Disinfection effectiveness of ultraviolet (UV) light for heterotrophic bacteria leaving biologically active filters

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ABSTRACT

Biologically operated filters are known to reduce elevated levels of biodegradable organic matter produced by the ozonation process, but they also consistently release high-levels of heterotrophic bacteria. An acceptable disinfection strategy for biofilter effluent bacteria is necessary to maintain distributed water quality. The efficiencies of various strategies for disinfecting naturally occurring heterotrophic bacteria in the effluent from an ozone/biofiltration plant treating California surface waters were compared. Bench-scale tests were conducted in the laboratory, using ultraviolet (UV) light (low-pressure and medium-pressure lamps), and the results were compared with those for the disinfection efficiency of free chlorine and chloramines. Inactivation efficiencies provided by the low- and medium-pressure UV lamps were similar ($k \approx 0.47$ cm^2 mJ^{-1}). To consistently reduce biofilter effluent bacteria levels to <10 colony-forming units per millilitre (CFU ml^{-1}) prior to distribution, this study showed that contact with either 1 min of free chlorine or 60 min of monochloramine (both at 2.5 mg l^{-1}, pH=8, 20°C) would be necessary, compared with a UV dose of 15 mJ cm^{-2} from either lamp. To evaluate bacterial regrowth potential following UV treatment, samples were incubated at 20°C in a dark environment to mimic transport/storage in the distribution system. Without residual disinfection, bacteria treated by 60 and 140 mJ cm^{-2} of UV were able to regrow to untreated biofilter effluent levels within 3 and 7 days, respectively. Samples treated with 20 mJ cm^{-2} of UV and 2.5 mg l^{-1} of chloramines maintained bacteria at levels of <10 CFU ml^{-1} for up to 7 days. To investigate the plausibility of bench-scale results, a full-scale UV reactor (treating 3 million gallons per day (0.13 m^3 s^{-1}) was operated to treat the biofilter effluent at the large-scale treatment plant for a period of 8 months. Continuous UV treatment was observed to provide long-term control of the biofilter effluent bacteria to levels similar to those afforded by bench-scale treatment. However, towards the end of the study, the number of bacteria leaving the UV reactor increased to levels exceeding 10^2 CFU ml^{-1}. It was observed that 2.5 mg l^{-1} monochloramine residual (no free-chlorine contact) applied at the inlet of a 60-min clearwell downstream from the UV reactor kept bacteria at a level of <10 CFUml^{-1} at the clearwell effluent. Based on these results, it is recommended that utilities using UV to control biofilter effluent bacteria apply a residual disinfectant (such as chloramines) to maintain low bacteria levels during distribution.

Key words | bacteria, chloramines, chlorine, disinfection, heterotrophic, ultraviolet light

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BACKGROUND

Increasingly stringent drinking water regulations for chlorinated disinfection by-products (DBPs) cause drinking water utilities in the United States to consider implementing ozone as a primary disinfectant. Following the ozonation process, biologically active filters can provide biological stability by reducing biodegradable organic matter (BOM) produced by ozone before water reaches the distribution system (Rittman & Snoeyink 1984).

Biologically active filters are typically used downstream from conventional treatment to provide particulate removal in conjunction with biological stability (Urfer *et al*. 1997).

Biofiltration consistently releases heterotrophic bacteria (LeChevallier *et al*. 1991). Although high levels of heterotrophic bacteria do not directly indicate public health risk, these nuisance organisms may degrade the water quality (Wolfe *et al*. 1990) and indicate that it may be compromised by human pathogens (Geldreich *et al*. 1972). To maintain water quality in the distribution system, water treated by biologically active filters requires a subsequent disinfection step (Servais *et al*. 1991). Ozone should not be applied downstream from biofiltration without careful consideration of the production of BOM and the ability to control resultant heterotrophs (Wolfe *et al*. 1989). Studies evaluating the disinfection efficiency of free chlorine and chloramines for the control of heterotrophic bacteria showed that chlorine provided more consistent and fast-acting control (Wolfe *et al*. 1985; Pernitsky *et al*. 1995). Therefore, utilities implementing the use of ozone followed by biofiltration may find that a polishing stage of chlorine followed by chloramines provides adequate control of heterotrophic bacteria and a biologically stable drinking water.

Ultraviolet (UV) light may control both naturally occurring heterotrophic bacteria from a biological filter and protozoan pathogens (Mofidi *et al*. 2001, 2002). UV light, when used for disinfection, does not alter drinking water BOM (Linden *et al*. 1998; Shaw *et al*. 2000; Liu *et al*. 2002) or produce DBPs regulated in drinking water (Stewart *et al*. 1993; Malley *et al*. 1995). Although the application of UV light to water does not allow direct measurement of disinfection residual, Lund and Hongve (1994) suggested that UV may provide prolonged bactericidal effects that deter bacterial growth. This finding, combined with many utilities' desire to reduce free-chlorine contact in order to reduce DBPs, warrants evaluation of post-biofiltration applications for UV disinfection.

MATERIALS AND METHODS

This study utilized a bench-scale, collimated-beam testing protocol to characterize the ability of UV light to disinfect for heterotrophic bacteria. The bacteria were naturally occurring in the effluent from a biological filter fed with ozonated California surface water. Bench-scale testing was used to evaluate the disinfection efficiency of UV light, free-chlorine and chloramines. Following disinfection, regrowth potential of the bacteria was evaluated under controlled laboratory conditions in order to understand temporal robustness of the disinfectant.

To provide practical application of the efficacy of bench-scale results, a full-scale surface water treatment plant treating 3 million gallons per day (mgd) ($0.13\ m^3\ s^{-1}$) was operated within the guidelines developed from bench data. Operational and water quality data were collected from the facility to provide guidance for other utilities considering implementation of the UV process.

Bench-scale disinfection protocols

Table 1 summarizes the water quality characteristics for both the bench- and full-scale portions of this study. For heterotrophic bacteria testing, water samples were collected from the effluent of the large-scale treatment plant filters (described below). Disinfection testing was conducted with a bench-top, collimated-beam device containing either a low- or medium-pressure UV lamp, as described elsewhere (Mofidi *et al*. 2001) and briefly here. Continuously stirred, 10-ml suspensions of microorganisms were exposed to UV light at a distance of 10, 20 or 50 in. (25, 50 or 127 cm). Distance (and thus UV intensity) was adjusted to maintain irradiance within acceptable limits for measurement by a single calibrated radiometer (model IL1700, SED240 detector with a 'W' diffuser; International Light, Inc., Newburyport, Massachusetts). The dosage of germicidal UV light was calculated by prorating the centre irradiance value across the surface of the Petri dish and compensating for the UV-light-absorbing quality of the microorganism suspensions according to the Beer-Lambert Law, per Morowitz (1950), as applied by Bolton and Linden (2003). The spectrum of germicidal UV light emitted by the medium-pressure lamp was measured by a spectrometer (model S2000; Ocean-Optics, Inc., Dunedin, Florida) and average irradiance was calculated according to DNA absorbance spectra. UV

Table 1 | Water quality data for bench- and full-scale testing

Parameter	Bench-scale (all data)	Full-scale phase 1 (CRW/SPW blend)	Full-scale phase 2 (SPW)	Full-scale phase 3 (CRW/SPW blend)	Units
Days	–	0–134	134–169	169–247	day
Alkalinity	NA	114–128	85–86	105–113	mg l^{-1} as $CaCO_3$
AOC					
Plant influent	NA	171	109	NA	μg l^{-1}
Filter Influent	NA	300	471	NA	μg l^{-1}
Biofilter effluent	NA	180	261	NA	μg l^{-1}
Biofilter AOC removal	NA	40	45	–	%
Hardness	180–250	222–266	114–115	208–231	mg l^{-1} as $CaCO_3$
Heterotrophic bacteria					
Biofilter effluent		9,600 ± 3,300**	11,000 ± 5,800**	12,000 ± 7,800**	CFU ml^{-1}
UV effluent	*	2.0–75	16–110	6.0–210	CFU ml^{-1}
UV, NH_2Cl clearwell effluent	*	1.0–1.6	1.0–4.0	5.0–10	CFU ml^{-1}
Cl_2, NH_2Cl clearwell effluent	*	1.0–1.9	1.0–1.0	0.1–3.0	CFU ml^{-1}
Percentage state project water	NA	28 ± 9**	99 ± 1**	37 ± 4**	%
Plant influent temperature	NA_5	10.4–19.3	19.2–23.5	22.0–25.3	°C
Specific UV absorbance (SUVA)					
Plant influent	NA	1.1–2.2	2.6–2.8	1.6–1.9	l mg^{-1} m^{-1}
Total organic carbon					
Plant influent	NA	3.4 ± 0.2**	3.8 ± 0.1**	3.0 ± 0.2**	mg l^{-1}
Biofilter effluent	NA	2.7 ± 0.1**	2.8 ± 0.3**	2.2 ± 0.2**	mg l^{-1}
Turbidity					
Biofilter effluent	0.07–0.13	0.05–0.12	0.07–0.19	0.01–0.12	ntu
UV absorbance at 254 nm					
Plant influent	NA	0.038–0.08	0.099–0.10	0.047–0.06	cm^{-1}
Biofilter effluent	0.04–0.02	0.02–0.04	0.34–0.06	0.023–0.03	cm^{-1}
UV transmittance at 254 nm_{254}‡					
Plant influent	NA	84–92	79–80	87–90	% cm^{-1}
Biofilter effluent	91–96	92–95	88–92	93–95	% cm^{-1}

NA=data not analysed.
Individual data represent result of a single measured value.
*Data reported in Table 2 and Figures 3–5.
**Average±standard deviation.
†Temperature was not analysed at time of UV exposure; however, samples were kept on ice at 4°C prior to exposure to UV light.
‡Transmittance of UV light at 254 nm calculated from absorbance readings.

dosage was recorded as a product of irradiance (milliwatts per square centimetre) and time (s) which provides units of millijoules per square centimetre (mJ cm^{-2}).

Chlorine/chloramine experiments were conducted by adding chlorine (buffered, sodium hypochlorite) alone, at the same time (preformed), or at set time intervals with ammonia (dissolved ammonium chloride solution) into 200 ml of sample in 250-ml amber, chlorine-demand free, glass bottles. The water was tested for both free-chlorine and chloramine demand prior to running the experiments. These preliminary demand tests allowed for the establishment of dosages necessary to achieve targeted free-chlorine or chloramine residuals. Chloramines were formed by applying a 4:1 weight ratio of ammonia-nitrogen to free-chlorine residual. After chlorine and/or ammonia had been added to the samples, they were completely mixed by inverting and shaking for 1 min to achieve homogeneity.

Microbial assays

Heterotrophic bacteria were assayed by membrane filtration and incubation on R2A media according to *Standard Methods* (1998), with plating conducted in triplicate. This plate-count method enumerates all aerobic bacteria that can grow on R2A media and provides results in units of CFU ml^{-1}.

Assimilable organic carbon (AOC) was assayed as a measure of biofilter performance. Assay techniques involved using a modified standard method (Huck *et al.* 2000).

Incubation protocols

To provide sufficient volume of sample for incubation over a 7-day period, three to six 10-ml, collimated-beam exposures of biological filter effluent containing heterotrophic bacteria were conducted. These samples were combined into a sterile, 50-ml centrifuge tube and then transferred to the laboratory into sterile incubation dishes (covered glass Petri dishes) placed in a dark laboratory cabinet. This larger, combined volume of UV-treated sample allowed subsequent samplings (at 3 and 7 days) to be made for heterotrophic bacteria and chloramine residual. Positive incubation controls consisted of non-UV-treated biological filter effluent and cartridge-filter-sterilized biological filter effluent spiked with an aliquot of nonsterile filter effluent (initial bacterial count of $\leq 10^1$ CFU ml^{-1}). Cartridge filters (disposable, sterile nylon filter systems; Corning Inc., Corning, New York) were rinsed three times with UV-treated, organic-free laboratory water (Milli-Q®; Millipore, Bedford, Massachusetts) prior to use. The spiked water control was used in an attempt to understand baseline heterotroph regrowth potential during bench-scale incubation. A negative control consisted of sterilized biofilter effluent using the filtering procedure described above. After UV exposure and before the start of incubation, some samples were dosed with preformed chloramines. The chloramine dosing procedures described above were used to ensure a 2.5 mg l^{-1} chloramine residual with no available free chlorine at the start of incubation.

Full-scale treatment plant

Operation and water quality

The large-scale facility illustrated in Figure 1 was operated for research purposes only and was not required to produce potable water. For this study, the plant was operated according to guidelines set forth by the Surface Water Treatment Rule (US Environmental Protection Agency 1989), specifically for meeting disinfection credit and effluent turbidity requirements. The plant utilized preozonation – 13 min contact time in an over/under baffled contactor described elsewhere (Metropolitan Water District 2000) – followed by a combination of conventional particle removal with biological filtration (anthracite and sand dual-media filtration). BOM removal by the biofilter was monitored approximately every 90 days by measuring removal of AOC. As reported in Table 1, the plant treated a blend of California state project water (SPW) and Colorado River water (CRW), with a brief period of operating with only SPW. Significant differences in these source waters can be seen in their hardness, alkalinity and reactive natural organic matter. Higher specific UV absorbance (SUVA) indicates higher percentages of

Table 2 | Test data used to calculate the rate constant for the photochemical reaction of heterotrophic bacteria to germicidal UV light from low- and medium-pressure lamps

Lamp type	UV dose (mJ cm^{-2})	ln [N/No] (cm^2 mJ^{-1})
Low-pressure*	0	0.12
	0	– 0.08
	0	– 0.10
	0	– 0.08
	0	0.04
	0	– 0.11
	5.1	– 1.86
	5.5	– 2.32
	5.7	– 2.07
	9.8	– 5.27
	10.9	– 5.95
	11.3	– 5.60
	14.8	– 6.53
	16.3	– 7.54
	16.5	– 7.95
Medium-pressure**	0	– 0.08
	0	0.09
	0	– 0.07
	0	– 0.09
	0	– 0.02
	0	0.02
	5.4	– 3.41
	5.5	– 2.45
	5.6	– 2.61
	10.5	– 5.30
	10.7	– 6.68
	11.3	– 5.41
	15.8	– 6.17
	16.2	– 8.33
	16.3	– 7.26

Note:Test results are presented here in order of increasing UV dose while actual tests were conducted in random order.
*Resulting first-order reaction model: ln [*N/No*] = – 0.48 *Deq*.
**Resulting first-order reaction model: ln [*N/No*] = – 0.47 *Deq*.

hydrophobic organic content (Krasner *et al*. 1997). During the time of this study, the plant operated at 3 mgd (0.13 m^3 s^{-1}) with an applied ozone dose (in terms of average ± standard deviation) of 1.1 ± 0.3 mg l^{-1} and a filtration flow rate of 5.1 ± 0.01 gal min^{-1} ft^{-2} (2.6 ± 0.2 m^3 day^{-1} m^{-2}). No chlorine or chloramines were applied upstream at the treatment plant. Chemicals were added at the rapid mixing process to enhance particulate removal (ferric chloride, 4.4 ± 1.3 mg l^{-1}; cationic polymer, 0.9 ± 0.2 mg l^{-1}). Calculated ozone disinfection effectiveness for *Giardia* and viruses provided 1.3 ± 0.1 and 2.6 ± 1.2 log_{10} inactivation credits, respectively, over the study period. AOC data presented in Table 1 show that the filter was operating biologically.

Downstream from filtration, a 24-in. (61 cm)-diameter, enclosed-pipe, medium-pressure UV reactor (Sentinel UV; Calgon Carbon Corp., Pittsburgh, Pennsylvania) was operated as shown in Figure 2. The reactor was controlled to automatically shut down during filter backwash (approximately 30 min long), and restart several minutes before the filter was set to come back on line. During filter backwash, the UV reactor remained full of stagnant UV-treated water. Restarting the UV reactor prior to the filter's return to service allowed enough time for the medium-pressure lamps to reach full UV output and for the reactor not to overheat before flow returned. During testing, the UV reactor operated at an energy consumption of 0.10 ± 0.03 kWh $1{,}000^{-1}$ gal^{-1} (26 ± 8 kWh m^{-3}). Due to cycling reactor power to match the filter backwash requirements, reactor lamp starts per phase averaged as high as 1.7 day^{-1}.

Following the full-scale treatment plant, a sidestream of water was directed to two distinct, pilot-scale, enclosed reservoir systems illustrated in Figure 1. These systems used 316-l stainless-steel, 1-in. (2.5 cm)-diameter piping and over/under baffled tanks to simulate storage that would occur downstream from the full-scale treatment plant prior to the distribution of water to customers. The first system directed water directly from the biofilter (before UV treatment) at a rate of 1 gal min^{-1} (3.8 l min^{-1}) and provided a 5-min theoretical contact time with 2.5 mg l^{-1} free-chlorine residual (sodium hypochlorite addition prior to a 5-gal (19-l) baffled tank), followed by a 60-min theoretical contact time with

2.5 mg l^{-1} of chloramines (4:1 weight ratio of ammonia-nitrogen to free-chlorine residual prior to a 60-gal (227-l) baffled tank). Chloramines were created by adding ammonium chloride solution made from organic-free laboratory water and mixed fresh in autoclaved polypropylene tanks each week to prevent nitrification. The second system directed water (also at 1 gal min^{-1} (3.8 l min^{-1})) from the effluent of the large-scale UV reactor. This water was then dosed to establish a residual of 2.5 mg l^{-1} of chloramines (ammonia solution injected prior to free chlorine). Chloraminated water from the second system was sent through a 60-gal (227-l) baffled tank. Sample tap locations without disinfectant residual (e.g. at the biological filter effluent and immediately downstream from the UV reactor) were cleaned weekly with a 10,000-mg l^{-1} chlorine solution.

Full-scale UV reactor dose characterization

Figure 2 shows the installed UV reactor and setup for its biodosimetry validation with MS-2 (male-specific) coliphage. The reactor consisted of four 4-kilowatt lamps and was validated under steady-state filter operation (3 mgd (8 m^3 s^{-1}) of flow) with MS-2 coliphage under these conditions: transmittance, 96.8 ± 1.0% cm^{-1}; turbidity, 0.07 ± 0.01 ntu; temperature, 14.1 ± 1.3°C; pH, 7.9 ± 0.1 units; hardness, 210 ± 35 mg l^{-1} as $CaCO_3$. The results of the validation provided a low-pressure equivalent dose that varied with the number of lamps operating in the reactor. This low-pressure equivalent dose at the beginning of lamp life was calculated to be 58 mJ cm^{-2} when four lamps were operating.

Statistical analysis

A student's *t*-test was performed on bacterial data collected during this study, as described by Kennedy and Neville (1986). This analysis was based on the nonpaired, two-sample test for means, assuming a null hypothesis that data observed for the two sample sets belong to the same sample population. Sample collection was not conducted in a 'paired' manner, so a paired *t*-test could not be conducted. The tests were conducted at a 99% level of significance.

RESULTS

Bench-scale disinfection and storage effects on heterotrophic bacteria

Free chlorine and chloramines

The results of three replicate chlorine/chloramine tests are summarized in Figure 3. The median densities of heterotrophic bacteria remaining after a transferred dose of 2.6 ± 0.1 mg l^{-1} (average ± standard deviation) of chlorine and/or chloramines are shown at various contact times. A 61-min contact with chloramines (median 4.3 log_{10} inactivation) provided similar heterotroph disinfection as either 1-min contact with free chlorine (median 3.9 log_{10} inactivation) or 1-min contact with free chlorine followed by 60-min contact with chloramines (median 4.1 log_{10} inactivation). However, a 1-min contact with chloramines provided only 2.2 log_{10} heterotroph inactivation.

UV light

Figure 4 illustrates the response of the heterotrophic bacteria to light from the low- and medium-pressure UV lamps at doses up to 17 mJ cm^{-2}. Tests were actually conducted at UV doses up to 60 mJ cm^{-2}; however, doses above 17 mJ cm^{-2} resulted in bacteria levels below the detection limit of the R2A assay. Linear regression of the data was characterized by R^2 values of 0.96 for the medium- and 0.98 for the low-pressure lamp. Using the equations that characterize these lines of regression, 1-, 2- and 3-log_{10} reduction of heterotrophic bacteria would be achieved with doses of 5, 10 and 15 mJ cm^{-2}, respectively.

Because mixed, uncharacterized populations of bacteria probably represent the number of organisms present in the R2A plate-count assay, it could be assumed that the assay detects the presence of many different heterotrophic bacteria, which may exhibit significantly different UV dose-response characteristics. However, linearity and

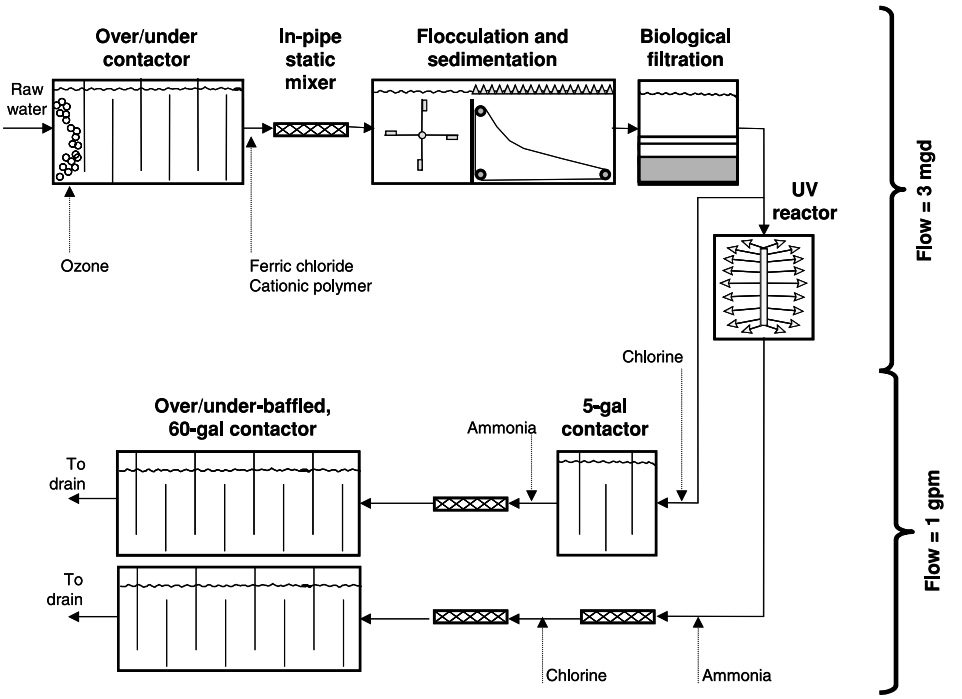


Figure 1 | Treatment processes used at Metropolitan's full-scale research facility in La Verne, California.

strong correlation of the regression indicate that the generic, heterotrophic bacteria dose-response may be characterized by a pseudo-first-order inactivation rate. Rate constants for photochemical reaction were calculated for the two lamps using an adaptation of the Chick-Watson disinfection kinetic model, as described in the literature (Blatchley 1997; Wright & Lawryshyn 2000):

$$ln\left[\frac{N}{N_O}\right] = -k\, D_{eq} \quad (1)$$

where:

N_o = number of viable target organisms prior to exposure to UV light

N = number of viable target organisms following exposure to UV light

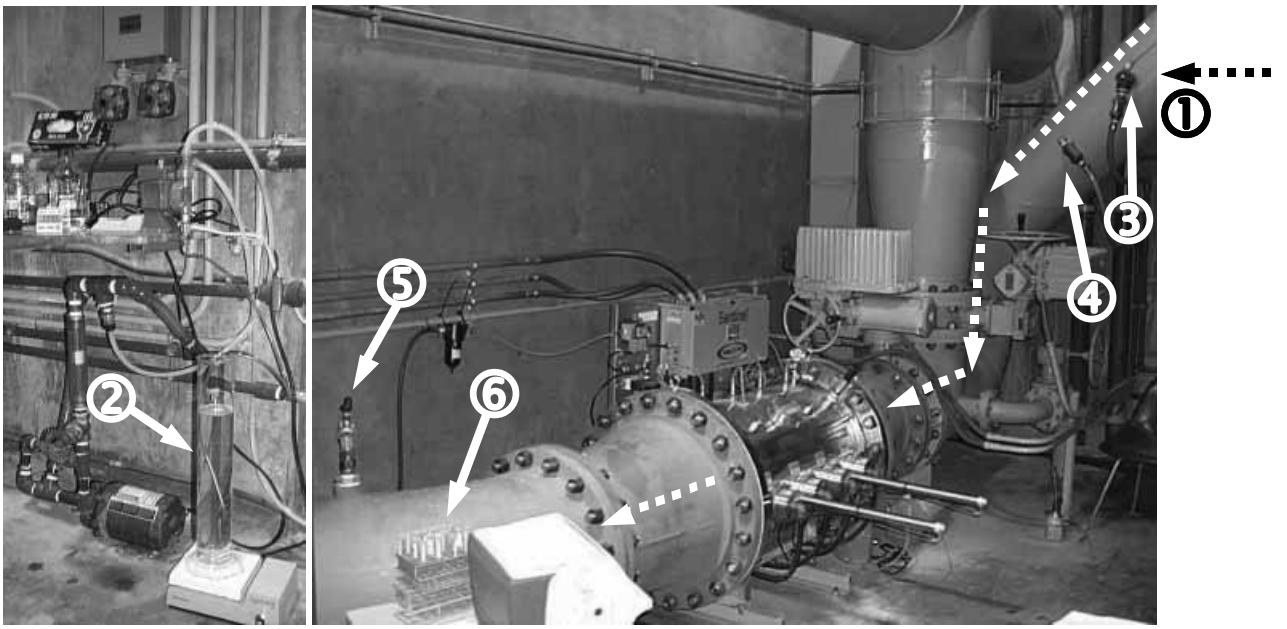
k = rate constant for photochemical reaction [$cm^2\ mJ^{-1}$]

D_{eq} = equivalent germicidal UV dose [$mJ\ cm^{-2}$]

The analysis of the rate constant for both lamps, across the UV doses evaluated, is summarized in Table 2. The results from this analysis show that the rate constants (k) were similar at -0.48 and $-0.47\ cm^2\ mJ^{-1}$, respectively, for the low- and medium-pressure lamps.

Simulated distribution system storage effects

Figure 5 illustrates results from the incubation of heterotrophic bacteria for both the experiment control samples (Figure 5a) and the samples exposed to UV light from the low-pressure lamp (Figure 5b). Control sample data showed that biological filter effluent (positive control) maintained a relatively steady level of bacteria at 10_5–$10_6\ CFU\ ml^{-1}$. The sterilized control sample (negative control) showed that bacteria remained at acceptably low levels through day three ($<10^1\ CFU\ ml^{-1}$) but tended to increase by day seven, to range between 10^0 and $10^2\ CFU\ ml^{-1}$. Interestingly, the inoculated regrowth control (no UV applied) showed dramatic repopulation of bacteria after 3 days (reaching the biological filter effluent



Legend
① Treated water from the biological filter entered the 18-inch diameter pipe here (dashed lines indicate flow path through system)
② $1x10^{11}$ plaque-forming units (PFU) ml^{-1} MS-2 stirred in graduated cylinder, pumped at 300 ml min^{-1} into transport water
③ Extraction location for transport water to make MS-2 slurry, pumped at a flow of 10 gpm
④ 10 gpm MS-2 slurry injection location (provided approximately $4x10^{6}$ PFU ml^{-1} MS-2 for a four minute period in the 3 mgd flow)
⑤ Sample location for characterizing reactor effluent water
⑥ MS-2 sampling tubes and ice chest

Figure 2 | Biodosimetry challenge setup showing injection and sample ports.

level), remaining constant through the remainder of the 7-day test. This control sample showed that sufficient BOM remained in the effluent of the biological filter such that the heterotrophs were not nutrient limited in their growth. These data may be contradictory to the literature indicating that UV may inhibit bacterial metabolism (Lund & Hongve 1994), but they agree with information showing that, absent residual disinfectants, heterotrophic bacteria thrive in the distribution system (Wricke *et al.* 2002).

For the UV-treated samples, mixed results were observed for disinfection and regrowth. Initial treatment of UV doses ranging from 20 to 140 mJ cm^{-2} resulted in significant reduction of the bacteria. However, the number of bacteria surviving UV exposure was greater than the number expected to survive based on the dose-response data previously collected and reported (see Figure 4). Following UV doses of 20, 60 and 140 mJ cm^{-2}, and based on results from the dose-response kinetics reported above, bacteria were expected to be present at nondetectable levels. Sampling following the application of UV light was conducted using aseptic techniques (see the 'Materials and methods' section) but showed slight elevation of viable bacteria – an increase in number from 1 to 51 CFU ml^{-1} – at the start of incubation.

Following UV treatment by 20 and 60 mJ cm^{-2}, measured levels of heterotrophic bacteria reached 10^5 CFU ml^{-1} within 3 days. Following treatment by 140 mJ cm^{-2}, there appeared to be minimal/zero regrowth after 3 days (consistently $<10^2$ CFU ml^{-1}). These 140-mJ cm^{-2} UV-dosed samples reached levels of bacterial growth similar to the lower UV-dosed samples ($>10^5$ CFU ml^{-1}) after a 7-day incubation.

When the 20-mJ cm^{-2} UV-exposed sample was subsequently combined with 2.5 mg l^{-1} of residual chloramines, the number of bacteria remained under

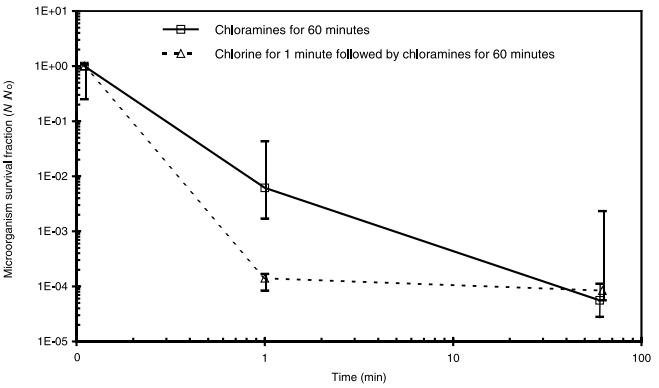


Figure 3 | Effect of post-disinfection with chlorine and/or chloramines on the number of naturally occurring heterotrophic bacteria leaving biological filtration (data collected at time 0 and 61 min plotted with off-set time values for visual clarity, data from three replicate tests; bars represent minimum and maximum values; data points represent median data; pH=8; temperature=20°C).

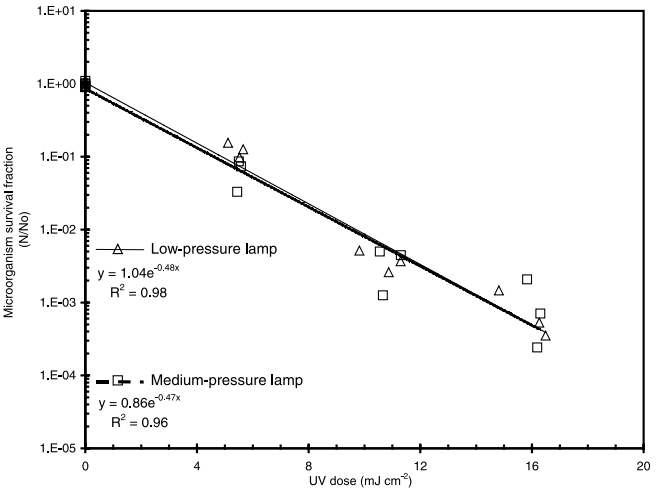


Figure 4 | Effect of post-disinfection with ultraviolet (UV) light emitted by low- and medium-pressure lamps on the number of naturally occurring heterotrophic bacteria leaving biological filtration.

control and no regrowth was observed (bacterial counts remained at or below 10^1 CFU ml^{-1}). Chloramine residuals for the 7-day test were measured to be 2.5, 1.0 and 0.5 mg l^{-1} at the 0-, 3- and 7-day incubation times, respectively.

Full-scale UV treatment of biofilter effluent

Following ozone/biological filtration, the full-scale UV reactor was operated and monitored for its ability to disinfect biofilter effluent heterotrophic bacteria (samples from the reactor effluent were collected at the sample tap shown in Figure 2). Trends in the monitoring for heterotrophic bacteria are presented in Figure 6. Table 1 summarizes bacterial and other water quality data. For ease in identifying changes in supply water quality, the study period was categorized in three distinct phases: phases 1 and 3 treated a blend of SPW and CRW (an average of 28 and 37% SPW, respectively), and phase 2 treated 100% SPW. Although temperature was observaed to increase consistently throughout the study period, the release of heterotrophic bacteria from the biofilter was fairly constant at about 10^4 CFU ml^{-1}. Changes in sourcewater were not expected to significantly affect UV treatment results.

Following UV disinfection, the number of bacteria was observed to remain at <10 CFU ml^{-1} until day 57 of operation. An uncharacteristically high bacterial count of 1,220 CFU ml^{-1} was measured at day 72 (samples immediately prior to and following this sample were observed to contain 12 and 13 CFU ml^{-1}, respectively). Following day 57, the number of bacteria leaving the reactor steadily increased to reach a high of 211 CFU ml^{-1} on day 177. This represented approximately a 1-$\log_{10}$ diminishing treatment effectiveness over time. The mean bacterial count leaving the UV reactor during phase 3 was 10^7 CFU ml^{-1}.

Downstream from the biofilter, UV/chloramines treatment was operated in parallel with the chlorine/chloramines treatment scheme. Chloramine residuals measured at the two clearwells are presented in Figure 7. As previously described, the clearwells were operated at a pilot flow of 1 gal · min^{-1} (3.8 l min^{-1}) and a targeted chloramine residual of 2.5 mg l^{-1}. During the study period, the clearwell following the UV reactor was observed to have influent and effluent chloramine residuals of 2.5 ± 0.4 and 2.3 ± 0.7 mg l^{-1}, respectively. Similarly, the clearwell following chlorine treatment had influent and effluent chloramine residuals of 2.4 ± 0.4 and 2.2 ± 0.8 mg l^{-1}, respectively.

At the effluent of the chloraminated clearwell following UV disinfection, bacterial counts were observed to be

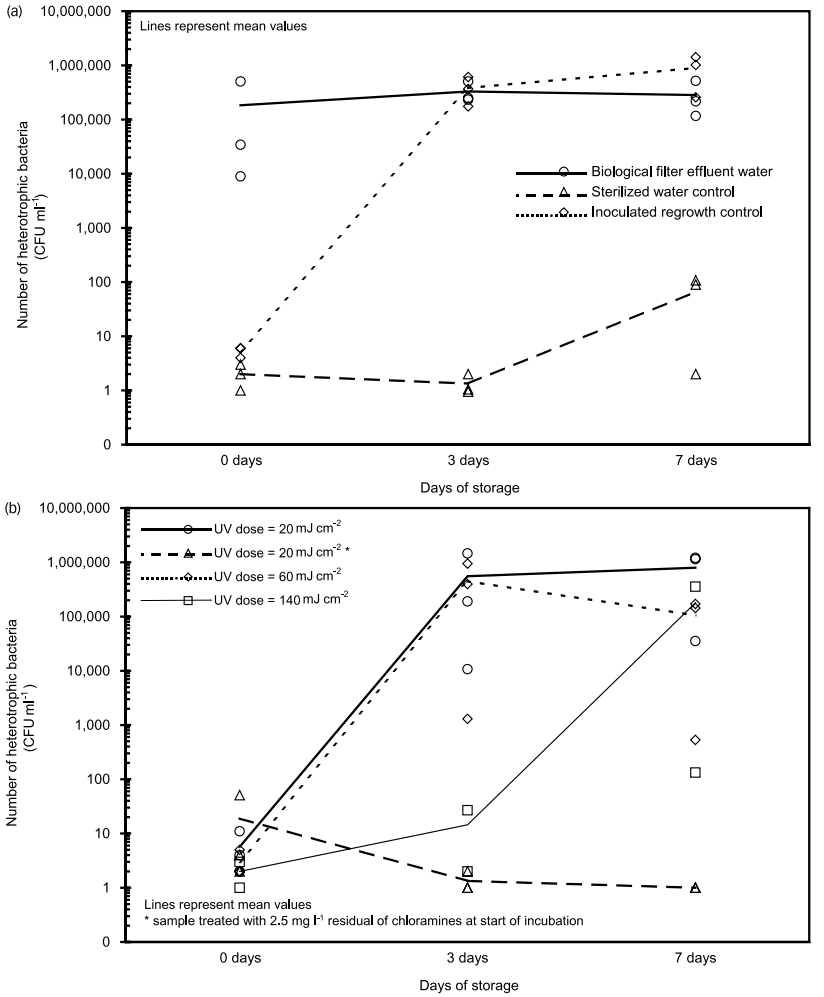


Figure 5 | Effect of 20°C, dark incubation on low-pressure, UV-light-treated heterotrophic bacteria. (a) Experiment controls; (b) samples (for the sample with chloramines added, the residuals at 0, 3 and 7 days were 2.5, 1.0 and 0.5 mg l^{-1}, respectively).

consistently managed at low numbers. The number of bacteria leaving UV/chloramines treatment peaked at 10 CFU ml^{-1} well into the study, on day 197. The clearwell following chlorine/chloramines treatment also provided stable, low numbers of bacteria, with the highest bacterial value following this treatment measured at 4 CFU ml^{-1}, on day 65. Bacterial-count data from the two treatment trains were evaluated by a student's *t*-test (99% significance, nonpaired data) and found to be statistically similar; this similarity was maintained whether or not nondetect values were included in the *t*-test analysis. UV reactor effluent bacterial counts were statistically greater than bacterial counts following either the UV/chloramines or the chlorine/chloramines residual disinfection practice.

DISCUSSION AND CONCLUSIONS

To meet regulatory compliance guidelines, many utilities in North America may switch from chlorine to ozone treatment. Utilities will probably implement biofiltration to reduce elevated levels of BOM produced by ozonation.

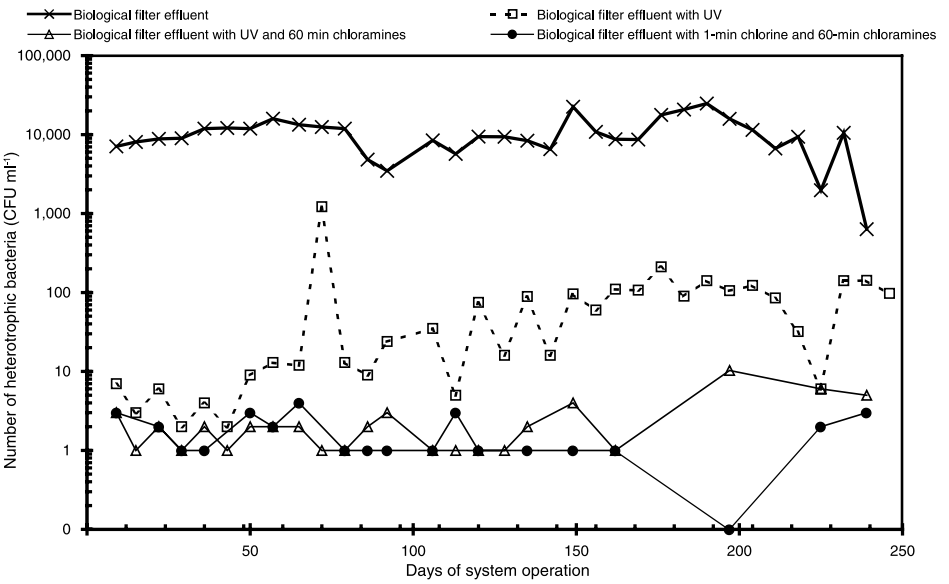


Figure 6 | Effect of treatment on heterotrophic bacteria leaving full-scale biologically active filters (chloramine dose=2.5 mg l^{-1}; chlorine dosed to achieve a 2.5-mg l^{-1} residual; bacterial counts <1 CFU ml^{-1} plotted at 0 value).

This study compared the ability of 2.6 mg l^{-1} of free chlorine, chloramines or combined chlorine/chloramines, as well as UV light and UV light combined with 2.6 mg l^{-1} chloramines, to provide adequate control of bacteria leaving biofilters. Bench-scale results showed that 1 min chlorine, 60 min chloramines and 15 mJ cm^{-2} germicidal UV light all provided bacterial control at a level of <10 CFU ml^{-1} in treated samples (4-, 4- and 3-log^{10} inactivation, respectively). To control heterotrophic bacteria prior to distribution, utilities may choose from these three strategies, based on both the space requirements for the technologies (e.g. 1- or 60-min contact requirements for chlorine or chloramines) and the amount of DBPs that each strategy may provide (e.g. the levels of halogenated DBPs generated by chlorine, chloramines or UV). Because disinfection-level doses (<200 mJ cm^{-2}) of UV light have been demonstrated not to produce or increase the formation potential of halogenated DBPs (Stewart *et al*. 1993; Malley *et al*. 1995; Liu *et al*. 2002), it may be an attractive biofilter-effluent disinfection technology for many utilities.

Following evaluations of disinfection effectiveness, further bench testing showed that a disinfectant residual was mandatory to limit bacterial regrowth in stored/distributed water. This observation was inconsistent with previous reports that UV light may impart bacteristatic qualities to treated water (Lund and Hongve 1994). Some utilities may wish to control biofilter effluent bacteria (1) without free-chlorine residual (to reduce formation of halogenated DBPs, as described above) or (2) more rapidly than in the 60 min exposure required in a chloramine contactor (to reduce the process footprint).

For these utilities, implementation of a UV disinfection process may be beneficial. However, bench testing presented here also revealed that UV light alone may not provide adequate control of bacteria in a distribution system (3- to 7-day batch sample incubation). This shows that sufficient BOM remains following biofilter-treated water such that heterotrophs may not be nutrient limited in their growth. This regrowth phenomenon is not necessarily an indication of poor biofiltration or UV disinfection performance; rather, it is in agreement with previous literature describing the robust nature of the natural bacterial communities present in drinking water. The literature has indicated that heterotrophic bacteria are able to colonize finished water conduit (1) following treatment by micron and sub-micron pore-size membrane barriers (microfiltration and nanofiltration) (Sibille *et al*. 1998;

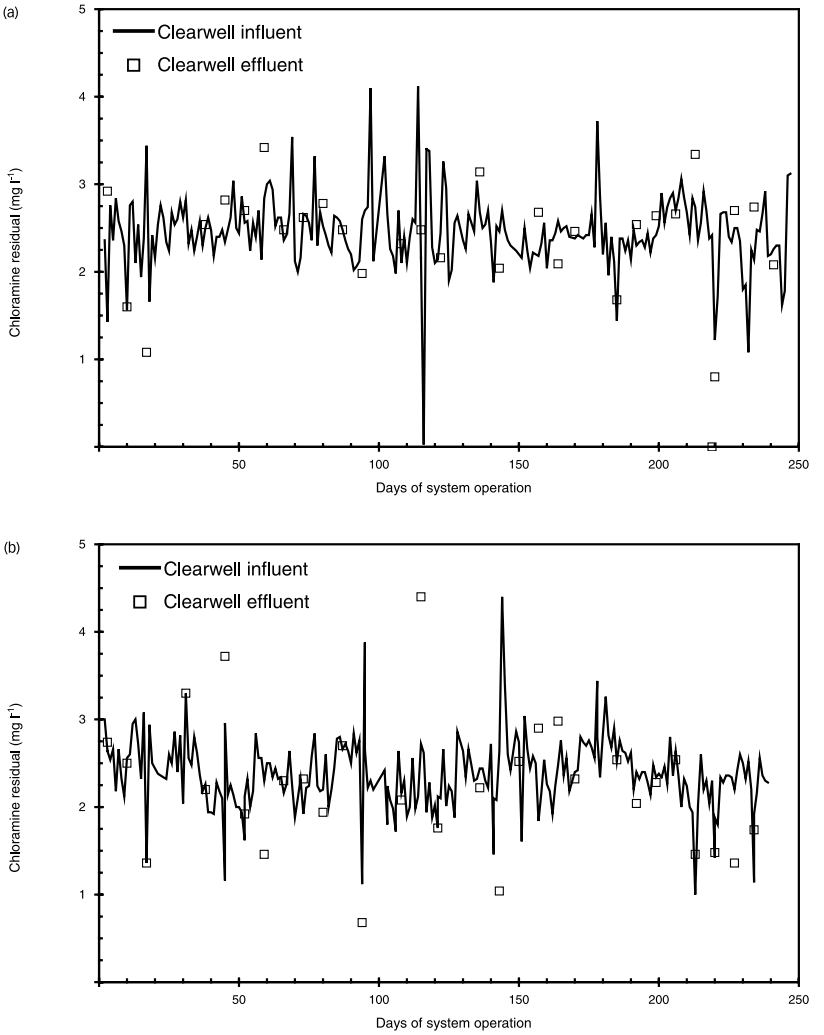


Figure 7 | Chloramine residuals at the inlet (lines) and outlet (open squares) of the clearwells following (a) biofiltration/UV and (b) biofiltration/chlorine.

Mofidi *et al*. 2000) and (2) in the absence of a residual disinfectant (Geldreich *et al*. 1985; van der Kooij & Hijnen 1988). Therefore, proper procedures for controlling biofilter effluent bacteria would be likely to include treatment by UV light or chlorine, followed by chloramines.

To investigate the plausibility of implementing these processes on a large scale, this study evaluated the performance of a 3 mgd ($0.13\ m^3\ s^{-1}$), medium-pressure UV reactor placed downstream from a treatment plant utilizing ozone and biofiltration processes. Two post-biofilter treatment scenarios were evaluated, including (1) 5-min chlorine contact followed by 60-min chloramine contact (Cl_2/NH_2Cl) and (2) UV light followed by 60-min chloramine contact (UV/NH_2Cl), where ammonia was added before chlorine to avoid free-chlorine contact and hence reduce the potential for halogenated DBP formation. The UV reactor was operated at a validated UV dose of approximately $60\ mJ\ cm^{-2}$.

At the onset of the study, treatment provided by the UV reactor was observed to reduce biofilter effluent bacteria by more than $2\ log_{10}$, providing bacterial counts of $<10\ CFU\ ml^{-1}$. As the study progressed past 166 days, the number of bacteria present following UV treatment steadily increased to a level of $>100\ CFU\ ml^{-1}$. This

increase in bacterial count over time downstream of the UV reactor may have been a result of colonization downstream of the UV irradiance field by the consistently low numbers of bacteria that passed through the reactor. This suspected colonization would have been made possible by a lack of residual disinfectant. In the case of photosynthetic bacteria, it is possible that this may be enhanced by visible light emitted by medium-pressure lamps (visible wavelengths transmit much further through water than UV wavelengths). When a residual disinfectant was applied (either by UV/NH_2Cl or Cl_2/NH_2Cl), statistically similar control of bacteria was achieved at levels reliably less than 10 CFU ml^{-1}.

For drinking water utilities to maintain adequate control of biofilter effluent bacteria, disinfection by UV light alone may not be not adequate. This study demonstrated that viable bacterial counts following UV-treated biofilter effluent may increase to levels of 100 CFU ml^{-1} within 250 days. The presence of bacteria following full-scale UV treatment was not attributed to problems with the UV disinfection process (i.e. there were no significant deviations from validated reactor conditions during the study). Bench-scale testing showed that naturally occurring heterotrophic bacteria have an inherent ability to regrow while in low-nutrient waters. Heterotroph proliferation downstream of full-scale UV treatment with medium-pressure lamp reactors may be due to (1) biofilm seeding from more UV-resistant strains of heterotrophs, (2) ability of bacteria to regrow immediately downstream of the reactor's UV irradiance field, and (3) possible bacterial growth enhancement from visible light that is emitted by medium-pressure lamps. Optimum treatment of heterotrophic bacteria released from biofiltration may require that utilities control bacteria prior to the distribution system and also operate with a target of low DBP formation potential (i.e. minimization of free-chlorine contact).

These conclusions indicate that it may be beneficial for utilities to at least implement a short-term chlorination programme for UV reactors in order to maintain low levels of bacteria entering distribution systems. Short-term periods of chlorinating UV reactors may allow utilities to maintain bacterial control while minimizing DBP formation. Future research should be conducted to further characterize post-biofilter disinfection of bacteria (i.e. range of organism resistivity, impact of BOM) and the practice of sustaining long-term UV reactor inactivation of heterotrophic bacteria with periodic chlorination.

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