarm dialer can be eliminated from the package. A deduct is shown for this on each equipment option.

Option A – Monitor/Alarm System with Standard Dialup Phone Line and Phonetics Alarm Dialer

Item	Qty	Description
1	1	ACS PlantGuard Controller with analog inputs for the following: *CFE Chlorine Residual *CFE Turbidity *Clear Well Level
2	1	Phonetics 8-channel alarm auto-dialer with power supply and battery backup. Requires standard dial-up telephone line connected to alarm dialer. Provides voice message alarm only.

3	1	System Wiring Diagram – custom wiring diagram for specific analyzer types in use at Owners site. Exact terminal numbers will be provided based on Owners equipment to allow installation by local electrical contractor.
4	-	Furnish onsite calibration, programming and alarm configuration for all equipment and provide full onsite testing for all equipment including alarm testing and dial-out for plant designated phone numbers and/or pager numbers.
5	-	Provide onsite operator training on maintenance and standardization of above equipment.
6	4	O&M Manuals with complete Instruction Manuals for the above system.

Total System Price: $8,860.00
Delivery: 2-3 Weeks ARO

Estimated Installation Cost: $2,000.00
Deduct for use of Owner Furnished Alarm Dialer: ($1,400.00)

Option B – Monitor/Alarm System with Standard Dialup Phone Line and RACO Alarm Dialer

Item	Qty	Description
1	1	ACS PlantGuard Controller with analog inputs for the following: *CFE Chlorine Residual *CFE Turbidity *Clear Well Level
2	1	RACO 8-channel alarm auto-dialer with power supply and battery backup. Requires standard dial-up telephone line connected to alarm dialer. Provides voice message alarm only.
3	1	System Wiring Diagram – custom wiring diagram for specific analyzer types in use at Owners site. Exact terminal numbers will be provided based on Owners equipment to allow installation by local electrical contractor.
4	-	Furnish onsite calibration, programming and alarm configuration for all equipment and provide full onsite testing for all equipment including alarm testing and dial-out for plant designated phone numbers and/or pager numbers.
5	-	Provide onsite operator training on maintenance and standardization of above equipment.
6	4	O&M Manuals with complete Instruction Manuals for the above system.

Total System Price: $9,980.00
Delivery: 2-3 Weeks ARO

Estimated Installation Cost: $2,000.00
Deduct for use of Owner Furnished Alarm Dialer: ($2,500.00)

Option C – Monitor/Alarm System with Cellular Alarm Dialer

Item	Qty	Description
1	1	ACS PlantGuard Controller with analog inputs for the following: *CFE Chlorine Residual *CFE Turbidity *Clear Well Level
2	1	ACS cellular alarm notification system with 8-channel alarm input with power supply and battery backup. No dial-up telephone line is required. Provides text and email alarm notification.
3	1	System Wiring Diagram – custom wiring diagram for specific analyzer types in use at Owners site. Exact terminal numbers will be provided based on Owners equipment to allow installation by local electrical contractor.
4	-	Furnish onsite calibration, programming and alarm configuration for all equipment and provide full onsite testing for all equipment including alarm testing and dial-out for plant designated phone numbers and/or pager numbers.
5	-	Provide onsite operator training on maintenance and standardization of above equipment.
6	4	O&M Manuals with complete Instruction Manuals for the above system.

Total System Price: $9,700.00
Delivery: 2-3 Weeks ARO

Estimated Installation Cost: $2,000.00

Please give me a call at 1-800-441-4844 if you have any questions.

Sincerely,

Paul C. Mamzic
President

PCM/

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	Product #	Product Name	Quantity	USD Unit Price	Total Price	Availability ?	
	LXV404.99.51532	SC200 Universal Controller 100-240 V AC (North America power cord) with one digital sensor input, one analog flow sensor input, MODBUS RS232 & RS485 and two 4-20mA outputs	Update	$2,596.00	$2,596.00	Ships within 1 week	
	LZY807.97.00002	Maintenance Kit for TU5300 sc and TU5400 sc Laser Turbidimeter	Update	$1,100.00	$1,100.00	Call for ship date	
	LZY876	Desiccant Cartridge for TU5300 sc and TU5400 sc Laser Turbidimeter	Update	$16.64	$16.64	Available	
	LXV445.99.23212	TU5400 sc Ultra-High Precision Low Range Laser Turbidimeter with Flow Sensor, RFID, and System Check, EPA Version	Update	$6,142.00	$6,142.00	Available	
	2843100	Chart Recorder Paper -- 7-DAY 0-100 PK/100	Update	$59.85	$59.85	Available	
	2842900	Chart Recorder, 10" Round Dual Pen	Update	$1,657.00	$1,657.00	Call for ship date	
	2843200	Chart Recorder Green Replacement Pens,	Update	$78.45	$78.45	Available	
				Subtotal	$11,649.94		

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Remove All Items

	Product #	Product Name	Quantity	USD Unit Price	Total Price	Availability ?	
	2978100	1720E Turbidimeter with sc200 Controller, 1 Channel	Update	$2,881.00	$2,881.00	Call for ship date	
	2660153	Stabical® Turbidity Standard, 20.0 NTU, Bottle (1 L)	Update	$139.00	$556.00	Ships within 3 days	
	4415300	1720 Series Calibration Cylinder, 1 L	Update	$88.69	$88.69	Available	
	1895000	Lamp Assembly for 1720D and 1720E Low-range Turbidimeters	Update	$62.00	$62.00	Available	
	2842900	Chart Recorder, 10" Round Dual Pen	Update	$1,657.00	$1,657.00	Call for ship date	
	2843100	Chart Recorder Paper -- 7-DAY 0-100 PK/100	Update	$59.85	$59.85	Available	
	2843200	Chart Recorder Green Replacement Pens,	Update	$78.45	$78.45	Available	
				Subtotal	$5,382.99		

Shipping & Transportation Policy | Returns Policy | Hach Warranty | More Policies

Terms and Conditions

Taxes and shipment charges are not included on the subtotal shown in this page. Shipping charges will be included on the checkout and order summary pages. You will be charged state taxes for your state. Taxes are determined prior to shipment and stated in your invoice.

Prices are in U.S. currency and are FOB USA Factory. Shipping and related transportation fees are for the account of the purchaser. Prices shown on this site are for orders and products to be used in the 50 United States. Export orders are not allowed. Hach maintains a network of international distributors offering sales and support services. Distributor pricing will vary due to shipping, duties, and other import costs. See Standard Terms and Conditions of Sale for complete information.

Hazardous Items

Items with this mark may be considered hazardous under some shipping conditions. If necessary, we will change your selected shipping method to accommodate these items.

Obsolete Items

Items with this mark may be obsolete or unavailable through eCommerce. Please contact Hach customer service for further assistance.

CHAT NOW