MAXIMIZING FILTRATION CAPACITY FOR PRODUCTION OF TERTIARY RECYCLED WATER

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Abstract

This paper summarizes the final report of a WRF-supported, five-year, collaborative project to investigate conditions under which granular media filtration capacity may be increased significantly while maintaining or possibly improving filter effluent quality. Several full-scale recycled water production facilities in California participated in a series of experiments in which filter loading rate and coagulant dose were varied while effluent characteristics were continuously monitored and disinfectability of the effluent was assessed using grab samples.

The project began with a pilot phase at the Monterey Regional Water Pollution Control Agency (MRWPCA), in which five different filter loading rates were simultaneously tested in laboratory columns, holding coagulant dose and other variables constant. This effort established filter performance variation with loading rate, and was roughly consistent with clean bed filtration theory. In general, increasing filtration rate caused degradation of filter effluent quality. Next, coagulant dose was increased for the higher filter loading rate (at 7.5 gpm per sq ft) compared with the coagulant dose at the standard 5 gpm per sq ft filter loading rate. The result was that there was no statistically significant effluent quality difference at the two filter loading rates—as indicated by results of turbidity, particle counts at two ranges, virus inactivation, and the ability to adequately disinfect the filter effluent. In fact virus removal was superior at the higher loading rate, presumably due to the higher coagulant dose associated with the higher loading rate.

Based on the pilot testing results, California regulatory agencies granted approval for full-scale tertiary filter loading rate testing of at the following participating recycled water production facilities: MRWPCA, the City of Santa Rosa's Laguna Treatment Plant, the San José/Santa Clara Water Pollution Control Plant, and the Delta Diablo Sanitary District. Recently, the California Department of Public Health concurred with the findings from full-scale testing at MRWPCA—confirming pilot testing results—and granted a permanent waiver from the 5 gpm per sq ft.

Introduction

Additional filtration capacity is needed during the high-demand summer months, wherever recycled water is used primarily or entirely for irrigation. Providing this additional capacity only for a short period of time is extremely costly when the same objective can be achieved with an increase in filtration rate across the same existing filtration infrastructure. Based on this rationale, the regulatory agencies were approached and they agreed to consider the idea if it could be shown that an equivalent water quality could be produced at the higher filter loading rate.

California is the only state to specify a maximum filter loading rate for water recycling, at 5 gpm/ft^2. Other states set limits on filter loading rates for drinking water and wastewater treatment. Appropriate loading rate guidelines, based on rigorous science, do not exist for granular-media tertiary filtration treatment plants. A recent pilot-scale study provided a historical review of filter loading rate studies in water and wastewater treatment, and identified the need for a full-scale filter loading rate study for water recycling (Williams et al., 2007). In this pilot study, the impact of loading rate on granular media filtration of wastewater was determined using a pilot-scale filtration plant. With all other factors kept equal, higher loading rate led to a decrease in filter performance, but by optimizing the coagulant dose specific to the loading rate, equivalent performance could be achieved at loading rates of 5.0 and 7.5 gpm/ft^2. The results from the pilot-scale study motivated filter loading rate studies at two full-scale water recycling facilities.

Additional research objectives were to: (1) determine what (if any) pretreatment changes are necessary to achieve equivalent performance at loading rates of 5 and 7.5 gpm/ft^2 for each treatment facility; (2) determine the impact of loading rate on production capacity and backwashing requirements for each plant; and (3) identify potential design factors at different treatment plants that influence the degree to which filter loading rate affects filter performance.

Experimental Methods

Tertiary filters at water recycling facilities were operated at a constant loading rate of either 5 or 7.5 gpm/ft^2 for the duration a filter run—defined as the operational time between two sequential backwashings. Filters were operated according to protocols specific to each treatment facility. The test loading rate alternated between filter runs, to avoid bias due to variations in filter influent water quality over time. Both loading rates were tested an equal number of times for a given plant. In addition, the start times of filters were varied, to ensure that filters were in operation at all times throughout a day.

Description of Recycling Facilities

Loading rate experiments were conducted using full-scale filters at recycling facilities at Monterey and San Jose, both in California.

Monterey

The Monterey Regional Water Pollution Control Agency's (MRWPCA) Regional Treatment Plant located in Marina, CA, hereafter referred to as Monterey, treats a wastewater stream with an average dry weather flow of 29.6 MGD with a peak flow of 38.5 MGD. The wastewater treatment train includes enhanced primary settling (coagulated), followed by trickling filters, bioflocculation (i.e. solids contact), and secondary clarification. Monterey experiences a strong diurnal cycle in plant flow and water quality.

Chlorine gas is added to the filter effluent (average dose 12.9 mg-Cl_2/L), and because Monterey does not nitrify the secondary effluent, the free chlorine is rapidly converted to chloramines. Two parallel chlorine contact basins provide at least 120 min contact time depending on the flow rate. The tertiary effluent is stored in a holding pond before entering the irrigation distribution system for 12,000 acres of edible crops.

San Jose

The San Jose/Santa Clara Water Pollution Control Plant in San Jose, hereafter referred to as "San Jose", treats an average dry weather flow of 158 MGD with a peak flow of 223 MGD. The wastewater flow process includes primary sedimentation, followed by activated sludge with biological nutrient removal (nitrification and denitrification) and secondary clarification. Because primary effluent flow equalization basins are used, the secondary effluent flow rate and water quality were relatively constant throughout the day. During this study, secondary effluent flowed directly from the secondary clarifiers to the tertiary filters without pretreatment. San Jose has the ability to add alum coagulant prior to filtration, but this is only done when the secondary effluent exceeds 4.5 NTU. No coagulant addition occurred during the course of this study.

San Jose used sequential chlorination (a combination of chloramine and free-chlorine disinfection). Chlorine gas (4 mg-Cl_2/L) and ammonium hydroxide (3 mg-NH_3/L) were added to form chloramines for disinfection through a serpentine contact basin with approximately 90 min contact. Additional chlorine gas (8-10 mg-Cl_2/L) was then added to reach breakpoint chlorination and the tertiary effluent flows through a diversion pipe providing a minimum of 90 min addition contact.

Meeting Regulatory Requirements

The Monterey facility was required to obtain an exception from the state of California's Water Recycling Criteria limit of 5 gal/ft^2-min to participate in the study. An engineering report was prepared that thoroughly described all treatment processes and capacities, and upon acceptance by California Department of Public Health (CDPH), a temporary waiver was requested from the Central Coast Regional Water Quality Control Board. The Monterey's waiver allowed for twelve months of testing under increased effluent water quality limitations, while also meeting all other requirements in the Water Recycling Criteria. San Jose was able to by-pass this regulatory process by performing testing on bay discharge filters, which are identical to the recycling filters, except that they are not subject to the Water Recycling Criteria.

Other California treatment plants, including the Delta Diablo Sanitation District (Anitoch), the Laguna Treatment Plant (Santa Rosa), and the Los Angeles County Sanitation District's San Jose Creek East and West Plants (Whittier), also prepared engineering reports and received authorization from CDPH to participate, but due to various circumstances, were unable to perform or complete their testing before the conclusion of this study.

Filter Performance Metrics

Filter performance was continuously measured using online turbidimeters and particle counters located at the filter influent and effluent of each test filter. Monterey also continuously monitored turbidity and particle counts in the secondary effluent prior to coagulation. Particle counts were collected in the 2-3, 3-4, 4-5, 5-7, 7-10, and 10-15 µm size ranges. Data were also collected for particles in 15-20 and > 20 µm size ranges. However, these data were of limited utility, because the instrument calibration range is only from 2-15 µm. To simplify the analysis, particle count data were grouped into 2-5 and 5-15 µm size ranges; these ranges include the characteristic sizes of C*ryptosporidium* oocyts and G*iardia* cysts, respectively.

Due to limitations in the maximum particle counter capacity (16,000 particles > 2 µm per mL) a dilution system (previously described in Williams et al. 2007) was required for both the secondary effluent and filter influent particle counters at Monterey. Head loss, coagulant dose, and filter loading rate were also continuously monitored. All continuously monitored data were recorded once per minute.

Disinfection Assessments and Microbial Analyses

Bench scale disinfection experiments were conducted onsite at both treatment facilities (once per run at Monterey, and three times per run at San Jose) to determine if increasing the loading rate interfered with the ability to disinfect bacteria in the filter effluent. The bench-scale disinfection mimicked the full-scale process at each plant. For Monterey, sodium hypochlorite was added to filter effluent samples to produce an approximate 10 mg-Cl_2/L residual at 120 min detention time (since there was already a high concentration of ammonia, chlorine was present as combined chlorine). At San Jose, sodium hypochlorite and ammonia were simultaneously added to produce chloramines for 90 min (average residual of 1.5 mg-Cl_2/L combined chlorine), followed by addition of 8-10 mg-Cl_2/L to achieve breakpoint chlorination and additional disinfection with free-chlorine (average residual of 4.7 mg-Cl_2/L combined chlorine; 3.5 mg-Cl_2/L free-chlorine). Samples were continuously mixed for the entire duration of each experiment.

One virus disinfection test was performed per loading rate at each treatment plant. The procedure was the same for both plants; filter effluent samples were shipped overnight on ice to the University of California Berkeley for analysis. The filter effluent samples were spiked with MS2 coliphage ($2x10^7$ PFU/mL target concentration) and divided into 50-mL aliquots. Three different chlorine doses were applied, resulting in 90-min chlorine residuals of 5, 13.3, and 27 mg-Cl_2/L (chlorine demand was determined prior to starting experiment). For Monterey, three additional aliquots were chlorinated to breakpoint to determine inactivation of phage by free-chlorine (no ammonia was added to San Jose samples, so all chlorine residuals were as free chlorine). Samples were then dechlorinated using sodium thiosulfate and F^+ male specific coliphage concentrations were quantified using double-layer agar method (Adams 1959) using media with antibiotics (streptomycin and ampicillin) and antibiotic-resistant host *E. coli* (ATCC 700891) to prevent host contamination on the plates.

Filter Testing Configurations

Different filter testing configurations were used in San Jose and Monterey. At San Jose, simultaneous testing of loading rates was possible, in which two test filters were utilized such that at any given time during the testing (unless a filter was being backwashed) the full-scale tertiary flow was treated at both 12.2 and 18.3 m/h. The loading rate tested on an individual filter was switched each run (with the same number of filter runs per rate on both filters) to avoid any bias due to slight differences between filters and equipment.

Because Monterey required a coagulant dose specific to the loading rate to achieve equivalent filter performance and only one coagulant dose could be used for all filter influents at any one time, simultaneous testing was not possible. Instead, Monterey used one test filter and the test-loading rate alternated each filter run to minimize temporal differences in influent water quality. Turbidity and particle count monitoring of the secondary effluent was monitored for both loading rates, and because the filter influent water quality was statistically equivalent for both loading rates at Monterey, the results for the two testing figurations used in this study are directly comparable. In addition, the following two coagulation optimization strategies were used at Monterey: (Condition A) producing the same average effluent turbidity at both rates, and (Condition B) producing a lower effluent turbidity at the 7.5 gpm/ft^2 filter loading rate. Unless otherwise specified, the results presented for Monterey were collected under Condition B.

Statistical analysis

The mean value for each parameter was determined for each filter run, and then the overall mean and statistics for each rate were determined from the filter run values. Results from both loading rates were compared using two-sample hypothesis testing. All data (except disinfection results) approximated a normal distribution and values are reported at *mean ± 95% confidence level*. Enough filter runs were conducted at each facility such that the least significant difference (LSD) between loading rates met the definition of significance as agreed upon with CDPH for filter effluent turbidity, 2-5 µm particles, and 5-15 µm particles[1]. The resulting LSD was defined as 12 and 15% for these parameters at Monterey and San Jose, respectively.

Results

Comparison of Water Quality at Monterey and San Jose

At each treatment plant, the average secondary effluent quality was not significantly different for the two loading rates. Coagulation of the Monterey secondary effluent consistently increased filter influent turbidity by approximately 3 NTU (more with higher coagulant doses), but decreased the total particle counts (> 2 µm) and shifted the particle size distribution towards larger particles (Table **3**1 and Figure **1**1).

[1] See CDPH Equivalency Criteria in Chapter 1

Table 1 – Particle Removal Metrics at San Jose

Loading Rate (m/h)	Turbidity (NTU)		Particles 2-5 μm (mL^{-1})		Particles 5-15 μm (mL^{-1})	
	Secondary/ Filter Influent	*Filter Effluent*	*Secondary/ Filter Influent*	*Filter Effluent*	*Secondary/ Filter Influent*	*Filter Effluent*
12.2	1.65 ± 0.21	0.72 ± 0.03	4400 ± 300	1890 ± 270	1650 ± 200	396 ± 56
18.3	1.70 ± 0.25	0.76 ± 0.03	4300 ± 300	1940 ± 220	1600 ± 140	440 ± 48
% difference	2.9%	5.4%	-1.4%	3.1%	-3.3%	11%

Table 2 – Particle Removal Metrics at Monterey (Condition A) during period when coagulant dose was optimized to produce the same filter effluent at both loading rate (1.6 NTU)

Loading Rate (m/h)	Turbidity (NTU)		Particles 2-5 μm (mL^{-1})		Particles 5-15 μm (mL^{-1})	
	Secondary	*Filter Effluent*	*Secondary*	*Filter Effluent*	*Secondary*	*Filter Effluent*
12.2	3.44 ± 0.40	1.60 ± 0.07	13500 ± 1400	1400 ± 220	6160 ± 730	222 ± 25
18.3	3.25 ± 0.53	1.64 ± 0.12	12000 ± 1500	1610 ± 320	5800 ± 1370	339 ± 34
% difference	-5.7%	2.6%	-11%	15%	-5.6%	53%*

Table 3 – Particle Removal Metrics at Monterey (Condition B) during period when coagulant dose was optimized such that filter effluent turbidity was 0.4 NTU lower at the 18.3 m/h rate

Loading Rate (m/h)	Turbidity (NTU)			Particles 2-5 μm (mL^{-1})			Particles 5-15 μm (mL^{-1})		
	Secondary	*Filter Influent*	*Filter Effluent*	*Secondary*	*Filter Influent*	*Filter Effluent*	*Secondary*	*Filter Influent*	*Filter Effluent*
12.2	4.05 ± 0.22	7.00 ± 0.39	1.78 ± 0.05	13700 ± 1200	8900 ± 1100	1170 ± 130	4990 ± 540	4960 ± 450	239 ± 20
18.3	4.00 ± 0.30	7.41 ± 0.43	1.38 ± 0.06	14400 ± 1200	11000 ± 1600	950 ± 100	5230 ± 560	4700 ± 400	239 ± 26
% difference	-1.2%	6.0%	-22%*	4.6%	24%*	-19%*	4.7%	-5.3%	0%

*Significant difference ($\alpha = 0.05$)

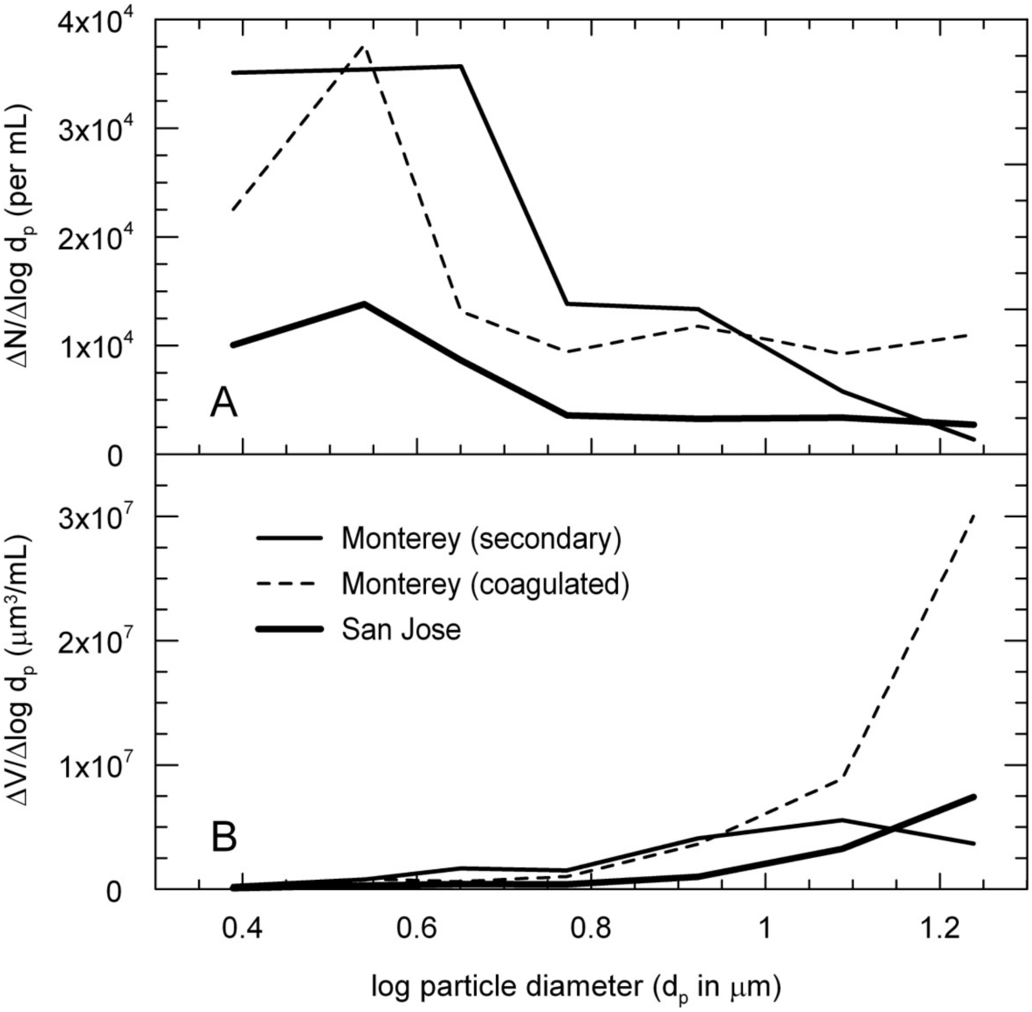

Figure 1 – Average filter influent particle size distributions by (A) number of particles, and (B) volume of Monterey (Condition B) and San Jose.

Filter operation at higher loading rates

There were several significant operational differences between the two loading rates at both plants (Tables 2 and 3). San Jose did not add any coagulant during the filter testing at either rate, whereas Monterey added 51% more coagulant when operating their filters at 7.5 gpm/ft^2 than at 5 gpm/ft^2. A higher loading rate always has greater head loss due to the increase shear through the filter; thus higher clean bed head losses were observed at the 7.5 gpm/ft^2 filter loading rate at both plants (Table 4). As a result, the volume of water treated per filter run was reduced at both plants (20 and 13% reductions at Monterey and San Jose, respectively; Table 5). After accounting for the increased backwash frequency (due to the shorter run time) and the reduced production per filter run, there was still a significant net increase in daily recycled water production when operating at 7.5 gpm/ft^2 than at 5 gpm/ft^2 (39 and 48% for Monterey and San Jose, respectively). The clean bed head loss was monitored in all test filters over the course of the study. No significant changes in clean bed head loss were detected, so no changes to the backwash procedure were made for the higher loading rate.

Table 4 – Summary of clean bed and terminal head loss through filters

Treatment Plant	Loading Rate (m/h)	Clean Bed Head Loss (cm)	Clean Bed Head Loss (cm)
San Jose	12.3 + 0.0	46.1 ± 3.7	310 ± 10
	18.4 + 0.0	98.2 ± 6.0	317 ± 11
Monterey	12.2 ± 0.0	35.4 ± 0.3	326 ± 16
	18.3 ± 0.0	61.8 ± 0.6	351 ± 6

Table 5 – Summary of coagulant usage and filter production

Treatment Plant	Loading Rate (m/h)	Coagulant Dose (mg/L)	Run Time (h)	Run Production (m^3/m^2-run)	Daily Production (m^3/m^2-day)
San Jose	12.3 + 0.0	0	24.8 ± 2.6	305 ± 32	286 ± 1
	18.4 + 0.0	0	14.4 ± 1.3	266 ± 23	422 ± 2
Monterey	12.2 ± 0.0	5.1 ± 0.6	22.7 ± 0.8	276 ± 9	252 ± 1
	18.3 ± 0.0	7.7 ± 0.8	12.0 ± 0.6	220 ± 11	352 ± 4

Filter performance and higher loading rates

Particle removal through filtration was quite different at the San Jose and Monterey treatment plants (**Figure** 2 and **Table 6**). The San Jose filter influent already met the turbidity standard, no removal was necessary from a regulatory prospective. Therefore, no coagulant was added and particle removal was lower than at Monterey due to the significantly higher particle load in the filter influent, greater particle removal was needed through the Monterey filters to meet the 2 NTU effluent turbidity requirement and thus coagulation prior to filtration was required. Filter effluent turbidities were higher at Monterey, but interestingly the particle counts were actually lower for the majority of the time (except for 5-15 μm particles at the end of the run; e.g., see **Figure 3**3).

At both plants, filter performance through the filter run exhibited typical filter behavior with a filter ripening, followed by a steady state performance for both loading rates (**Figure 3**3). On average, the filter effluent water quality remained constant for the duration of each filter run at San Jose. At Monterey, the turbidity remained relatively constant throughout the steady-state period, but the particle counts gradually increased. This increase was most visible in the 5-15 μm particles, where midway through the run the rate of particle increase seemed to accelerate and the particle concentration increased three-fold over the course of a typical run at Monterey (Figure **3**3C). This apparent breakthrough of larger particles was not captured by the turbidity measurements. Further, this apparent breakthrough of 5-15 μm particles occurred at a lower throughput volume for the 18.3 m/h rate. In general, however, the overall pattern of a typical filter run was the same for both loading rates.

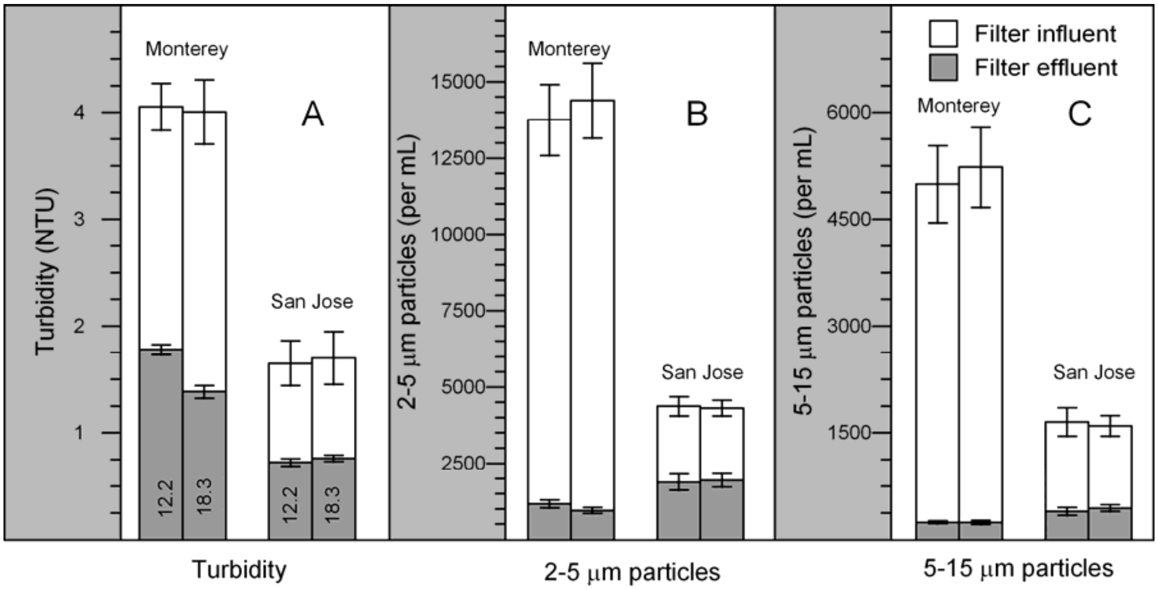

Figure 2 – Secondary effluent and filter effluent turbidities and particle counts from full-scale testing at Monterey and San Jose. Loading rates (m/h) indicated on bar. Error bars are 95% confidence interval.

Table 6 – Removal fractions of particle indicators for different treatment plants.

Treatment Plant	Loading Rate (m/h)	Turbidity (NTU)	2-5 μm particles (per mL)	5-15 μm particles (per mL)
San Jose	12.2	0.563 ± 0.056	0.568 ± 0.051	0.760 ± 0.056
	18.3	0.553 ± 0.064	0.548 ± 0.039	0.724 ± 0.064
	Difference	*-0.010 ± 0.083*	*-0.020 ± 0.062*	*-0.036 ± 0.083*
Monterey (Condition A)	12.2	0.535 ± 0.048	0.896 ± 0.016	0.964 ± 0.005
	18.3	0.494 ± 0.074	0.866 ± 0.026	0.942 ± 0.012
	Difference	*-0.041 ± 0.081*	*-0.030 ± 0.028*	*-0.022 ± 0.012*
Monterey (Condition B)	12.2	0.561 ± 0.026	0.915 ± 0.012	0.952 ± 0.006
	18.3	0.654 ± 0.029	0.934 ± 0.009	0.954 ± 0.007
	Difference	*0.093 ± 0.039*	*0.019 ± 0.014*	*0.002 ± 0.009*

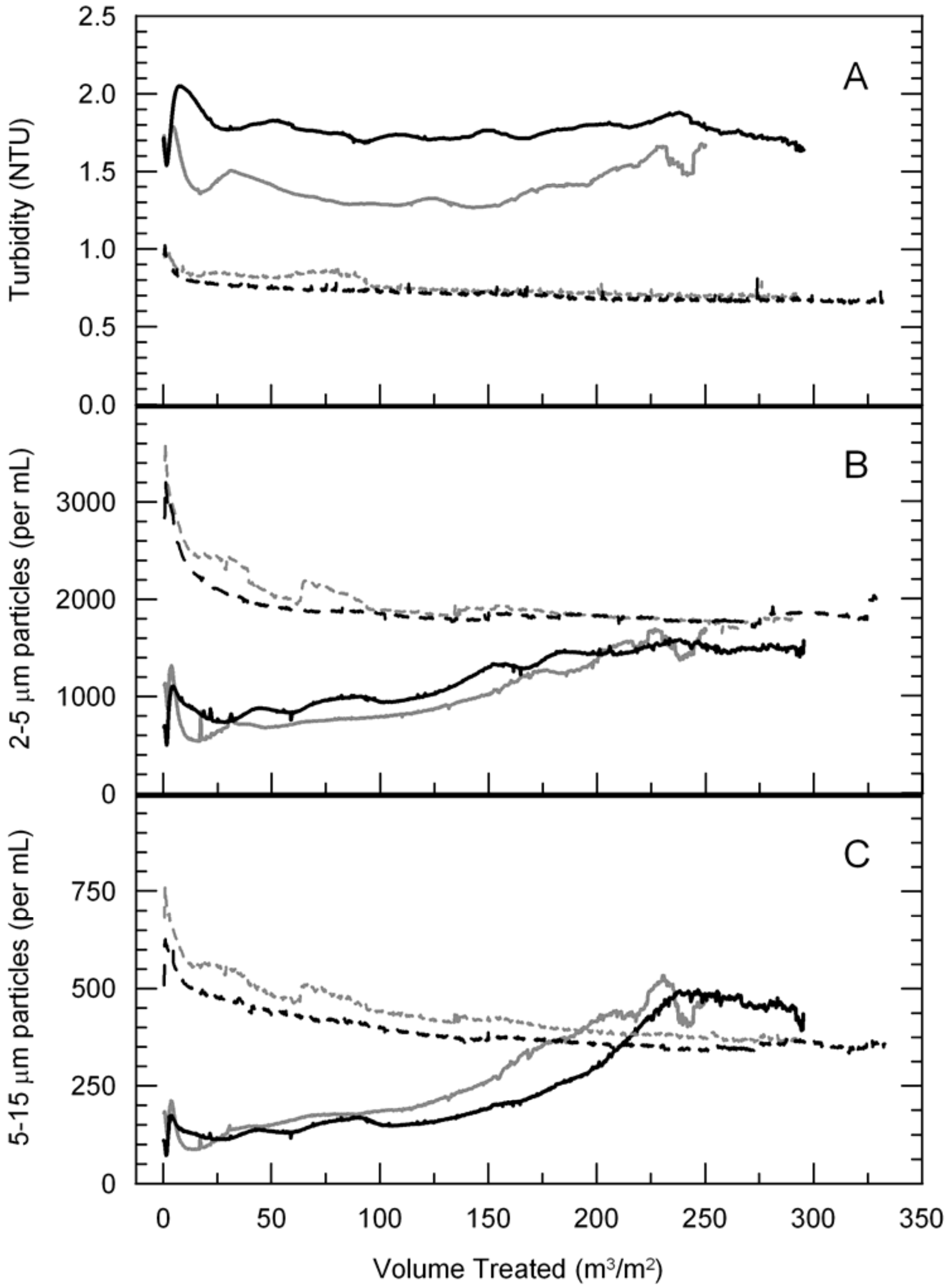

Figure 3 – The average filter effluent water quality across all filter runs as a function of the volume of water treated as measured by (A) turbidity, (B) 2-5 μm particles, and (C) 5-15 μm particles. Solid lines represent data from Monterey; dashed lines are San Jose Data. Black lines are for data while operating at 12.2 m/h, while gray lines are at 18.3 m/h operation.

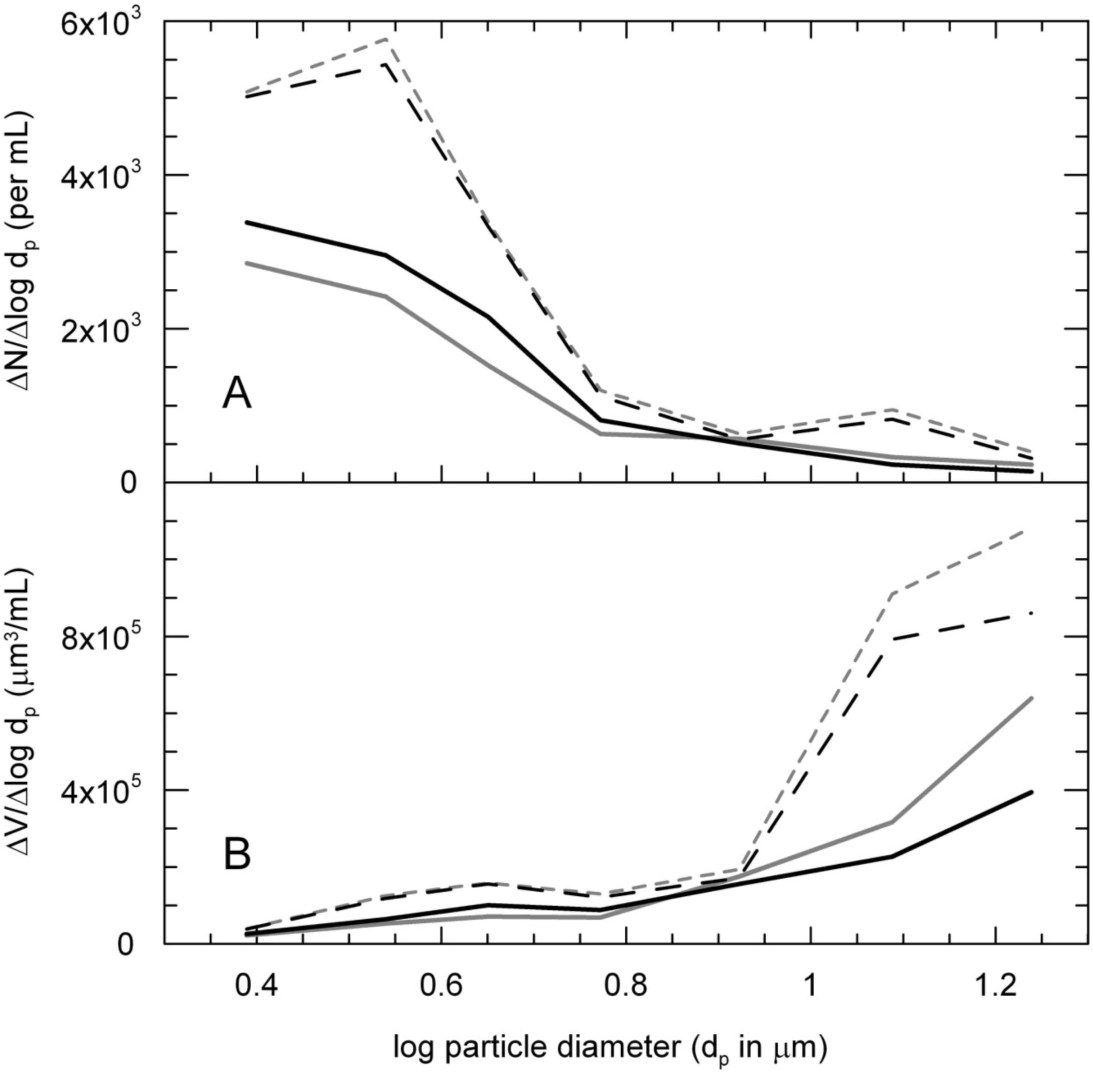

Figure 4 – Average filter effluent particle size distribution by (A) number of particles, and (B) volume of particles for San Jose (dashed) and Monterey (solid) for loading rates of 12.2 and 18.3 m/h (black and grey lines, respectively)

Disinfection of filter effluent

No differences in disinfection ability were detected between loading rates of 7.5 gpm/ft^2 and at 5 gpm/ft^2 at either plant. Two virus disinfection experiments were conducted for each treatment plant (one at each rate). Several chlorine doses were applied to filter effluent samples, and inactivation of seeded MS2 coliphage was measured after 90 min of contact time, as shown in Figure 5. For San Jose, with free chlorine, no plaques formed for any of the disinfected samples at either rate, a reduction of greater than 6.5 log (PFU/mL), even at the lowest C*T tested (450 mg/L-min). Monterey, on the other hand, with chloramines, the inactivation rate of MS2 was much slower. Regardless, the dose-inactivation curves at Monterey for water treated at both loading rates were similar and not statistically different (a = 0.05). A fourth chlorine dose was selected to achieve breakpoint chlorination and disinfect with free chlorine, where inactivation of coliphage (greater than 7 logs) was observed. The chlorine dose required to achieve breakpoint chlorination was extremely high (~270 mg Cl/L), making this practice infeasible for the full-scale treatment plant.

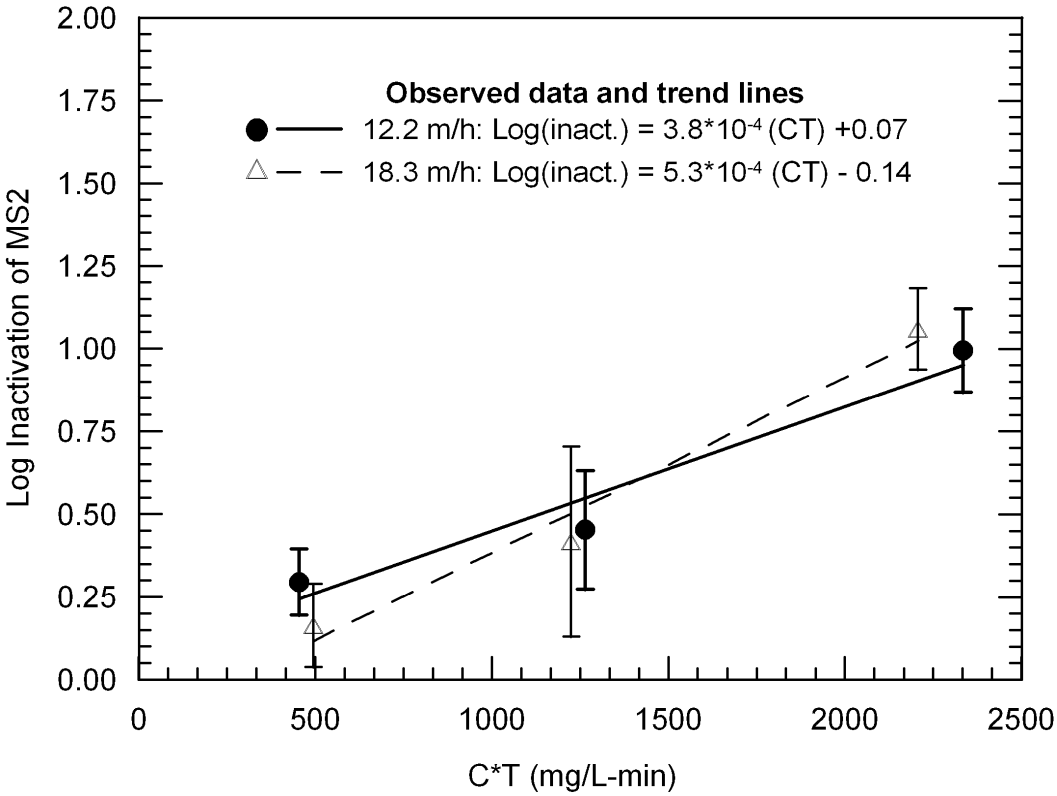

Figure5 – Observed chloramine disinfection of MS2 spiked into Monterey filter effluent treated at 12.2 and 18.3 m/h. Curves represent best-fit linear regression lines with equations specified on plot.

Implications of Study

The results from this study indicate that comparable filter performance can be achieved while operating at loading rates of 7.5 gpm/ft^2 and at 5 gpm/ft^2. For the San Jose plant, no changes in operation were required, while the Monterey required a lower target filter effluent turbidity (0.4 NTU lower) for the higher rate, which resulted in significantly more coagulation usage (51% increase). The results from this study can be used by municipalities to begin dialog with CDPH about operating at loading rates above the specified 5 gpm/ft^2 limit in the California Water Recycling Criteria. In deciding on the maximum loading rate, treatment facilities must consider the amount of particle removal through the filter and use of coagulation pretreatment, as these two factors are believed to have significant influence on the effect of filter loading rate.

References

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