Pilot-scale assessment of the impacts of transient particulate water quality events on the UV disinfection of indigenous total coliform bacteria in drinking water treatment

Michael R. Templeton, Raymond E. Cantwell, Claire Quinn, Ron Hofmann and Robert C. Andrews

ABSTRACT

On-line particle count and turbidity data was used to monitor the impacts of transient particulate water quality events on the inactivation of indigenous total coliform bacteria by a pilot-scale ultraviolet (UV) disinfection unit at two drinking water treatment plants (referred to as WTPs 'A' and 'B'). The intent of the study was to assess the performance of UV disinfection when exposed to temporary 'worst case' particulate water quality conditions in a drinking water treatment context. The pilot unit was installed downstream of a poorly operating filter at WTP 'A' and downstream of an intentionally destabilized Actiflo® system at WTP 'B'. In each case, elevated particle content (turbidity up to 2.9 NTU) did not cause observable adverse effects on the UV disinfection of total coliform bacteria over the test periods, even when a particle extraction technique was applied to count particle-associated bacteria in the water samples.

Key words | coliform bacteria, particle association, particles, turbidity, ultraviolet disinfection

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INTRODUCTION

Previous studies of the ultraviolet (UV) disinfection of coliform bacteria in wastewater have reported that bacteria can survive UV disinfection by being attached onto or within particles that are larger than approximately 10 μm in size (Loge *et al.* 1999; Jolis *et al.* 2001). However, there is comparatively little information on the potential for particle shielding of bacteria in a drinking water treatment context. While it can be assumed that there are usually fewer particles of the size that is required to shield bacteria in drinking water compared to wastewater, transient particulate water quality is still an occasional problem for many water treatment plants. Examples are treatment plants that suffer from unstable upstream particle-removal processes (e.g. granular media filtration, sedimentation) prior to the disinfection stage, or plants that remove particles poorly during periods of heavy rainfall (e.g. plants that draw source water from relatively shallow rivers that are susceptible to short temporal variations in water quality).

Microorganisms cannot be inactivated by UV light unless a direct (macroporous) pathway exists between the target microorganism and the UV source (Örmeci & Linden 2002; Dietrich *et al.* 2003). When a particle surrounds a bacterium, this light pathway may be blocked, thus protecting the enmeshed bacterium. Aggregation of bacterial spores to one another in source waters has also been shown as a potential shielding mechanism against UV light (Mamane-Gravetz & Linden 2005). These previous studies have suggested that bacteria may possibly survive UV disinfection under certain conditions which are conducive to the shielding of organisms from UV light (e.g. presence of suspended particles). However, this has not been investigated for a flow-through UV reactor nor by considering

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indigenous organisms (i.e. versus spiked organisms) and real particle-laden water matrices.

Research objective

The objective was to investigate the impact of transient particulate water quality events (spikes in particle counts/size and turbidity) on pilot-scale UV disinfection of indigenous total coliform bacteria in selected drinking water treatment plants.

MATERIALS AND METHODS

Pilot study overview

A pilot UV reactor was used to assess UV performance under sub-optimal particulate water quality conditions at two water treatment plants, both of which treated river water. Total coliforms were chosen as the microbiological indicator of disinfection performance in each case.

Water treatment plant (WTP) 'A' was a conventional water treatment plant with coagulation, clarification, dual-media (gravel/anthracite) filtration and chlorine disinfection. The chemical coagulants used for coagulation/flocculation were alum and activated silica. The plant regularly experienced sub-optimal particulate water quality due to clarifier process upsets. Heavy rainfall also drastically and rapidly increased surface water turbidity to levels that could not easily be controlled by the clarifier and the filter.

WTP 'B' used an Actiflo® system prior to filtration and chlorination. Chemical coagulants were used in conjunction with the Actiflo® system, namely STERNPAC®/activated silica/sand/LT27A. In order to simulate a process upset for this study, the treatment plant operators intentionally disrupted the addition of the polymer to one of the Actiflo® units which resulted in a turbidity spike immediately downstream of the process. The UV pilot reactor was installed at this point, prior to the filters. Excellent filter performance downstream of the pilot UV setup ensured that there was no impact on final water quality during the trials.

A portable pilot test unit, which included a pilot-scale low pressure UV reactor (Advanced UV Inc., Torrance, CA, USA) and on-line monitoring instrumentation (turbidimeter, particle counter and flowmeter), was installed at each treatment facility. At WTP 'A', the test unit was placed after one of the dual-media filters and before chlorine injection. The test period ran for four summer months over which a range of UV transmittance (%UVT) data, turbidity data and particle count information were measured in the post-filter water. At WTP 'B', the test unit drew water from the settling tank of the Actiflo® system. The test period ran for approximately two weeks.

Data was recorded using a mobile instrumentation panel equipped with an on-line turbidimeter (Model 7997-202 ABB Instrumentation Ltd. Stonehouse, UK) and particle counter (WPCS model, IBR®, Grass Lake, MI, USA). The particle counter had four channels: 2–5 μm, 5–10 μm, 10–50 μm and >50 μm. Continuous on-line turbidity and particle count measurements were recorded at 10 min intervals. The time interval of 10 min was selected to delineate spikes that persisted over a long enough period that they could be identified and then captured via grab samples for off-line water quality and microbiological analysis. Flow rates were measured using an on-line ABB MagMaster (ABB Instrumentation Ltd. Stonehouse, UK).

In each case the test flow rate was throttled to 170 L/min using a downstream globe valve. All piping was 50 mm (2 inch) diameter Schedule 40 PVC pipe. The filter unit configuration in WTP 'A' prevented gravity flow through the pilot system and so a centrifugal pump (Model QP-10, Myers, Ashland, OH, USA) was used to circulate water through the system. Ideally, the pump should have been located downstream of the pilot unit to mitigate the impact of pumping on the particles (e.g. pumping may shear particles into smaller particles). However, a downstream pump would have resulted in a vacuum within the system, preventing sampling. Therefore, the pump had to be installed at the front end to maintain the flow rate and allow sampling. Neither pumping nor a backflow preventer were required for the testing at WTP 'B'.

Pilot UV reactor trials

Indigenous total coliforms were enumerated in samples collected upstream and downstream of the pilot-scale low pressure UV reactor in autoclaved 1 L or 9 L Nalgene® sample bottles. Since this study examined UV disinfection

performance with specific emphasis on organisms entrained within particles in a real drinking water matrix, this therefore required consideration of an indigenous organism rather than a spiked test organism, which may not become associated with particles in the same way as indigenous organisms. Total coliform bacteria was selected as the indicator bacteria since it is ubiquitous in the natural environment, a common microbial indicator, and easy to enumerate in the laboratory.

Turbidity and particle count measurements were recorded in real-time and sampling was timed to coincide with periods of elevated particle content– e.g. after a heavy rainfall or during regular process upsets that occurred during routine operation of the plant. Periodically the pilot turbidity measurements were cross-referenced with the WTP on-line instrumentation for confirmation of accuracy. The particle counter was factory-calibrated and referenced to bench-scale measurements using a Multisizer™ 3 Beckman Coulter Counter® (Beckman Coulter Canada, Mississauga, ON, Canada).

UV collimated beam experiments

In addition to the pilot-scale UV disinfection trials, a simultaneous bench-scale experiment was conducted to assess disinfection performance over a controlled range of UV doses and well-defined hydraulic conditions. Samples were collected upstream of the pilot UV reactor in autoclaved 1 L plastic bottles and were transported on ice to the laboratory where they were stored at 4°C until analysis within 24 h of sampling. A low pressure UV collimated beam apparatus (Suntec Environmental, Concord, ON, Canada) was used to apply UV doses (0, 3, 5, 7, 10 and 40 mJ/cm^2) to duplicate samples. The UV lamp was allowed to warm up for a minimum of 30 min prior to measurement of the UV intensity (or 'fluence rate') of the beam. Intensity across the exposure surface was measured using an IL1700 radiometer and SUD240 sensor (International Light Inc., Newbury Port, MA, USA). UV absorbance at 254 nm was measured using a spectrophotometer (Hewlett-Packard 8452A Diode Array, Mississauga, ON, Canada). The exposure times required for a specified UV dose (or 'fluence') was calculated by inserting the measured exposure surface intensities and the sample UV absorbance into an MS Excel® spreadsheet calculator (Bolton Photosciences Inc., Ayr, ON, Canada). All bench-scale exposures were conducted at room temperature.

Pilot UV dose validation–MS2 biodosimetry

Dose validation of the reactor was conducted at each WTP at a flow rate of 170 L/min. The purpose of the biodosimetry was to quantify the UV doses being applied at pilot-scale. Stock MS2 phage was injected at 300 mL/min well upstream of the UV reactor (final phage concentration of $\sim 10^6$ PFU/mL) using a gear pump (Labcor Technical Sales, Concord, ON, Canada). MS2 phage is a non-pathogenic surrogate organism that is commonly used as a challenge organism for UV biodosimetry tests and recommended in standardized biodosimetry protocols (NWRI/AWWARF 2000; USEPA 2006). A static mixer was not used at WTP 'A' because it was assumed that the centrifugal pump and backflow preventer, both located upstream of the injection port, would provide complete mixing. The pilot installation at WTP 'B' employed static, in-line PVC mixers (Labcor Technical Sales, Concord, ON, Canada).

Samples used for microbial enumeration were collected upstream and downstream of the UV reactor in sterile 15 mL sampling tubes. To measure any changes in phage concentration by factors other than UV disinfection, samples were collected prior to the injection point to measure for background phage levels and downstream of the reactor while the UV lamps were off. To prevent introduction of the MS2 phage into the full-scale treatment flow, a backflow preventer was installed upstream of the injection port. Flow was sent to waste during biodosimetry trials.

The log reduction of MS2 phage across the reactor was compared to bench-scale UV dose–response curves to determine the UV dose delivered by the pilot UV reactor. Dose–response curves for MS2 phage in each water matrix were generated in the lab within 72 h of the pilot test using the low pressure UV collimated beam apparatus (Suntec Environmental, Concord, ON, Canada). The MS2 phage stock used for generating the dose–response curve with the collimated beam was from the same stock as that used for measurements across the pilot UV reactor. Twenty milliliter aliquots were dispensed into 100 × 15 mm sterile

polystyrene Petri dishes and gently stirred using a Teflon® micro stir bar. Collimated beam UV doses of 0, 20, 40, 60, 80 and 100 mJ/cm^2 were delivered to duplicate samples to develop the UV dose–response curves for the MS2 phage.

Microbiological methods

All samples from the pilot plant were packed with ice packs in coolers for transport to the lab, and stored at 4°C until analysis. Microbial analysis was initiated within 24 h of sampling.

Coliform extraction from particles was conducted using an approach developed by Camper *et al.* (1985) for enumeration of coliforms in wastewater. A final sample concentration of 10^{-6} M Zwittergent 3–12 (Sigma Chemical Co., D-4516, St. Louis, MO, USA), 10^{-3} M EGTA (Sigma Chemical Co., E-3889, St. Louis, MO, USA), 0.1% peptone (VWR DF 0118-15) and 10^{-3} M Tris buffer (Sigma Chemical Co, T-5941 and T-6066, St. Louis, MO, USA) was added prior to blending at 20,000 rpm for 3 min in a 1 L stainless steel blender (Waring 700S, Torrington, CT, USA).

The membrane filtration (MF) technique, Standard Method 9222 (APHA/AWWA/WEF 1998), using M-Endo LES (Difco 273620, Sparks, MD, USA) agar was used to enumerate total coliforms. Typical and atypical colonies were confirmed using brilliant green lactose (2%) bile broth (Que-Lab 2373, Montreal, QC, Canada) as per Standard Methods 9222 and 9221B (APHA/AWWA/WEF 1998).

The MS2 phage growth and enumeration followed conventional methods and are described elsewhere (Templeton *et al.* 2005).

Analytical methods

Particle counts were analyzed in the lab to compare the particle size distribution of grab samples of post-filter water taken from the pilot stream, with particle size distributions measured by the on-line particle counter at the time of sampling. This was to determine if there was any significant impact of sample handling between the field and lab analysis. Grab-sample particle counts were analyzed with a Multisizer™ 3 Beckman Coulter Counter® (Beckman Coulter Canada, Mississauga, ON, Canada) using 0.9% ionic solution with a 100 μm aperture. Calibration in this range was conducted using nominal 10 μm latex beads (CC Size Standard L10, Beckman Coulter Canada, Mississauga, ON, Canada).

Turbidity was measured in the laboratory using a Hach 2100N turbidimeter (Hach Company, Loveland, CO, USA). Grab samples were compared with daily ranges recorded by on-line monitoring equipment.

%UVT was determined by measuring the absorbance at 254 nm (UV254) with a spectrophotometer (Hewlett-Packard 8452A Diode Array, Mississauga, ON, Canada) using a 1 cm quartz cuvette (%UVT $= 10^{-\mathrm{UV254}} \times 100$).

RESULTS AND DISCUSSION

WTP 'A'

Water quality data

Pilot on-line turbidity and particle size data were collected over a four-month period spanning May to August 2003 (example online data for May is shown in Figure 1). Monthly averages for turbidity and particle counts are shown in Table 1. Figure 1 shows the observed scatter in the data for these water quality parameters.

Spikes in particle counts and turbidity resulted from filter ripening immediately following plant start-up (Figure 2). Operation of 'WTP A' was not continuous since it was regulated by the water level in the clearwell. Following filter start-up, particle counts and turbidity readings would increase for a period of approximately 10–60 min.

Precipitation data (Environment Canada 2003) was also compared with turbidity and particle count data. There was a distinguishable impact of rainfall events on particulate water quality (Figure 3), but there was a lag time of up to about one and a half days between the event and the observance of higher turbidity/particle counts. This was likely in part due to the lag time for the stormwater to transit the catchment. The greatest spike in particle counts was evident in the 2–5 μm particle size range during such events.

Particle counts were highest in the 2–5 μm and 5–10 μm size ranges. These two ranges represented 93–9% of all particles, with standard deviations of 2% for all three months. The 10–50 μm size range made up

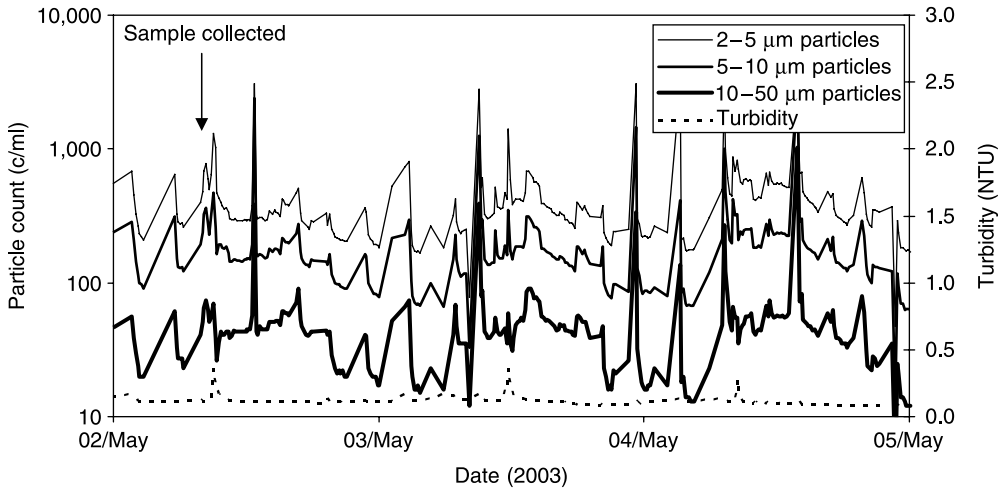

Figure 1 | Sample on-line particle counts and turbidities over a 72 h duration at WTP 'A'.

most of the balance, as counts >50 μm averaged less than 1% (Figure 4). The largest temporal fluctuations occurred in the 2–5 μm size range and this size range drove the overall variations in the total particle size distributions.

%UVT was dependent on source water conditions and upstream treatment processes performance and varied significantly over the test period, with post-filter %UVT ranging from 48% to 81% due to unstable operation of the clarifier and filter upstream of the reactor. Flow through the UV reactor was only during testing and therefore neither lamp aging nor long-term mineral scaling of lamp surfaces were assumed to be significant variables during the test period.

Table 1 | Turbidity and particle counts at each WTP during the test periods

Parameter (average*)	WTP 'A' May	WTP 'A' June	WTP 'A' July	WTP 'A' August	WTP 'B' settling tank
Turbidity (NTU)	0.14	0.11	0.07	0.09	0.74
%particles >10 μm	7%	5%	6%	5%	3.8%
Particle count/mL 2–5 μm	374	218	198	307	1,344
Particle count/mL 5–10 μm	191	83	57	113	359
Particle count/mL >10 μm	69	13	10	16	76

*Average = monthly averages from pilot on-line monitoring data.

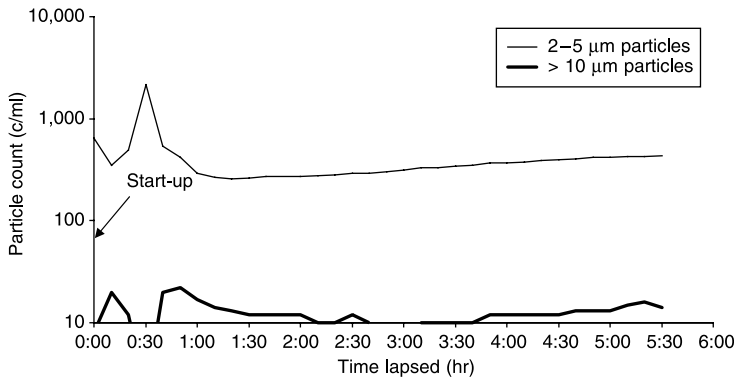

Figure 2 | Spike in particle counts attributed to filter ripening following plant start-up at WTP 'A'.

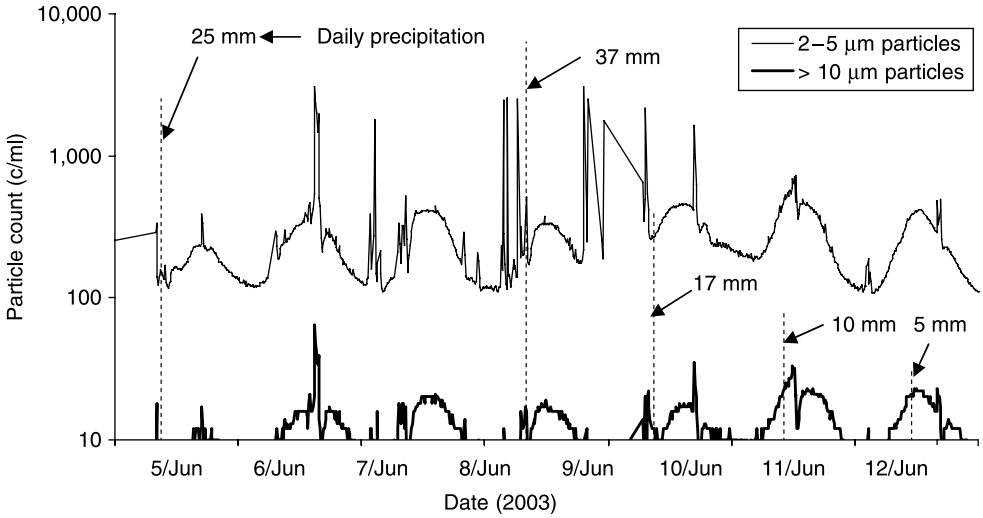

Figure 3 | Daily precipitation data compared with on-line particle count data over a 7 d duration at WTP 'A'. Source: Environment Canada (2003).

UV dose validation

Three MS2 biodosimetry tests were performed over two months, when post-filter %UVT values were 60, 64 and 70%. Inactivation of MS2 phage fell within the calibration limits of the NWRI guidelines (2000) in the UV dose–response curve (Figure 5), with R^2 values of 0.95–0.99. Based on these tests, the UV reactor was determined to be delivering UV doses between 60 to 90 mJ/cm^2 at 170 L/min (Figure 6), a typical operating UV dose range for drinking water treatment (NWRI/AWWARF 2000; USEPA 2006). It was assumed therefore that UV doses of the magnitude delivered by the pilot reactor would inactivate all non-particle-associated (i.e. dispersed) coliform, since total coliform inactivation by UV light is known to occur at a rate of about 5.0–6.5 mJ/cm^2 per log inactivation (Qualls *et al.* 1985). Any total coliform bacteria survivors of the applied UV dose range in this study would therefore be assumed to be benefitting from some form of protection from UV light, such as by particle shielding.

Total coliform enumeration after pilot UV reactor dose

The flow rate was held constant at 170 L/min for all tests (this was the manufacturer-rated flow rate for the UV reactor) to

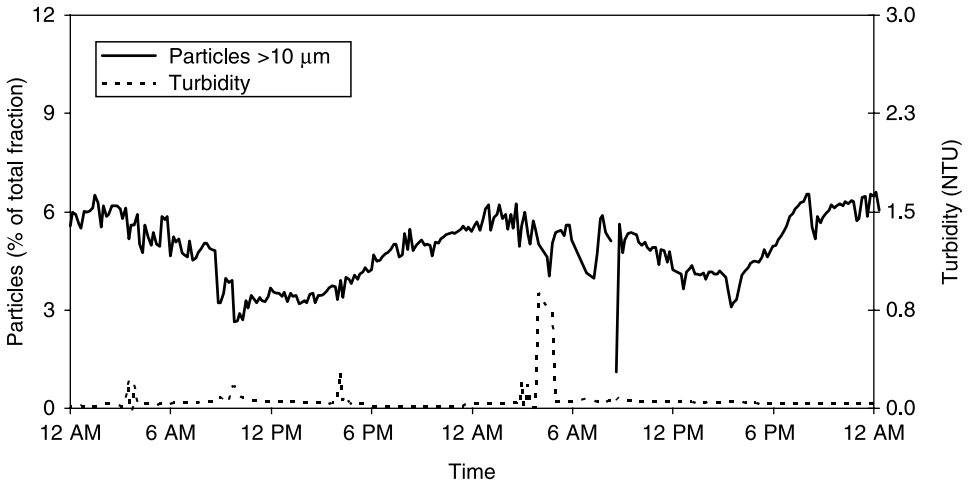

Figure 4 | Typical % fraction of particles >10 μm passing through pilot reactor at WTP 'A' over a sample 48 h duration.

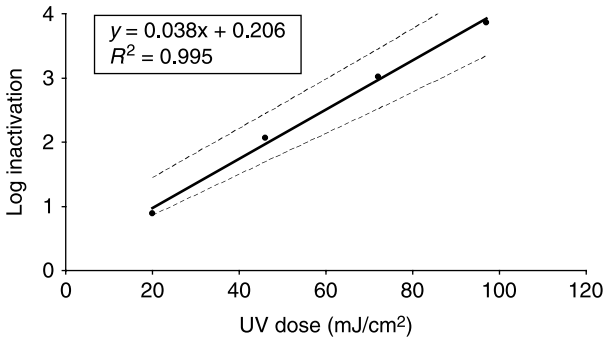

Figure 5 | UV dose–response curve for stock MS2 phage. Upper and lower boundaries follow NWRI/AWWARF (2000) guidelines (dotted lines).

achieve a dose of between 60–90 mJ/cm^2. Total coliform bacteria were not detected in post-UV pilot water, both before and after particle extraction of the samples. Indigenous total coliform bacteria densities upstream of the UV reactor were in the range of 250–1,900 CFU/100 mL over the six test days, so the total coliform inactivation therefore exceeded 2-log inactivation across the UV reactor in all tests. No particle impact was observed at the applied UV doses. It is hypothesized that this could have been due to: (a) the concentration of particles >10 μm not being high enough to protect the coliform population to a measurable degree and/or (b) because the particle structures in this particular water matrix contained enough light pathways to allow a germicidal UV dose to reach any particle-enmeshed bacteria.

Total coliform enumeration after UV collimated beam doses

Post-filter water samples were collected immediately upstream of the UV pilot reactor such that the impact of UV exposure could be assessed at bench-scale under more controlled conditions using a collimated beam apparatus. UV doses in the low range (0–10 mJ/cm^2) were applied to determine a dose–response curve for the naturally occurring dispersed coliform bacteria present in the post-filter sample. Coliform bacteria should be almost completely inactivated by doses >10 mJ/cm^2 (Qualls *et al.* 1985). A coliform inactivation coefficient k was derived from the slope of the UV dose–response curve to characterize the survival of the total coliforms population after UV exposure. The k value was compared between experiments to measure the consistency of the UV dose–response of the organisms. One collimated beam test was performed on a day following rainfall and another test was performed after a one hour plant shutdown to observe the effect of filter loading. The remaining four tests were performed on samples collected during typical operation. Six tests over a three month period showed an average k value of 0.28 cm^2/mJ with a standard deviation of only 0.04 cm^2/mJ (Figure 7). No surviving coliform bacteria were detected in any samples following a UV dose $\geqq 10$ mJ/cm^2 in any of the tests.

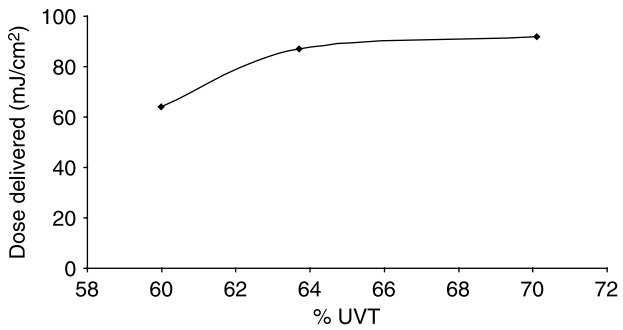

Figure 6 | Dose delivered by pilot UV reactor for a range of %UVT observed at WTP 'A' based on MS2 biodosimetry results.

WTP 'B'

Water quality data

Pilot on-line turbidity and particle size data were collected over a period of six days. Higher total particle counts (particularly in the >10 μm range) were measured at WTP 'B' compared with WTP 'A', since pre-filtered water was used at WTP 'B'. However, the average percent fraction of total particles >10 μm in the WTP 'B' (3.8%) was less than the average observed in WTP 'A' (5–7%) (Table 1).

Two sets of tests were conducted at WTP 'B'. The %UVT of the two UV pilot trials carried out over a one-week period was 81% and 73%. For the first test, sampling took place during 'normal' operation (i.e. no reported process upset conditions). For the second test, process upset conditions were simulated by disrupting the polymer addition (Figure 8).

UV dose validation

The UV dose validation followed the method used at WTP 'A'. The MS2 biodosimetry test showed that for a %UVT of

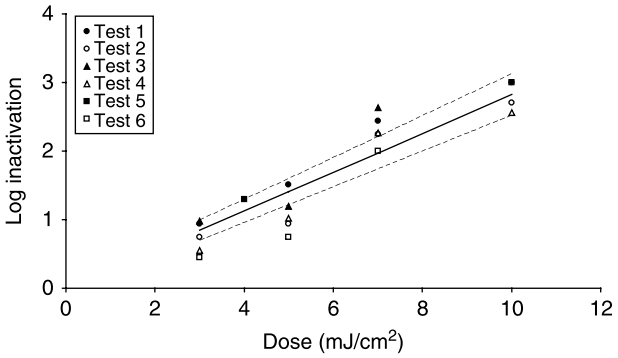

Figure 7 | UV collimated beam inactivation for indigenous total coliform bacteria in water from WTP 'A'. $k = 0.28\,cm^2/mJ$. Upper and lower boundaries denote one standard deviation.

81% the UV dose delivered by the pilot UV was $70\,mJ/cm^2$.Recall that the same UV dose range was observed at WTP 'A' ($60-90\,mJ/cm^2$) but with lower %UVT values (60–70%). Also, recall that surviving coliform bacteria following exposure to UV doses in the range of $60-90\,mJ/cm^2$ would indicate the potential for particle shielding since virtually all dispersed total coliform bacteria would be expected to be inactivated at such UV doses (Qualls *et al.* 1985).

Total coliform enumeration after pilot UV reactor dose

At WTP B, no total coliforms were detected in the post-UV pilot test water, both with and without conducting the particle extraction method. Indigenous coliform bacteria densities immediately upstream of the UV reactor were between 2,380 CFU/100 mL and 5,360 CFU/100 mL for the two tests, so total coliform inactivation exceeded 3-log inactivation across the UV reactor in all tests. Any particle impacts on coliform bacteria survival under these conditions were therefore negligible.

Total coliform survival in UV collimated beam tests

Water samples were collected immediately upstream of the UV pilot such that the impact of exposure to UV disinfection on indigenous coliform bacteria could be assessed in the laboratory using the collimated beam apparatus. Membrane filtration of 100 mL samples showed that >2.3 log inactivation of total coliforms occurred at UV collimated beam doses of $7\,mJ/cm^2$. When compared with the post-filtered water in WTP 'A', the pre-filtered water had, on average, higher turbidity, particle counts (in ranges 2–5 μm, 5–10 μm and >10 μm) and initial total coliform bacteria density. Despite this generally poorer water quality, no quantifiable protection of bacteria by particles was observed, even when taking into account the possible presence of particle-enmeshed bacteria by applying the special particle extraction method to the water samples (Figure 9). In fact, in some samples in which there were higher particle counts than others, there was even a slightly higher inactivation of coliform bacteria measured at bench-scale (Figure 9), perhaps due to improved scattering of UV light throughout the sample or due to particle break-up during stirring of the sample contained in the Petri dish.

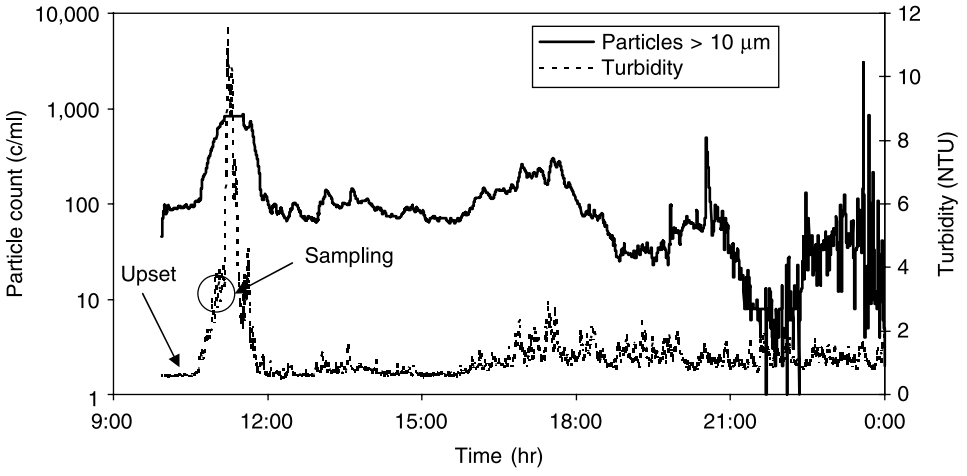

Figure 8 | On-line monitoring data for particle counts >10 μm and turbidity after simulated upset in Actiflo® unit at WTP 'B'.

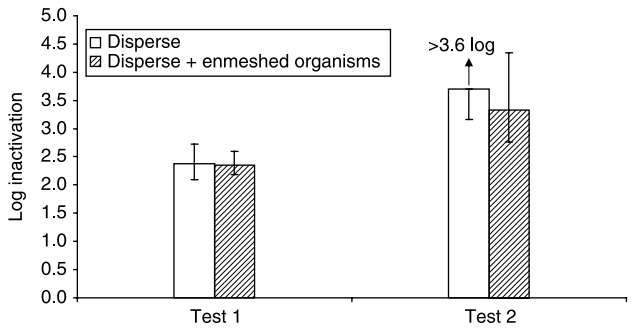

Figure 9 | Coliform bacteria inactivation by a bench-scale UV dose = 7 mJ/cm^2 applied to water from WTP 'B'. Total particle counts were 49 c/mL (Test 1) and 326 c/mL (Test 2). Bars are upper and lower bounds of 95% confidence levels.

Potential shielding of other waterborne microorganisms in drinking water treatment

Since *Cryptosporidium* and *Giardia* cysts are approximately the same size as coliform bacteria, it is hypothesized that these organisms may not be significantly protected against UV disinfection by particles either, under 'worst-case' drinking water treatment conditions. A bench-scale study considering the effects of particles on the UV inactivation of protozoan cysts seems to provide initial support for this hypothesis (Amoah *et al.* 2005). Viruses, however, have been shown to be potentially shielded by much smaller particles in bench-scale studies (Templeton *et al.* 2005), although this is difficult to assess at pilot or full scale due to the very low concentration of indigenous viruses in typical drinking water samples.

CONCLUSIONS

The disinfection performance of the pilot-scale UV reactor was not adversely impacted by particle shielding in the pre-filter, post-filter or raw water quality conditions that were considered at the two water treatment facilities in this study. Sampling during periods when sub-optimal water quality could be predicted did not reveal surviving coliform bacteria in the water that was treated by pilot-scale UV reactor doses (ranging from approximately 60–90 mJ/cm^2) or bench-scale UV collimated beam doses, even after special particle extraction methods were applied to enumerate particle-associated bacteria. The lack of any negative particle-shielding effect on the UV disinfection in these 'worst-case' drinking water treatment applications could have been due to: (a) the concentration of particles $>10\,\mu$m not being high enough to offer significant protection for the coliform bacteria and/or (b) because the structure of the particle types in the particular waters considered this study contained enough light pathways to allow lethal UV doses to reach the bacteria.

Particles in the $>10\,\mu$m size range were expected to have the most impact on potential particle protection of total coliforms. Particle counts (10–50 μm) ranged from 4–23 c/mL for tests conducted at WTP 'A' (turbidity 0.04–0.10 NTU) and 29–379 c/mL at WTP 'B' (turbidity 0.44–2.90 NTU). However, at neither plant was there any measurable evidence of a negative impact on UV disinfection performance caused by particle association of bacteria.

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