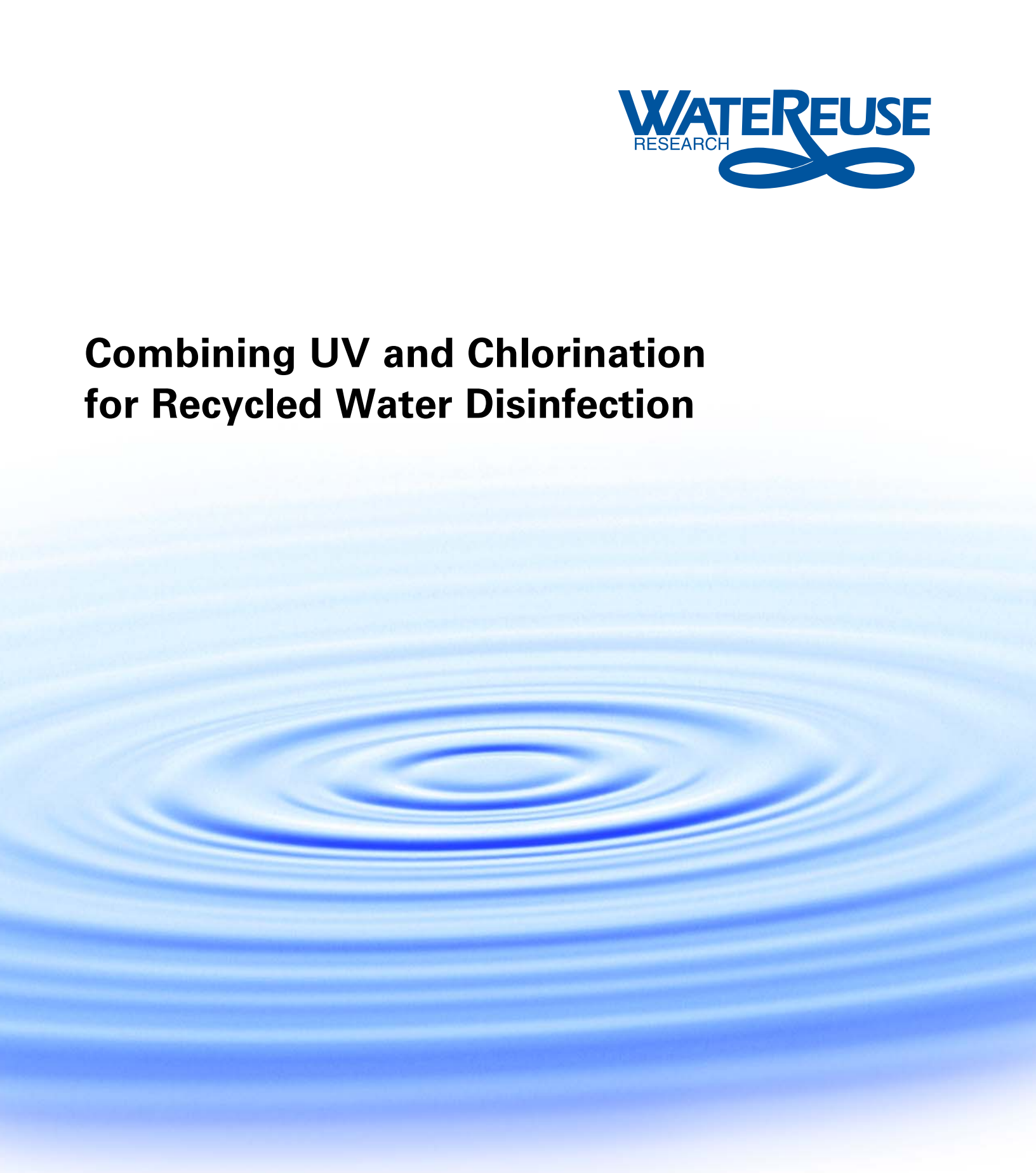
Combining UV and Chlorination for Recycled Water Disinfection



WateReuse Research Foundation

Combining UV and Chlorination for Recycled Water Disinfection

About the WateReuse Research Foundation

The mission of the WateReuse Research Foundation is to conduct and promote applied research on the reclamation, recycling, reuse, and desalination of water. The Foundation's research advances the science of water reuse and supports communities across the United States and abroad in their efforts to create new sources of high quality water through reclamation, recycling, reuse, and desalination while protecting public health and the environment.

The Foundation sponsors research on all aspects of water reuse, including emerging chemical contaminants, microbiological agents, treatment technologies, salinity management and desalination, public perception and acceptance, economics, and marketing. The Foundation's research informs the public of the safety of reclaimed water and provides water professionals with the tools and knowledge to meet their commitment of increasing reliability and quality.

The Foundation's funding partners include the Bureau of Reclamation, the California State Water Resources Control Board, the California Energy Commission, and the California Department of Water Resources. Funding is also provided by the Foundation's Subscribers, water and wastewater agencies, and other interested organizations.

Combining UV and Chlorination for Recycled Water Disinfection

Chi-Chung Tang, Ph.D., P.E., D.E.E.
Naoko Munakata, Ph.D.
Shiaw-Jy Huitric, P.E.
April Garcia
Shawn Thompson, Ph.D.
Sanitation Districts of Los Angeles County

Jeff Kuo, Ph.D., P.E.
California State University, Fullerton

Cosponsors
Bureau of Reclamation
Sanitation Districts of Los Angeles County

WateReuse Research Foundation
Alexandria, VA

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For more information, contact:
WateReuse Research Foundation
1199 North Fairfax Street, Suite 410
Alexandria, VA 22314
703-548-0880
703-548-5085 (fax)
www.WateReuse.org/Foundation

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CONTENTS

FIGURES

TABLES

ABBREVIATIONS

ATCC	American Type Culture Collection
AWWA	American Water Works Association
CCR	California Code of Regulations
CDPH	California Department of Public Health
CFU	colony forming unit
COD	chemical oxygen demand
CT	total chlorine residual times contact time
DBP	disinfection byproduct
DFB	chlorine-demand-free buffer
DMA	dimethylamine
ESI	electrospray ionization
GC	gas chromatography
gpm	gallons per minute
HAA	haloacetic acid
IU	infectious unit
LC	liquid chromatography
LP	low pressure
MGD	million gallons per day
MP	medium pressure
MPN	most probable number
MPN IU	most probable number of infectious unit
MRM	multiple reaction monitoring
MS	mass spectrometry
NDMA	N-nitrosodimethylamine
nm	nanometer
NPDES	National Pollutant Discharge Elimination System
NWRI	National Water Research Institute

PAA	peracetic acid
PFU	plaque forming unit
POTW	publicly owned treatment work
PSD	particle size distribution
SJCWQL	San Jose Creek Water Quality Laboratory (Whittier, CA)
SPE	solid phase extraction
TCEP	tris(2-carboxyethyl)phosphine
TCPP	tris(chloroisopropyl)phosphate
TDCPP	tris(2,3-dichloropropyl)phosphate
THM	trihalomethane
TKN	total Kjeldahl nitrogen
TrOC	trace organic constituent
TTHM	total trihalomethane
US	United States
USEPA	United States Environmental Protection Agency
UV	ultraviolet
UVDGM	*Ultraviolet Disinfection Guidance Manual for the Final Long Term 2 Enhanced Surface Water Treatment Rule*
UVT	UV transmittance

FOREWORD

The WateReuse Research Foundation, a nonprofit corporation, sponsors research that advances the science of water reclamation, recycling, reuse, and desalination. The Foundation funds projects that meet the water reuse and desalination research needs of water and wastewater agencies and the public. The goal of the Foundation's research is to ensure that water reuse and desalination projects provide high-quality water, protect public health, and improve the environment.

An Operating Plan guides the Foundation's research program. Under the plan, a research agenda of high-priority topics is maintained. The agenda is developed in cooperation with the water reuse and desalination communities including water professionals, academics, and Foundation Subscribers. The Foundation's research focuses on a broad range of water reuse research topics including:

- Defining and addressing emerging contaminants;
- Public perceptions of the benefits and risks of water reuse;
- Management practices related to indirect potable reuse;
- Groundwater recharge and aquifer storage and recovery;
- Evaluation and methods for managing salinity and desalination; and
- Economics and marketing of water reuse.

The Operating Plan outlines the role of the Foundation's Research Advisory Committee (RAC), Project Advisory Committees (PACs), and Foundation staff. The RAC sets priorities, recommends projects for funding, and provides advice and recommendations on the Foundation's research agenda and other related efforts. PACs are convened for each project and provide technical review and oversight. The Foundation's RAC and PACs consist of experts in their fields and provide the Foundation with an independent review, which ensures the credibility of the Foundation's research results. The Foundation's Project Managers facilitate the efforts of the RAC and PACs and provide overall management of projects.

The Foundation's primary funding partners include the Bureau of Reclamation, California State Water Resources Control Board, the California Energy Commission, Foundation Subscribers, water and wastewater agencies, and other interested organizations. The Foundation leverages its financial and intellectual capital through these partnerships and funding relationships.

Disinfection is essential for ensuring the safety and quality of recycled water. Combining disinfectants has recently attracted increasing attention. Because chlorine and ultraviolet (UV) radiation are the most common disinfectants used at wastewater treatment plants, and because each method has specific disinfection and reaction mechanisms, this research project was undertaken to evaluate the combination of UV with either free chlorine or chloramines for disinfection of recycled water.

David L. Moore
Chair
WateReuse Research Foundation

G. Wade Miller
Executive Director
WateReuse Research Foundation

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This study would not have been possible without the insights, efforts, and dedication of many individuals and organizations. These include the members of the research team, project advisory committee (PAC), and Expert Panel, as identified below; Anna Durden, the project manager from the WateReuse Research Foundation; Brian Petri, Willem Verhulst, and Ji An of Trojan Technologies; Rick Eismin of Coombs-Hopkins; and many key individuals at the Sanitation Districts of Los Angeles County, including Stephen R. Maguin, Philip L. Friess, Victoria Conway, Dave Snyder, Michael Creel and the operations staff, and Dwayne Fischer, Maria Pang, and the laboratory staff.

Principal Investigator and Project Manager

Chi-Chung Tang, Ph.D., P.E., *Sanitation Districts of Los Angeles County*

Research Project Team, Sanitation Districts of Los Angeles County

Naoko Munakata, Ph.D.
Jeff Kuo, Ph.D., P.E.
Shiaw-Jy Huitric, P.E.
April Garcia
Shawn Thompson, Ph.D.
Philip Ackman, P.E.
Ramon Gonzalez
Charles Harris
Jessy Avelar

Project Advisory Committee

Ric DeLeon, *Metropolitan Water District of Southern California*
Scott Irvine, *Bureau of Reclamation*
Karl Linden, *University of Colorado, Boulder*
Andrew Salveson, *Carollo Engineers*

Expert Panel

Brian Bernados, *California Department of Public Health*
David Jenkins, *David Jenkins and Associates*
Margie Nellor, *Nellor Environmental Associates*
Richard H. Sakaji, *East Bay Municipal Utilities District (CA)*
George Tchobanoglous, *Tchobanoglous Consulting*
Rhodes Trussell, *Trussell Technologies, Inc.*

Participating Organizations

Trojan Technologies
The Coombs-Hopkins Company
David Jenkins and Associates, Inc.
Tchobanoglous Consulting
Nellor Environmental Associates
Trussell Technologies, Inc.
California Department of Public Health

EXECUTIVE SUMMARY

Disinfection is essential for ensuring the safety and quality of recycled water. Combining disinfectants has recently attracted increasing attention, because of benefits such as disinfection of a wider range of pathogens, improved reliability through redundancy, reduced disinfection byproducts (DBPs), and potential cost savings. Because chlorine and ultraviolet (UV) radiation are the most common disinfectants used at wastewater treatment plants, and because each method has specific disinfection and reaction mechanisms, research was undertaken to evaluate the combination of UV with either free chlorine or chloramines for disinfection of recycled water. Limited data are available currently, and information is especially sparse on DBPs, removal of trace organic constituents (TrOCs, such as hormones, pharmaceuticals, personal care products, and other compounds present at low levels in wastewater effluents), and the optimum configuration of a combined UV/chlorine system. Given these gaps in knowledge, the goal of this project was to investigate combinations of UV with free chlorine or chloramines with respect to:

- disinfection efficacies for poliovirus, adenovirus, MS2 coliphage (MS2), and total coliforms in recycled effluents;
- formation of DBPs and the removal of TrOCs; and
- effects of water quality, UV and chlorine doses, disinfectant application order, and synergism.

To achieve these goals, bench- and pilot-scale experiments were conducted to evaluate UV disinfection in combination with either free chlorine or chloramines. UV was tested at doses of 33, 67, or 100 mJ/cm^2, alone or in combination with free chlorine at applied doses of 2, 4, or 6 mg Cl_2/L, or chloramines at CT values of 150, 300, or 450 mg-min/L (where CT is the product of total chlorine residual and contact time). Bench-scale experiments tested UV in combination with free chlorine, the ammonia-chlorine process (where chloramines were formed from the addition of ammonia, followed by free chlorine), and the chlorine-ammonia process (where chloramines were formed from the addition of free chlorine, followed by ammonia). Pilot-scale experiments tested UV in combination with free chlorine. The effects of disinfectant application order were investigated by dosing UV before, simultaneously with, or after chlorine in the bench-scale experiments, and by dosing UV before or simultaneously with chlorine in the pilot-scale experiments. Synergistic effects were also analyzed in both the bench- and pilot-scale experiments.

In the bench-scale experiments, disinfection of seeded poliovirus, seeded MS2, and indigenous total coliforms were monitored in fully nitrified secondary effluent (secondary effluent), fully nitrified filtered secondary effluent (filtered effluent), and chlorine-demand-free buffer; disinfection of seeded adenovirus was tested on filtered effluent. In the pilot-scale experiments, disinfection of seeded MS2 and indigenous total coliform levels were monitored in filtered effluent, and indigenous adenovirus was tested in selected experiments with filtered effluent.

In some pilot-scale experiments, samples were also analyzed for DBPs and TrOCs. The following DBPs were measured: trihalomethanes (THMs), N-nitrosodimethylamine (NDMA), cyanide, and cyanogen chloride. For TrOCs, 43 compounds were analyzed: acetaminophen, atenolol, atorvastatin, o-hydroxy atorvastatin, p-hydroxy atorvastatin, azithromycin, bisphenol A, caffeine, carbamazepine, clofibric acid, DEET, diclofenac, dichlorprop, dilantin, erythromycin, estradiol, estrone, ethynylestradiol, fenofibrate, fluoxetine, furosemide, gemfibrozil, ibuprofen, iopromide, ketoprofen, mecoprop, metoprolol, naproxen, nonylphenol, octylphenol, phenacetine, primidone, progesterone, propranolol, salicylic acid, simvastatin OH acid, sulfamethoxazole, tris(2-carboxyethyl)phosphine (TCEP), tris(chloroisopropyl)phosphate (TCPP), tris(2,3-dichloropropyl)phosphate (TDCPP), triclosan, triclocarban, and trimethoprim.

The ammonia-chlorine process provided less disinfection than either free chlorine or the chlorine-ammonia process. UV combined with the ammonia-chlorine process generally achieved total coliform levels below 2 CFU/100 mL and a 5-log inactivation of poliovirus, but less than 4-log MS2 inactivation. Because UV was more effective than chloramines against MS2, adding UV to an ammonia-chlorine process would likely improve virus disinfection. However, at the dose combinations tested, the combined UV/ammonia-chlorine process might have difficulty demonstrating the ability to meet stringent standards such as the 5-log virus inactivation required by the CA Title 22 regulations for disinfected tertiary recycled water (22 CCR §60301 *et seq*.). Although combined UV/ammonia-chlorine could achieve 5-log poliovirus inactivation, most facilities do not have access to poliovirus and its use in a pilot-scale demonstration is impractical because of safety concerns. MS2 is commonly used as a surrogate, but 5-log inactivation of this organism was not achieved at the doses applied in this study.

The chlorine-ammonia process (which provides brief exposure to free chlorine before chloramines are formed) yielded more efficient disinfection than the ammonia-chlorine process, and free chlorine provided the highest levels of disinfection. Combined UV/free chlorine generally provided 5-log inactivation of poliovirus and MS2, and median total coliform levels below 2 CFU/100 mL in most of the bench- and pilot-scale experiments. In addition, average adenovirus inactivation was generally greater than 5-log with combined UV/free chlorine disinfection, compared to only 2-log inactivation achieved by the highest tested UV dose (100 mJ/cm^2). These results are consistent with other research indicating that adenovirus is more resistant to low-pressure UV than to chlorine (Thompson et al., 2003; Jackson and Thompson, 2008).

THMs were not detected in either the influent to or the effluent from UV treatment, but were found in the chlorinated effluents, and increased in concentration with increasing free chlorine dose. Total THM levels were below the US Environmental Protection Agency (USEPA) drinking water standard of 80 μg/L, and total cyanide levels were generally less than 2 μg/L for all tested disinfection schemes. UV radiation decreased NDMA levels, whereas free chlorination had no significant effect on NDMA concentrations; these results are consistent with literature (Jalali et al., 2005; Drewes et al., 2008).

Of the 43 TrOCs analyzed during the pilot tests, 24 were detected consistently at trace levels in the filtered effluent. Results with the individual disinfectants were consistent with literature data on drinking water (e.g., Snyder et al., 2007). Eleven compounds were strongly removed (>50%) by free chlorine doses of 6 mg Cl_2/L. UV radiation moderately removed (20–50%) five compounds, but increased the concentrations of octylphenol and nonylphenol, possibly because of the breakdown of precursor compounds.

Results indicated that free chlorine generally provided more inactivation of MS2, poliovirus, and total coliforms in filtered effluent than in secondary effluent. In filtered effluent, higher relative chlorine doses often provided more disinfection and TrOC removal than higher relative UV doses (i.e., 4 mg Cl_2/L of free chlorine combined with 33 mJ/cm^2 of UV yielded higher levels of disinfection and TrOC removal than 2 mg Cl_2/L of free chlorine combined with 67 mJ/cm^2 of UV), probably because the full free chlorine dose of 6 mg Cl_2/L provided more disinfection and TrOC removal than the full UV dose of 100 mJ/cm^2 for most microorganisms and compounds. Chlorine-first or simultaneous dosing generally provided more disinfection than UV-first dosing in both bench- and pilot-scale experiments. In some cases, chlorine-first or simultaneous dosing also yielded more disinfection than would be predicted from the additive effects of the individual disinfectants (i.e., synergistic effects). Similar effects were observed for several TrOCs. UV radiation decreased total chlorine residuals, suggesting that it may break down chlorine to radical species.

In summary, the experimental results confirm the benefits of using more than one disinfectant and indicate that the combination of UV and free chlorine is a promising method for the disinfection of recycled water. Combined UV and free chlorine disinfection generally provided equivalent or more disinfection of MS2, poliovirus, and adenovirus than UV alone at the highest tested dose (100 mJ/cm^2), and equivalent or more disinfection of total coliforms than free chlorine alone at the highest tested dose (6 mg Cl_2/L). Literature also indicates that UV is more effective than chlorine against protozoa such as *Cryptosporidium spp.* and *Giardia spp.* (Leong et al., 2008), so adding UV to a free chlorine disinfection process should also improve the disinfection efficiency for these species. In addition, concentrations of DBPs such as THMs and NDMA were lower with combined UV and free chlorine disinfection than with free chlorine alone at the highest tested dose of 6 mg Cl_2/L. Finally, UV and free chlorine removed some TrOCs, and in some cases, acted synergistically to increase their removals.

The results of this study also indicate that disinfection performance may vary with water quality. Site-specific testing is recommended for any facility interested in implementing the combined UV and chlorine disinfection process, to ensure that all relevant disinfection goals and effluent requirements are met.

CHAPTER 1

INTRODUCTION

Disinfection is essential for ensuring the safety of recycled water. In addition to pathogen inactivation, the ideal disinfection process should help to improve the quality of recycled water by minimizing the formation of disinfection byproducts (DBPs) and by reducing concentrations of trace organic constituents (TrOCs), such as hormones, pharmaceuticals, personal care products, endocrine disruptors, and other compounds present in wastewater effluents at low levels.

Most wastewater treatment plants in the United States have historically used chlorine for disinfection and continue to do so today. A recent Water Environment Research Foundation (WERF) survey found that chlorine disinfection was used by approximately 75% of publicly owned treatment works (POTWs) in the United States with design capacities of greater than 1 MGD (Leong et al., 2008). However, recent concerns over chlorine safety and security, regulatory requirements, and DBPs are causing a shift: more than 20% of the POTWs in the WERF survey were using ultraviolet (UV) disinfection.

In addition to the shift toward UV disinfection, increasing attention has been paid to disinfection schemes that use more than one disinfectant. The combination of UV and chlorine is logical, because these are the most common disinfectants used at POTWs (Leong et al., 2008), and a combined system could take advantage of existing infrastructure and would require the addition of only one disinfectant. Furthermore, the plant operating staff would be familiar with at least one of the disinfectant systems and may be familiar with both if the facility had recently changed from chlorine to UV disinfection, or vice versa.

A disinfection scheme that combines UV and chlorine can provide increased disinfection efficacy against a wider range of pathogens than disinfection processes employing only one disinfectant. For example, protozoa such as *Giardia spp.* and *Cryptosporidium spp.* are resistant to chlorine, but are easily inactivated by UV radiation. Conversely, adenovirus is more easily inactivated by free chlorine than by low pressure UV radiation (Jackson and Thompson, 2008). In addition to pathogen inactivation, UV and chlorine can both remove different TrOCs (Snyder et al., 2007).

Combined UV and chlorine disinfection may increase reliability by providing a backup in case one system encounters problems, for example, UV system power failure, low UV transmittance (UVT), or high chlorine demand. UV disinfection process guidelines (Melin, 2003) and/or regulatory authorities generally call for significant redundancy in UV systems; chlorine may provide this redundancy, thereby reducing overall system cost. Further, chlorine can produce a disinfectant residual in effluents, but UV does not. This residual can help to maintain disinfection throughout a recycled water distribution system.

Combining UV and chlorine might also allow the use of lower doses of each disinfectant. Lower chlorine doses would likely reduce the levels of DBPs such as trihalomethanes (THMs), N-nitrosodimethylamine (NDMA), and cyanide. Lower UV doses would require a smaller, more economical system. Because UV systems are usually designed for peak flows, it may be possible to design them for average flows and use chlorine to provide additional

disinfection during peak flows thereby substantially reducing the size and cost of the UV system.

Combining UV and chlorine may provide synergistic or antagonistic effects. Dosing chlorine before UV may increase the transmittance of the UV influent, making UV radiation more effective. UV radiation might also create chlorine or hydroxyl radicals that could increase disinfection efficiency and TrOC removals. Conversely, UV-induced degradation of chlorine could reduce disinfection efficacy and TrOC removal by reducing chlorine concentrations and/or absorbing UV radiation.

To date, performance data on combinations of UV and chlorine have been limited. Previous studies have:

- generally not focused on recycled water quality;
- been conducted at bench-scale batch systems, rather than in continuous flow pilot- or full-scale systems;
- not evaluated DBP formation or TrOC removals; and
- not provided systematic data for evaluation and optimization of disinfectant application order and the relative doses of UV and/or chlorine.

Given these gaps in knowledge, the goal of this project was to investigate combinations of UV with free chlorine or chloramines with respect to:

- disinfection efficacies for poliovirus, adenovirus, MS2 coliphage (MS2), and total coliforms in recycled effluents;
- formation of disinfection byproducts and the removal of TrOCs; and
- effects of water quality, UV and chlorine doses, disinfectant application order, and synergsim.

Chapter 2 provides a literature review on combined UV and chlorine disinfection. Chapter 3 describes the methods and materials used for bench-scale and pilot-scale experiments. Chapter 4 presents bench-scale experimental results for combinations of UV and free chlorine, the ammonia-chlorine process (chloramines formed by addition of ammonia, then free chlorine), and the chlorine-ammonia process (chloramines formed by the addition of free chlorine, then ammonia). Disinfection of poliovirus, MS2, and total coliforms were tested in fully nitrified secondary effluent (secondary effluent), fully nitrified filtered secondary effluent (filtered effluent), and chlorine-demand-free buffer; adenovirus was tested in two experiments with filtered effluent. Chapter 5 presents results of pilot-scale experiments with combined UV/free chlorine in filtered effluent. MS2 and total coliform levels were measured in all experiments, whereas adenovirus was measured in selected experiments. Some samples were analyzed for DBPs and TrOCs. The effects of disinfectant application order and synergism were evaluated in both bench- and pilot-scale experiments (Chapters 4 and 5 respectively). Chapter 6 summarizes the project results.

CHAPTER 2

LITERATURE REVIEW

This chapter provides the rationale for this project and the state of knowledge on combined disinfection with ultraviolet (UV) radiation and chlorine. Section 2.1 covers background information on chlorination and UV radiation, the two main disinfection technologies used by wastewater treatment plants in the United States (US) today. Advantages of each individual disinfectant are discussed, as well as the shortcomings that have led to the development of alternative methods. Section 2.2 provides an overview of the use of multiple disinfectants. This includes combinations of disinfectants for both water and wastewater treatment and provides an overview of the current state of combined disinfection. Section 2.3 focuses on the combined use of chlorine and UV, because they have the highest application potential in wastewater treatment. Specifically, this section examines the interactions of chlorine and UV, their combined disinfection efficacy, DBPs, and the selection of appropriate microbial surrogates. Section 2.4 summarizes the state of knowledge, and highlights some of the gaps in knowledge that this project addressed.

2.1 BACKGROUND

Agencies that produce recycled water are often faced with the dilemma of ensuring that the water is disinfected adequately and reliably, and minimizes DBP levels. There is also increasing concern about TrOCs such as endocrine disrupting compounds, pharmaceuticals, and personal care products. Finally, agencies must produce recycled water cost-effectively in a manner that ensures the safety of their employees and neighboring communities.

Chlorination has long been the most common technology for wastewater disinfection and remains the dominant disinfectant in the US today. However, because of concerns over safety and DBPs, the use of alternatives such as UV disinfection is growing. Of the more than 4,000 POTWs in the US with design capacities >1 MGD, approximately 75% use chlorination and >20% use UV disinfection (Leong et al., 2008). The following sections describe the advantages and disadvantages of these disinfection technologies.

2.1.1 Disinfection with Chlorine Species

Chlorination for disinfection can utilize breakpoint chlorination with free chlorine, or chloramination with combined chlorine (chloramines). Most facilities disinfect with chloramines for several reasons:

- Most POTW effluents contain ammonia. When chlorine is added for disinfection, the two compounds react to form chloramines. Free chlorine is not typically present because very high chlorine doses would be required (breakpoint chlorination).

- Because free chlorine forms compounds that have suspected adverse human health effects (DBPs such as THMs and haloacetic acids [HAAs]), even plants with nitrified effluents (low effluent ammonia levels) often use chloramines for disinfection.

- Some regulatory agencies require a high chlorine residual concentration and contact time for recycled water. Because free chlorine is highly reactive, it is difficult to maintain free chlorine residuals for extended periods of time without generating high DBP levels.

Disinfection with chloramines minimizes these specific issues because chloramines can be used in effluents containing ammonia while generating only relatively low THM and HAA levels and producing a relatively stable disinfectant residual. However, recent studies have shown that chloramines react with dimethylamine (DMA) to produce the carcinogen NDMA (Mitch and Sedlak, 2002). The CA Department of Public Health (CDPH) has established a notification level of 10 ng/L for NDMA in drinking water; notification levels are health-based advisory levels established by CDPH for chemicals of concern that lack drinking water standards. These notification levels can impact indirect potable reuse projects where NDMA treatment to below the notification level may be required, or National Pollutant Discharge Elimination System (NPDES) permits where the discharge has reasonable potential to cause or contribute to a violation of a water quality standard. In addition, regulatory limits on effluent ammonia and nitrogen levels are becoming increasingly stringent because of concerns over aquatic toxicity, nitrate contamination of groundwater, and algal growth. Because most of the nitrogen in chloramines reverts to ammonia upon dechlorination (prior to discharge), plants using chloramination may have difficulty meeting low ammonia discharge limits.

Many wastewater treatment plants have implemented biological nitrogen removal to produce effluents containing low ammonia levels. These low ammonia levels have made breakpoint chlorination a feasible disinfection alternative. Laboratory and full-scale tests indicate that free chlorine forms much less NDMA than chloramines (Huitric et al., 2006). In addition, breakpoint chlorination at CT doses between 40 and 300 mg-min/L (where CT is the product of the total chlorine residual and the contact time) maintained total THM levels below the drinking water standard of 80 µg/L and produced effluents containing low total coliform levels (Huitric et al., 2006). Several researchers have also reported that free chlorine provides the additional benefit of reducing concentrations of some TrOCs in recycled water at doses typically used for drinking water disinfection (Drewes et al., 2006; Snyder et al., 2007; Drewes et al., 2008). Table 2.1 summarizes literature reports of free chlorine effects on TrOCs.

2.1.2 Disinfection with UV Radiation

Because of some of the issues described earlier, as well as safety concerns with chlorine gas, the use of UV radiation for disinfection is growing. Properly designed and operated UV systems can effectively inactivate many indicator organisms and pathogens with very few byproducts (Leong et al., 2008). A review of six papers indicated that UV does not form THMs, HAAs, or cyanide, although low levels of aldehydes, glyoxyl, and nitrite have been observed (Leong et al., 2008). At a dose of 100 mJ/cm^2, UV radiation can remove approximately 0.2-log NDMA (Jalali et al., 2005); however, 1-log NDMA removal typically requires doses > 500 mJ/cm^2 (Wilczak et al., 2003). As shown in Table 2.1, UV can also remove some TrOCs at the doses used for drinking water disinfection (Drewes et al., 2006; Snyder et al., 2007; Drewes et al., 2008).

Table 2.1. Summary of Literature: Reactivity of TrOCs With Free Chlorine and UV

Compound	Free Chlorine Effect (Percent Removal Reported in Literature)			UV Effect (Percent Removal Reported in Literature)		
	Strong (>50%)	Moderate (20-50%)	Weak (<20%)	Strong (>50%)	Moderate (20-50%)	Weak (<20%)
Atenolol	–	–	a	–	–	–
Carbamazepine	–	–	a, b	–	a	b
DEET	–	–	a, b	–	–	a, b
Diclofenac	a, b	–	–	a, b	–	–
Dilantin	–	–	a, b	–	–	b
Erythromycin[-H_2O]	a, b	–	–	–	–	a, b
Estrone	a, b, c	–	–	–	–	a, b
Fluoxetine	–	–	a, b	–	–	a, b
Furosemide	–	–	–	–	–	–
Gemfibrozil	a, b	–	–	–	–	a, b
Iopromide	–	–	a, b	–	–	b
Metoprolol	–	–	a	–	–	–
Nonylphenol	a	c	–	–	–	c
Sulfamethoxazole	a, b	–	–	b	a	–
TCEP	–	–	a, b	–	–	a, b
TCPP	–	–	–	–	–	a
TDCPP	–	–	–	–	–	a
Triclosan	a, b	–	–	b	–	–
Trimethoprim	a, b	–	–	–	–	a, b

[a]Drewes et al. (2008): chlorine doses of 1 mg-Cl/mg-C, 24 h contact time, pH 8; UV doses of 30-40 mJ/cm^2

[b]Snyder et al. (2007): chlorine doses of 3 mg/L, 24 h contact time, pH 7.9-8.5; UV doses of 40 mJ/cm^2

[c]Drewes et al. (2006): chlorine doses of 3.5 mg/L, 35 min contact time; UV dose not specified

Although progress has been made in UV disinfection technology and equipment, some issues remain with equipment validation, system design, and operation (Tang et al., 2006). For example, UV does not provide a disinfectant residual for distribution systems, so it may be desirable to add chlorine or other disinfectants before delivery to end users. In addition, UV is relatively weak against adenovirus (the most UV-resistant health-related virus), although recent data indicate that 4-log inactivation of adenovirus in finished filtered drinking water may be achieved with medium pressure (MP) lamps at doses of <60 mJ/cm^2 and with pulsed UV at doses of <40 mJ/cm^2 (Linden et al., 2007a). For recycled water, the National Water Research Institute (NWRI) and American Water Works Association (AWWA) Guidelines recommend a UV dose of 100 mJ/cm^2, based on a target of 5-log poliovirus inactivation (Melin, 2003); this dose provides approximately 2-log adenovirus inactivation in drinking water (USEPA, 2006). Although there is currently no consensus on the level of adenovirus inactivation required for adequate protection of public health, researchers have sometimes used a benchmark of 4-log inactivation (Thompson et al., 2003; USEPA, 2006; Linden et al.,

2007a). The UV doses that would be required to meet this benchmark with low pressure (LP) lamps are much higher than the currently recommended dose (Thompson et al., 2003; USEPA, 2006), and LP UV systems designed to meet this benchmark would be more costly than chlorination systems.

2.1.3 Factors Affecting Disinfection

The following parameters can affect disinfection rate and extent:

- Temperature influences reaction rates and therefore the disinfection kinetics of chlorine and chloramines (Leong et al., 2008). Temperature can also affect UV disinfection, but the magnitude of the effect depends on the organism and is generally small (USEPA, 2006).

- pH can affect disinfection by altering the speciation of both chlorine (between hypochlorous acid and hypochlorite) and chloramines speciation (between monochloramine and dichloramine; Leong et al., 2008); pH has no known impact on UV disinfection (USEPA, 2006).

- Particulate material and dissolved compounds can shield microorganisms and reduce disinfection efficacy by reacting with chlorine or chloramines, or by absorbing/deflecting UV radiation. Dietrich et al. (2007) estimated that free chlorine penetrated and disinfected particles up to 45–80 μm in diameter with an initial residual of 50–60 mg/L and a contact time of 45 min. Based on data such as these, filtration to remove particles is recommended as a treatment process for effective disinfection with either UV radiation or chlorine species.

2.2 SEQUENTIAL DISINFECTION

It is challenging to find a single disinfectant that can meet all desirable disinfection goals. Combined or sequential uses of more than one disinfectant deserve consideration because they have the potential to:

- inactivate a wider range of organisms than single disinfectants,

- yield synergistic effects,

- reduce overall DBP formation,

- provide operational flexibility, and

- reduce costs (Leong et al., 2008).

Because of these benefits, utilities are likely to increasingly use disinfection processes that employ more than one disinfectant (Wallis-Lage et al., 2004). For example, the 80-MGD Lake Pleasant, AZ, Water Treatment Plant inactivates pathogens and reduces DBP formation with sequential disinfection using UV followed by free chlorine. The UV system provides primary disinfection, and free chlorine is used to maintain a disinfectant residual in the distribution system (Waer et al., 2005; Greenberg, 2009).

2.2.1 Experiences From the Water Industry

Most reported information on combined disinfection comes from the water treatment industry, where the sequential or simultaneous application of two or more disinfectants for drinking water disinfection has been increasing (USEPA, 1999). In drinking water disinfection, the primary disinfectant is typically used for pathogen inactivation, whereas the secondary disinfectant is used to provide a disinfectant residual in the distribution system. Disinfectant combinations that have been tested include:

- chlorine/chlorine
- chlorine/chloramines
- chlorine dioxide/chlorine dioxide
- chlorine dioxide/chloramines
- ozone/chlorine
- ozone/chloramines
- UV/chlorine
- UV/chloramines

In a two-year study of 35 water treatment facilities, 11 different combinations of chlorine, chloramine, chlorine dioxide, and ozone were evaluated for disinfection efficacy and DBP formation (USEPA, 1999). Inactivation of coliform bacteria, *Giardia* cysts, *Cryptosporidium* oocysts, and Poliovirus I appeared to improve when combined disinfectants were used; the inactivation of Hepatitis A virus and MS2 appeared to be lower with combined disinfectants than with a single disinfectant; and the inactivation of spores appeared to be the same for both single and combined disinfectants. The quantities and types of DBPs formed were site-specific and depended on water quality, disinfectant dose, and type.

2.2.2 Applications of Combined Disinfection in Wastewater Treatment

Several studies have investigated combining disinfectants for wastewater treatment and reclamation. Successful wastewater disinfection of reclaimed water was achieved for combinations of peracetic acid (PAA) and UV (Gori et al., 2004; Lubello et al., 2004; Caretti and Lubello, 2003; Liberti and Notarnicola, 1999). Koivunen and Heinonen-Tanski (2005) reported synergistic disinfection effects for combinations of PAA and UV for all enteric bacteria tested; less synergism was observed for coliphage. Diaz et al. (2001) found a synergistic effect between ozone and UV in the reduction in aerobic plate count bacteria in poultry-processing chiller water. Folch et al. (2003) found that lower disinfectant doses could be used for recycled water disinfection when ozone and chlorine dioxide were combined and used in conjunction with physical-chemical treatment processes. A more detailed discussion on the application of combined disinfection of wastewater appears in Leong et al. (2008).

2.3 COMBINED USE OF UV RADIATION AND CHLORINE

UV and chlorination are the most commonly used individual disinfection processes for wastewater, and a wealth of information exists on their performance and operation. Because a chlorination or UV system is often already in place at a wastewater treatment plant, implementation of combined UV/chlorination systems is relatively straightforward. For example, in 1996, the Vallejo Sanitation and Flood Control District replaced chlorine gas with a medium-pressure (MP) UV system, coupled with sodium hypochlorite for backup during wet weather periods. After start-up, several issues caused the District to operate both UV and sodium hypochlorite systems in series; the sequential application of UV and sodium hypochlorite has provided reliability and economy (Tekippe et al., 1999).

To better understand the combined use of UV and chlorine, Section 2.3.1 describes the effects that UV and chlorine have on each other. These interactions may help explain experimental results for disinfection efficacy (Section 2.3.2) and DBPs (Section 2.3.3). Section 2.3.4 discusses selection of an appropriate microbial surrogate for combined disinfection, based on literature reports.

2.3.1 Interaction of UV Radiation and Chlorine Species

2.3.1.1 Effects of Chlorine Species on UV Radiation

Ormeci et al. (2001, 2005) investigated whether chlorine species absorb UV light and/or oxidize organic matter. They found that up to 5 mg/L of chlorine species did not significantly impact the UVT of water, and that their presence was unlikely to have a significant influence on UV disinfection. A numerical model based on their experimental results predicted that 1 mg/L monochloramine or free chlorine would decrease MS2 inactivation by <0.1-log for a UV reactor with LP lamps, and between 0.1 to 0.3 log for a reactor with MP lamps (Ormeci et al., 2005).

2.3.1.2 Effects of UV Radiation on Chlorine Species

Although prechlorination appears to have little impact on UV disinfection, UV radiation may degrade chlorine species. Compounds that absorb UV light at 254 nanometers (nm) may undergo direct photolysis when exposed to monochromatic LP lamps. MP lamps emit at a wider range of wavelengths and may therefore degrade a broader range of compounds. Table 2.2 presents UV absorption data for several chlorine compounds. Ormeci et al. (2005) found that the amplitudes of the chlorine and chloramine absorbance peaks were similar for a given concentration but that the free chlorine peak occurred at approximately 290 nm, whereas the chloramine peak occurred at approximately 250 nm. Li and Blatchley (2007) found that trichloramine (NCl_3) absorbed more strongly than free chlorine at all wavelengths. Based on these data, NCl_3 would be expected to degrade more easily than free chlorine or chloramines. For a given amount of total UV energy, the monochromatic radiation at 254 nm from LP lamps should degrade more chloramines (absorption peak ~250 nm) than polychromatic radiation, whereas polychromatic radiation from MP lamps will degrade more free chlorine than monochromatic radiation at 254 nm from LP lamps.

Table 2.2. Peak Absorbance Data on Selected Chlorine Compounds

Compound	Absorbance Peak (nm)	Absorbance Peak (nm)	Source
Cl_2	220	290*	Li and Blatchley, 2007
Cl_2	<220	290	Ormeci et al., 2005
NH_2Cl	<220	240-255	Ormeci et al., 2005
NCl_3	<200	—	Li and Blatchley, 2007
CH_3NCl_2	<200	290*	Li and Blatchley, 2007

*Values are approximated from figures in the paper.

Experimental data generally support these hypotheses: Chlorine decay increases in the presence of UV and continues to increase as UV dose increases (Gurol and Itell, 1989; Ormeci et al., 2005; Li and Blatchley, 2007). Li and Blatchley (2007) exposed compounds to 0.56 mW/cm^2 of UV light at 254 nm for 10 min at an estimated UV dose of ~336 mJ/cm^2 and found that NCl_3 degraded much more rapidly than NaOCl; neither compound degraded in the dark. Ormeci et al. (2005) performed decay tests with free chlorine and chloramines in three types of water (deionized water, treated drinking water, and raw drinking water), and with two lamp types (low pressure and medium pressure). In all tested waters, monochloramine decay was more rapid under monochromatic light at 254 nm than under polychromatic light. In the raw waters and treated (drinking) waters, free chlorine decayed slower under monochromatic light at 254 nm than under polychromatic light. In addition, as the water quality increased from raw drinking water to treated drinking water to DI water, free chlorine decay rates decreased, whereas chloramine decay rates remained roughly the same.

These trends were obtained using much higher UV doses than those typically used for wastewater disinfection (100 mJ/cm^2). Li and Blatchley (2007) used doses of approximately 100 to 500 mJ/cm^2, Ormeci et al. (2005) used doses of 100 to 1,500 mJ/cm^2, and Gurol and Itell (1989) used doses of roughly 250 to 3,000 mJ/cm^2. In the experiments that used a dose of 100 mJ/cm^2, Ormeci et al. generally observed <5% change in free chlorine and chloramine levels, with measured concentrations increasing in some cases. The only exception was a raw drinking water (the poorest quality water used) exposed to MP lamps at a UV dose of 100 mJ/cm^2 and a chlorine dose of roughly 4.7 mg/L. Free chlorine concentrations in this sample decreased approximately 1.9 mg/L, whereas the sample kept in the dark lost approximately 1.5 mg/L. Because the rate of chlorine degradation increased as the water quality decreased, decay rates in wastewater effluents may be even higher; measurements are needed to determine whether UV radiation causes significant chlorine species losses.

UV radiation may also alter the distribution of chlorine species. Cassan et al. (2006) tracked total, free, and combined chlorine concentrations in a chlorinated indoor swimming pool, with and without UV, for one week each (8 samples/day). Continuous use of medium-pressure UV lamps at a dose of 145 mJ/cm^2 decreased the level of combined chlorine, and increased the levels of total and free chlorine. Total chlorine concentrations increased from 2.4 ± 0.2 mg/L to 2.6 ± 0.3 mg/L, free chlorine concentrations increased from 1.7 ± 0.2 mg/L to 2.1 ± 0.2 mg/L, and combined chlorine concentrations decreased from 0.6 ± 0.2 mg/L to 0.4 ± 0.2 mg/L. Although a statistical analysis of variance indicated that these changes in chlorine levels were significant, the absolute changes in concentrations were small.

2.3.2 Efficacy of Combined UV and Chlorine Disinfection

Combining UV and chlorine may provide multiple benefits. In pilot plant tests with drinking water, Magara et al. (1996) found that UV followed by free chlorine or chloramines maintained disinfection more effectively in a water distribution system than any of the individual disinfectants. In addition, sequential application of UV and chlorine has the potential to reduce required disinfectant doses. For example, Kinshella et al. (2007) found that UV treatment alone required a dose of at least 100 mJ/cm^2 to achieve non-detect fecal coliforms (<1.6 CFU/100 mL) in a tertiary treated effluent, and chlorine alone only achieved non-detect concentrations at a chlorine dose of 10 mg/L and a contact time of 20 min. Pre-oxidation with 2 to 10 mg/L of chlorine reduced the required UV dose to 10 to 40 mJ/cm^2. In bench studies, Murphy et al. (2007) found that chlorine-based disinfectants in combination with UV radiation were generally more effective than UV, ClO_2, or Cl_2 alone for reducing heterotrophic bacteria. UV/Cl_2 was the most effective disinfection method. Sobotka and Kryzystofik (1984) studied disinfection of water in large swimming pools and found that, with the use of UV, the chlorine residual in the pool could be reduced from 0.4 to 0.2 mg/L.

2.3.2.1 Adenovirus Inactivation

Adenovirus is more resistant to UV radiation than to free chlorine (Jackson and Thompson, 2008). Table 2.3 shows the results of bench-scale studies on drinking water, where dual disinfection with UV and chlorine was much more effective than UV alone for adenovirus inactivation.

In all of the three studies shown in Table 2.3, a 1-log adenovirus inactivation was achieved with a UV dose of 40 mJ/cm^2. Ballester and Malley (2004) and Baxter et al. (2007) found that free chlorine was a much more effective disinfectant than preformed chloramines and yielded higher levels of inactivation at much lower doses. Ballester and Malley (2004) found that the ammonia-chlorine process (chloramines formed when ammonia was added to the sample, followed by free chlorine) yielded comparable disinfection at lower doses than preformed chloramines. Similarly, Durance et al. (2005) found that UV in combination with free chlorine provided more disinfection at much lower chlorine doses than UV in combination with preformed chloramines.

Ballester and Malley (2004) also observed synergistic effects when UV was combined with the ammonia-chlorine process. The ammonia-chlorine process alone at a CT of 41 mg-min/L and UV alone at a dose of 40 mJ/cm^2 each yielded 1-log inactivation, but 40 mJ/cm^2 of UV combined with the ammonia-chlorine process at a CT of 27 mg-min/L yielded up to 4-log inactivation. However, Baxter et al. (2007) did not observe synergistic effects and found no statistically significant difference in disinfection between preformed monochloramine at a CT of 350 mg-min/L, with and without a UV dose of 40 mJ/cm^2.

In addition to these studies, recent experiments conducted by the Sanitation Districts of Los Angeles County (Districts) indicated that the sequential use of UV and free chlorine was more effective than UV alone for adenovirus inactivation (Jackson and Thompson, 2008). A 4-MGD UV pilot system with low-pressure high-output lamps was used to deliver doses of 76 to 101 mJ/cm^2 to recycled water; doses were calculated using a laboratory collimated beam bioassay. The adenovirus detection limit varied across experiments, between approximately 0.02 and 1 MPNIU/100L. Adenoviruses were detected in two tests with delivered UV doses of 76 and 101 mJ/cm^2, but not in the third test with a delivered UV dose of 119 mJ/cm^2. In contrast, UV radiation (77 to 95 mJ/cm^2) in conjunction with free chlorine (doses of 0.5 to 1.5 mg/L) reduced adenovirus concentrations to below detection levels in five of six experiments.

Table 2.3. Disinfection of Adenovirus in Drinking Water With Low Pressure UV and Various Chlorine Disinfectants

		Durance et al., 2005		Ballester and Malley, 2004		Baxter et al., 2007	
Disinfection Method	**Dose Units**	**Dose**	**Log Inactivation**	**Dose**	**Log Inactivation**	**Dose**	**Log Inactivation**
UV alone	mJ/cm^2	40	1	40	1	40	1
Free chlorine (Cl_2) alone	mg-min/L	NR	NR	1.2	3.7	0.22	4
Preformed chloramines (NH_2Cl) alone	mg-min/L	NR	NR	265	1.2	350	2.5
Ammonia-chlorine process ($NH_3 + Cl_2$) alone	mg-min/L	NR	NR	41	1	NR	NR
UV + free chlorine (Cl_2)	mJ/cm^2 + mg-min/L	40 + 0.15	4	NR	NR	NR	NR
UV + preformed chloramines (NH_2Cl)	mJ/cm^2 + mg-min/L	40 + 350	2.5	NR	NR	40 + 350	~2.5
UV + ammonia-chlorine process ($NH_3 + Cl_2$)	mJ/cm^2 + mg-min/L	NR	NR	40 + 27	Up to 4	NR	NR

Note. NR= not reported.

2.3.2.2 Inactivation of Other Organisms

Kashinkunti et al. (2004) found that the application of free chlorine to drinking water (with a residual of 1 mg/L and contact time of 24 h) after any UV dose resulted in extensive inactivation of *E. coli*, MS2, and PRD-1 viruses. Ryu et al. (2007) modeled human health risks for *Cryptosporidium* oocysts and *Giardia* cysts in non-potable tertiary-treated recycled water and determined that the risk of infection was lower with combined UV/chlorine disinfection than with chlorine alone.

2.3.2.3 Effects of Disinfectant Application Order

The existing literature suggests that disinfection performance may be affected by the order in which disinfectants are applied. However, results are conflicting: one study found that simultaneous dosing of UV and chlorine (free chlorine or chloramines) was more effective than applying UV first (i.e., before chlorine), whereas two other studies indicated that applying UV first was more effective than applying chlorine first. Shang et al. (2007) tested UV doses of 17 mJ/cm^2 in combination with 1 mg Cl_2/L of free chlorine or 7 mg Cl_2/L of chloramines in a phosphate buffer solution. Simultaneous dosing yielded higher levels of MS2 inactivation than when UV was applied first; this effect was more evident for free chlorine than for chloramines. Using *Bacillus subtilis* spores in laboratory water samples, Zhang et al. (2006) found that a UV dose of 40 mJ/cm^2 followed by chlorination at a CT value of 300 mg-min/L achieved 6.2-log reduction, whereas the reverse order of disinfectant addition yielded a 3.9-log reduction. Linden et al. (2004) tested secondary effluent samples from two wastewater treatment plants with typical ammonia concentrations of 0.5 and 3 mg N/L. Using UV doses of less than 40 mJ/cm^2 and initial total chlorine residuals of 10 mg Cl_2/L, they found that UV-first doses provided more inactivation of *Clostridium perfringens* spores than chloramine-first doses.

2.3.2.4 Synergistic and Antagonistic Effects

Literature reports disagree on whether the combination of chlorine and UV is synergistic, additive, or antagonistic. In field studies, Murphy et al. (2007) observed synergistic effects in the control of microbial regrowth in a drinking water distribution system when UV radiation was followed by chlorine-based disinfection. Shang et al. (2007) also observed synergistic effects when low pressure or medium pressure UV was combined with free chlorine or chloramines. Ballester and Malley (2004) observed synergistic effects on adenovirus disinfection when UV was combined with the ammonia-chlorine process, but Baxter et al. (2007) observed no synergism when UV was combined with preformed chloramines. Cho et al. (2006) found no synergism in the inactivation of *Bacillus subtilis* spores during sequential application of UV and free chlorine, regardless of which disinfectant was applied first. Potapchenko et al. (1993) studied *Escherichia coli* disinfection using combined chlorine at doses of 0.2 to 1 mg/L with UV, and found antagonism at a chlorine concentration of 1.0 mg/L and at UV doses up to 7 mJ/cm^2. For *Bacillus subtilis* spores in laboratory water samples, Zhang et al. (2006) found 0.5-log reduction with chlorine alone at a CT value of 300 mg-min/L, and 3.3-log reduction with a UV dose of 40 mJ/cm^2. Combining these doses with chlorination followed by UV achieved 3.9-log reduction (essentially additive), whereas UV followed by chlorination exhibited synergism with a 6.2-log reduction. These discrepancies may be caused by a number of factors, including the water quality, the organisms tested, or the order of the disinfectant application.

2.3.3 DBP Formation During Combined UV and Chlorine Disinfection

Chlorination can generate THMs, HAAs, and other compounds such as NDMA, cyanide, and cyanogen chloride. In contrast, UV alone at typical doses generates few DBPs; small increases were observed in concentrations of aldehydes, carboxylic acids, and nitrite (Liu et al., 2002; Linden et al., 2007b). The addition of UV radiation to chlorination may alter the quantities and types of DBPs by generating radicals that can form DBPs, as suggested by Gurol and Itell (1989), Cassan et al., (2006), Watts and Linden (2007).

Table 2.4 shows that the effects of combined UV/chlorine on DBPs vary widely. For example, the combination of UV and chlorine increased, decreased, or did not affect THM concentrations relative to chlorination alone. Rand et al. (2007) and Gurol and Itell (1989) observed lower THM levels with chlorine alone than with combined UV/chlorine. Because Gurol and Itell also found that chlorine decay rates were higher in the presence of UV and increased with the UV intensity, they suggested that UV-generated chlorine atoms might produce more THMs than chlorine molecules.

Table 2.4. DBP Formation With Combined UV/Chlorine, Relative to Chlorine Alone

Byproduct	Change	Order	Lamp Type	Source
THMs	Increase	UV + Cl_2	LP	Rand et al., 2007
THMs[1]	Increase	Simultaneous	LP	Gurol and Itell, 1989
THMs	No Change[2]	UV + Cl_2	LP, MP, Pulsed	Liu et al., 2002
THMs	Decrease[3]	UV + Cl_2	LP, MP, Pulsed	Liu et al., 2002
Chloroform	Increase	Simultaneous	MP	Cassan et al., 2006
Bromodichloromethane	Increase	Simultaneous	MP	Cassan et al., 2006
Chlorodibromomethane	Decrease	Simultaneous	MP	Cassan et al., 2006
Bromoform	Decrease	Simultaneous	MP	Cassan et al., 2006
HAAs	No Change	UV + Cl_2	LP	Rand et al., 2007
HAAs	No Change[2]	UV + Cl_2	LP, MP, Pulsed	Liu et al., 2002
HAAs	Decrease[3]	UV + Cl_2	LP, MP, Pulsed	Liu et al., 2002

[1]Experiments conducted in aqueous fulvic acid

[2]For UV doses < 1,000 mJ/cm^2

[3]For UV doses > 1,000 mJ/cm^2

Liu et al. (2002) tested low pressure, medium pressure, and pulsed UV and found that UV doses less than 1,000 mJ/cm^2 did not affect THM and HAA formation in subsequent chlorination processes, but UV doses greater than 1,000 mJ/cm^2 decreased concentrations of THMs and HAAs. Cassan et al. (2006) observed both increases and decreases in THM concentrations, depending on the species. For chlorinated water from an indoor swimming pool, medium-pressure UV lamps significantly increased levels of chloroform and bromodichloromethane, but significantly decreased levels of chlorodibromomethane and bromoform. The authors hypothesized that UV photolyzed combined chlorine and that the resulting radicals caused additional chloroform and bromodichloromethane formation.

These studies suggest that the effects of combining UV and chlorine may be compound-specific. For instance, Cassan et al. (2006) observed that the concentrations of some THMs increased with the addition of UV radiation, whereas others decreased. Similarly, Rand et al. (2007) found that THM levels increased with UV, but HAA levels were unaffected. Liu et al. (2006) studied the formation of DBPs with combined UV/chlorine and found that UV had a stronger effect on the subsequent formation of chloroform than on the formation of dichloroacetic acid, trichloroacetic acid, and cyanogen chloride.

In addition to compound-specific effects, Liu et al. (2006) found that in most cases, UV doses from MP lamps (normalized to LP UV doses using MS2 biodosimetry) gave similar or slightly larger changes in DBP yields than the equivalent UV dose with LP lamps; the authors attributed these results to the broader spectrum of radiation from MP UV lamps. Different application sequences changed the relative quantities of some DBPs, but no general trend was found. These data suggest that different DBPs may have different formation mechanisms and reactions, so that observed results may vary with the compound, disinfectant application order, UV lamp type, and water quality.

2.3.4 Microbial Surrogates for Combined UV and Chlorine Disinfection Studies

Tree et al. (1997) compared the inactivation of mono-dispersed laboratory-grown bacterial indicators (*Escherichia coli* and *Enterococcus faecalis*), human enterovirus (poliovirus) and F^+ bacteriophage (MS2) by UV and chlorination. Under their experimental conditions, the inactivation of bacterial indicators was rapid, relative to MS2 inactivation. Seeded poliovirus was more susceptible to inactivation by chlorine and UV radiation than MS2, but was more resistant than bacterial indicators. Because MS2 was more resistant to chlorine and UV radiation than was poliovirus or indicator bacteria, use of MS2 as a surrogate is likely to provide a conservative estimate of virus inactivation for UV disinfection and chlorination.

2.4 SUMMARY

Chlorine and UV are the most commonly used disinfectants in wastewater treatment plants. This literature review indicates that their combined use may provide substantial benefits for disinfection of water and recycled wastewater, including the following:

- Inactivation of a wider spectrum of pathogens. For example, adenoviruses are more resistant to LP UV at conventional doses than other waterborne pathogens, but are susceptible to low doses of free chlorine. Conversely, *Cryptosporidium* is resistant to free chlorine and chloramines, but is susceptible to UV radiation.

- Removal of a wider range of TrOCs, relative to chlorine or UV alone, because each disinfectant reacts with different TrOCs.

- Synergism between two disinfectants such as UV and chlorine to provide more disinfection and/or greater removal of TrOCs than would be predicted from their individual performances.

- Ability to add lower chlorine doses in chlorine/UV disinfection process, thereby reducing DBP formation.

- Ability to maintain a disinfectant residual in recycled water distribution systems by adding chlorine to a UV-only process.

- Ability to reduce the size of a UV system (and capital costs) by adding chlorine. This is particularly important for facilities that are converting to UV and have existing infrastructure for chlorination.

- Improvement of disinfection reliability and operational flexibility by having two disinfectants in a combined chlorine/UV system.

More detailed evaluation of the dual UV/chlorine disinfection of recycled water is needed to fully explore the advantages listed herein. Previous studies did not:

- agree on whether the efficacy of combined UV/chlorine was synergistic, additive, or antagonistic;

- agree on the effects of combined UV/chlorine on DBP formation;

- conduct detailed investigations of adenovirus inactivation in recycled water;

- fully evaluate TrOC removal;

- systematically investigate the effects of relative doses of UV and chlorine;

- conduct extensive pilot-scale studies (if at all).

This study was undertaken to provide additional information on dual disinfection processes using UV and chlorine. The study was structured to produce information that will help utilities evaluate the design and performance of a disinfection system that combines chlorine and UV for the production of recycled water.

CHAPTER 3

EXPERIMENTAL AND ANALYTICAL METHODS

3.1 DISINFECTANTS AND DOSES

UV, free chlorine, and chloramines were used as disinfectants, alone and in combination with each other. Each disinfectant was tested at three doses: the maximum (full) dose, which was applied when only a single disinfectant was tested, and two partial doses. The full UV dose was 100 mJ/cm^2, which is the dose recommended by NWRI/AWWA Guidelines (Melin, 2003) for media-filtered secondary effluents. The full free chlorine dose of 6 mg Cl_2/L was based on prior experience that suggested that 6 mg Cl_2/L and 100 mJ/cm^2 of UV would yield similar levels of virus inactivation at the plant where the study was conducted (unpublished data). The full chloramine CT value (where CT is the product of the total chlorine residual and the contact time) of 450 mg-min/L was based on the CA Title 22 regulations for disinfected tertiary recycled water (22 CCR §60301 *et seq*.), which require a modal contact time at peak dry weather design flow of at least 90 min and CT value of at least 450 mg-min/L.

Combinations of UV and chlorine were also tested to determine whether part of the full chlorine dose could be replaced by UV, and vice versa. Experiments were designed to test the effects of relative dose, i.e., whether disinfection performance was the same for doses that were "mostly UV" vs. "mostly chlorine." Therefore, the experiments tested two different combined UV/chlorine doses. The first was a "mostly UV" dose, in which one third of the full UV dose was replaced by one third of the full chlorine dose (2 mg Cl_2/L of free chlorine or a chloramine CT of 150 mg-min/L). The second was a "mostly chlorine" dose, in which one third of the full chlorine dose was replaced by one third of the full UV dose (33 mJ/cm^2). The following disinfectant application orders were evaluated: UV followed by chlorine, UV and chlorine applied simultaneously, and chlorine followed by UV. Table 3.1 lists the abbreviations used for each of these disinfection schemes.

The partial chloramine CT values could be achieved by reducing either the modal contact time or the total chlorine residual at the end of the contact time. Linden et al. (2004) reported that for a given CT value, different combinations of residuals and contact times did not significantly alter disinfection of *Clostridium perfringens*, somatic coliphage, male-specific coliphage, and *Cryptosporidium parvum*. For this study, partial CT values were achieved by reducing the contact time, because contact time was more easily controlled than total chlorine residual. The residual is expected to be the difference between the applied chlorine dose and the chlorine demand. However, the demand depends on the dose, and doubling the chlorine dose generally less than doubles the total chlorine residual; the exact demand and residual depend on the effluent water quality. Consequently, determining applied doses that would result in the desired residual values would have required involved testing. However, the total chlorine residual was fairly stable once formed, so the one third and two thirds CT values could be obtained simply by reducing the contact time from 90 to 30 or 60 min, respectively.

Table 3.1. Notation for Combined UV/Chlorine Experiments

Description	Notation
UV followed by free chlorine or chloramines	UV-first
Free chlorine or chloramines applied simultaneously with UV	Simultaneous or Sim
Free chlorine or chloramines followed by UV	Chlorine-first
Any order of 2 mg Cl_2/L of free chlorine and 67 mJ/cm^2	2*67
67 mJ/cm^2 followed by 2 mg Cl_2/L of free chlorine	67+2
2 mg Cl_2/L of free chlorine and 67 mJ/cm^2 applied simultaneously	2+67(sim)
2 mg Cl_2/L of free chlorine followed by 67 mJ/cm^2	2+67(seq)
Any order of 4 mg Cl_2/L of free chlorine and 33 mJ/cm^2	4*33
33 mJ/cm^2 followed by 4 mg Cl_2/L of free chlorine	33+4
4 mg Cl_2/L of free chlorine and 33 mJ/cm^2 applied simultaneously	4+33(sim)
4 mg Cl_2/L of free chlorine followed by 33 mJ/cm^2	4+33(seq)
Any order of a chloramine CT of 150 mg-min/L and 67 mJ/cm^2	150*67
67 mJ/cm^2 followed by a chloramine CT of 150 mg-min/L	67+150
Chloramine CT of 150 mg-min/L and 67 mJ/cm^2 applied simultaneously	150+67(sim)
Chloramine CT of 150 mg-min/L followed by 67 mJ/cm^2	150+67(seq)
Any order of a chloramine CT of 300 mg-min/L and 33 mJ/cm^2	300*33
33 mJ/cm^2 followed by a chloramine CT of 300 mg-min/L	33+300
Chloramine CT of 300 mg-min/L and 33 mJ/cm^2 applied simultaneously	300+33(sim)
Chloramine CT of 300 mg-min/L followed by 33 mJ/cm^2	300+33(seq)

3.2 MATERIALS AND ANALYTICAL METHODS

Chlorine was obtained as a 4 to 6% sodium hypochlorite solution (Fisher Scientific). Chlorine stock solutions were prepared daily, at concentrations of 5000 mg Cl_2/L for laboratory experiments, and 750 to 2000 mg Cl_2/L for pilot experiments (Table C12, Appendix C). Chloramines were formed by mixing a 1000 mg N/L aqueous ammonia solution (Environmental Resource Associates, Arvada, CO) and the chlorine stock solution.

The following organisms were measured during experiments: indigenous total coliforms and adenovirus, seeded MS2, poliovirus 1 "chat," and adenovirus Type 6. MS2 (American Type Culture Collection (ATCC #15597B1) was purchased from GAP Enviromicrobial Services (London, Ontario, Canada) and was used as received, with no further seed growth or propagation. Poliovirus (ATCC #VR192, a predecessor to the currently available #VR1562) and adenovirus (ATCC #VR1083) were both obtained from ATCC. Using a slightly modified version of a method in Killington et al. (1996), both poliovirus and adenovirus were propagated by polyethylene glycol precipitation followed by freon extraction. The cell lines used were BGMK for poliovirus and A549 for adenovirus. Virus samples collected for the bench-scale study were not concentrated; 0.2% fetal bovine serum was added directly to the sample, which was then frozen at -80ºC until assay. The samples were thawed and assayed without any further processing. Parasites such as *Giardia* and *Cryptosporidium* were not analyzed, because they are difficult and expensive to quantify accurately, and the effluent used in this study was expected to have low indigenous levels.

Table 3.2 provides the analytical methods and the reporting limits for the chemical and microbial parameters measured during this study. In addition, particle size data were collected for secondary and filtered effluents; details of the measurements and the resulting data are presented in Appendix A.

During the pilot experiments, samples were analyzed for DBPs and TrOCs. Four types of DBPs were measured: THMs, which are common DBPs of concern with free chlorine disinfection; NDMA, which is a DBP of concern with chloramination; and total cyanide and cyanogen chloride, which are DBPs from chlorination that have been increasingly detected in the effluents of wastewater treatment plants (Kavanaugh et al., 2003). The analyzed TrOCs were chosen because they are widely used and/or commonly reported in literature. In total, 43 compounds were measured: acetaminophen, atenolol, atorvastatin, o-hydroxy atorvastatin, p-hydroxy atorvastatin, azithromycin, bisphenol A, caffeine, carbamazepine, clofibric acid, DEET, diclofenac, dichlorprop, dilantin, erythromycin, estradiol, estrone, ethynylestradiol, fenofibrate, fluoxetine, furosemide, gemfibrozil, ibuprofen, iopromide, ketoprofen, mecoprop, metoprolol, naproxen, nonylphenol, octylphenol, phenacetine, primidone, progesterone, propranolol, salicylic acid, simvastatin OH acid, sulfamethoxazole, tris(2-carboxyethyl)phosphine (TCEP), tris(chloroisopropyl)phosphate (TCPP), tris(2,3-dichloropropyl)phosphate (TDCPP), triclosan, triclocarban, and trimethoprim. Detailed descriptions of the TrOC analysis performed by Aqwatec Laboratory (Golden, CO) and the Districts' San Jose Creek Water Quality Laboratory (SJCWQL in Whittier, CA) are presented in Appendix B.

3.3 WATER SAMPLES

One bench-scale experiment was conducted with chlorine-demand-free buffer (DFB). The solution was prepared according to Thurston-Enriquez et al. (2003). The laboratory reagent water used to prepare the buffer was tested before use to ensure that it did not contain any chlorine residual.

Effluent samples for the bench and pilot-scale experiments were taken from the Districts' San Jose Creek West Water Reclamation Plant. Under normal operation, this plant uses primary sedimentation, biological nitrogen removal using a step-feed activated sludge process, secondary sedimentation, and secondary effluent filtration through a deep-bed anthracite medium. In the secondary process, a Mannich-type polymer is mixed with chloraminated final effluent and added to the mixed liquor to enhance solid settling and for foam control. Because the polymer contains DMA that can react with chloramines to form NDMA, NDMA concentrations at this facility may be slightly higher than at plants not using this polymer.

Disinfection is accomplished using both free chlorine and chloramines. Chlorine is added to the secondary effluent (which is virtually free of ammonia) upstream of the filter. Filtered effluent flows into a wet well, and is then pumped into a channel where ammonia and then chlorine are added to form chloramines. This effluent flows through the chlorine contact tanks and is dechlorinated with sulfur dioxide before discharge or reuse. Secondary effluent samples for the laboratory experiments were taken from the secondary effluent channel, upstream of chlorine addition. Filtered effluent samples for laboratory experiments were taken between the filter and the wet well. The effluent supply for the pilot studies was taken from the wet well. For filtered effluent samples, plant operations were modified so that no chlorine was added upstream of the filters.

Table 3.2. Analytical Methods and Reporting Limits for Chemical and Microbial Parameters

Parameters	Analytical Method	Reporting Limit
pH	SM[a] 4500-H^+ B	0.1 pH unit
Chlorine Demand	SM[a] 2350B	0.05 mg Cl_2/L
Free Chlorine Residual	SM[a] 4500-Cl G	0.05 mg Cl_2/L
Total Chlorine Residual	SM[a] 4500-Cl G	0.05 mg Cl_2/L
UVT	Note[b]	Note[b]
Turbidity	SM[a] 2130 B	0.1 NTU
Ammonia Nitrogen	SM[a] 4500-NH_3 H	0.1 mg N/L
Total Kjeldahl Nitrogen	USEPA 351.2, SM 4500-N	0.2 mg N/L
Nitrite Nitrogen	SM[a] 4500-NO_2 B	0.03 mg N/L
Nitrate Nitrogen	SM[a] 4500-NO_3 F	0.2 mg N/L
NDMA	USEPA Method 1625	2 ng/L
Total Cyanide	SM[a] 4500-CN C	5.0 µg/L[c]
Cyanogen Chloride	SM[a] 4500-CN J	5.0 µg/L[c]
Trihalomethanes (THMs)	USEPA Method 8260	2 µg/L[d]
Total COD[a]	USEPA Method 410.1	10 mg/L
Total Coliform	SM[a] 9222B	1 CFU[a]/100 mL[e,f]
MS2	USEPA Method 1601	1 PFU[a]/mL[e]
Poliovirus	Note[g]	0.4 PFU[a]/mL[e]
Adenovirus Type 6 – Laboratory	Note[h]	Note[e,h]
Adenovirus – Pilot	Note[h,i]	~0.001 MPN IU/L[e,h]

[a]CFU = colony forming unit, COD = chemical oxygen demand, MPN IU = most probable number of infectious unit, PFU = plaque forming unit, SM = *Standard Methods* (American Public Health Association, 2005), UVT = ultraviolet transmittance.

[b]UVT was measured with a BioRad SmartSpec 3000, which autocalibrated before each sample measurement.

[c]The method detection limits for total cyanide and cyanogen chloride were 1.0 µg/L; concentrations between 1.0 and 5.0 µg/L were estimated.

[d]Four THM species (chloroform, bromoform, bromodichloromethane, and dibromochloromethane) were measured, and the reporting limit was 2 µg/L for each species. The sum of all four measurements yielded the total trihalomethane (TTHM) concentration; the reporting limit for TTHM concentrations was 8 µg/L.

[e]For microorganisms, reporting limits and method detection limits are equivalent.

[f]The method detection limit is 1 CFU/100 mL; however, only 50 mL of sample (half the standard sample volume) was available for the laboratory tests, so the reporting limit was 2 CFU/100 mL in those tests.

[g]Plaque assays for poliovirus used a modified version of Chapter 10 of the USEPA *Manual of Methods for Virology* (USEPA, 1989). Analysis used the BGM cell line, obtained from the USEPA.

[h]The adenovirus method was developed at the Districts, as documented in Thompson et al. (2003) and used cell line A549 (ATCC #CCL185), obtained from ATCC.

[i]A modified version of Standard Method 9510C was used to concentrate samples, and a modified version of Standard Method 9510G was used for quantification. The cell line used was A-549, obtained from ATCC. The detection limit depends on the sample volume; for the 300-gallon samples taken during the pilot experiments, the detection limit was approximately 0.001 infectious units/L.

Tables 3.3 through 3.5 summarize measured water quality data for the DFB, filtered effluent, and secondary effluent. Detailed data from each experiment are provided in Tables C1 through C5 of Appendix C. Details on the water quality samples taken during the bench- and pilot-scale experiments are provided in Sections 3.5 and 3.6, respectively.

Table 3.3 shows that ammonia levels for both the DFB and filtered effluent were generally below reporting limits, while the secondary effluent ammonia concentration averaged 0.14 mg N/L. The DFB sample had the highest UVT value and COD concentration, and the lowest levels of chlorine demand, turbidity, total Kjeldahl nitrogen (TKN), nitrate, and nitrite; the presence of chlorine demand in the DFB sample is likely due to organics associated with the seeded MS2 stock. Relative to the secondary effluent samples, the filtered effluent samples had higher levels of nitrate and lower levels of chlorine demand, TKN, and particle concentrations (Tables 3.3 and 3.4). Other parameters had similar concentrations in the secondary and filtered effluents. Seeding increased the total COD of the samples, but otherwise did not change the water quality. Table 3.5 indicates that water quality was fairly constant between the beginning and end of each pilot experiment.

3.4 DISINFECTION BENCHMARKS

Disinfection benchmarks were based on two requirements of the CA Title 22 regulations for disinfected tertiary recycled water: ≥ 5-log inactivation of poliovirus or MS2 and a 7-day median concentration of ≤ 2.2 MPN/100 mL total coliforms. The NWRI/AWWA Guidelines on UV disinfection (Melin, 2003) used the 5-log poliovirus benchmark in recommending a UV dose of 100 mJ/cm^2 for recycled water, and CDPH has historically required that new UV systems demonstrate the ability to provide this recommended dose. However, the NWRI/AWWA Guidelines also note that MS2 is more resistant than poliovirus to UV disinfection, and that the recommended dose of 100 mJ/cm^2 should yield 3.5 to 4.6-log inactivation. Accordingly, the benchmarks for this study were 4-log inactivation of MS2, 5-log inactivation of poliovirus, and ≤ 2.2 MPN/100 mL total coliforms.

In many cases, final microorganism concentrations were below detection. It was not possible to overcome this problem by increasing stock solution concentrations or by adding more stock solution to the effluent samples. Viruses could not be grown to higher concentrations in the stock solution, and adding more stock solution to the effluent samples increased the level of constituents that interfered with chlorine disinfection. The non-detect samples indicated effective disinfection, but made quantitative analysis difficult. To deal with this issue, a conservative estimate of disinfection was made by assuming the worst possible disinfection. For example, if the data indicated greater than 6-log inactivation, a value of 6-log inactivation was assumed.

Table 3.3. Water Quality Data for Bench-Scale UV/Free Chlorine and UV/Chloramine Experiments With DFB, Filtered Effluent, and Secondary Effluent: Average and Standard Deviation Values

		Free Chlorine					Ammonia-Chlorine Process		Chlorine-Ammonia Process	
		DFB	Filtered Effluent		Secondary Effluent		Filtered Effluent		Filtered Effluent	
Parameter	Units	Post-seed	Pre-seed	Post-seed	Pre-seed	Post-seed	Pre-seed	Post-seed	Pre-seed	Post-seed
No. of samples		1	7	7	4	1[d]	2	2	2	2
pH		7.1	7.3 ± 0.2	7.5 ± 0.1	7.4 ± 0.1	7.5	7.0	7.2 – 7.3	7.0 – 7.1	7.2 – 7.3
Chlorine Demand	mg Cl_2/L	1.0	3.0 ± 0.2	—	3.7 ± 0.4	—	3.3	—	3.4 – 3.5	—
Turbidity	NTU	0.11	0.6 ± 0.1	0.7 ± 0.1	0.9 ± 0.4	0.7	0.4 – 1.0	0.5 – 1.1	0.4 – 1.8	0.4 – 2.0
UVT	%	99.6	76.8 ± 0.9	77.3 ± 1.5	76.3 ± 0.6	75.6± 0.5[d]	76.6 – 76.7	75.9 – 76.6	75.9 – 76.2	76.0 – 76.0
Ammonia	mg N/L	<0.10	<0.10	<0.10[b]	0.14 ± 0.06	0.18	<0.10	<0.10	<0.10	<0.10[c]
TKN[a]	mg N/L	0.4	1.0 ± 0.05	1.2 ± 0.2	1.3 ± 0.2	1.6	1.1 – 1.2	1.1 – 1.3	1.0 – 1.5	1.2 – 1.3
Nitrate	mg N/L	<0.2	3.0 ± 0.6	3.0 ± 0.6	2.3 ± 0.3	2.0	2.5 – 2.9	2.5 – 2.8	2.9 – 3.9	2.9 – 3.9
Nitrite	mg N/L	<0.03	0.05 ± 0.02	0.05 ± 0.02	0.05 ± 0.02	0.04	0.05 – 0.06	0.06	0.05 – 0.07	0.05 – 0.07
Total COD	mg/L	22	15 ± 3	20 ± 5	15 ± 3	17	<10 – 13	20 – 23	10 – 15	17 – 25
Total Coliform	CFU/100 mL[e]	—	6200	10,900 ± 2,000	17,400 ± 11,200	19,000 – 23,000[d]	—	13,000 – 15,000	—	14,000 - 22,000

[a]TKN: total Kjeldahl nitrogen.

[b]Ammonia was below the reporting limit of 0.10 mg N/L in 6 of 7 samples; in one sample it was 0.13 mg N/L.

[c]Ammonia was below the reporting limit of 0.10 mg N/L in one sample; and was 0.10 mg N/L in the other.

[d]Three UVT samples and two total coliform samples were taken after seeding in secondary effluent with UV/free chlorine.

[e]Total coliform samples were taken either before or after seeding (not both). With UV/free chlorine in filtered effluent, one sample was taken before seeding and four were taken after seeding; in secondary effluent, two samples each were taken before and after seeding. With the ammonia-chlorine and chlorine-ammonia processes, two samples each were taken after seeding.

Table 3.4. Particle Counts* in Secondary and Filtered Effluents: Average and Standard Deviation Values

Particle Size Range (μm)	Particle Concentration (No./mL)	
	Secondary Effluent	Filtered Effluent
2-5	708 ± 246	310 ± 95
5-10	209 ± 92	37 ± 10
10-20	68 ± 26	32 ± 20
20-50	13 ± 14	< 0.625
50-100	0.3 ± 0.4	< 0.013
100-200	0.1 ± 0.1	< 0.0063
200-500	0.2 ± 0.2	< 0.0063
>500	0.7 ± 0.8	< 0.0013

*An eight-channel Hach 2200 PCX particle counter was used to monitor particle size distributions in filtered and secondary effluents. Data points were taken every 5 min over a total of approximately 10 days for each type of effluent.

Table 3.5. Water Quality Data for Pilot-Scale UV/Free Chlorine Experiments With Seeded Filtered Effluent: Average and Standard Deviation Values

Parameter	Units	Initial Sample	Final Sample	All Samples
pH		7.0 ± 0.2	7.2 ± 0.2	7.1 ± 0.2
Turbidity	NTU	0.6 ± 0.1	0.5 ± 0.1	0.5 ± 0.1
UVT	%	76.5 ± 1.1	78.0 ± 0.8	77.2 ± 1.2
Ammonia	mg N/L	<0.10[b]	<0.10[b]	<0.10[b]
TKN[a]	mg N/L	0.98 ± 0.18	1.00 ± 0.08	0.99 ± 0.14
Nitrate	mg N/L	3.5 ± 0.8	3.4 ± 0.8	3.4 ± 0.9
Nitrite	mg N/L	0.05 ± 0.01	0.05 ± 0.01	0.05 ± 0.01
Soluble COD	mg/L	16 ± 5	15 ± 4	16 ± 5
Total COD	mg/L	20 ± 6	18 ± 5	19 ± 6
Total Coliform	CFU/100 mL	9800 ± 2400	8600 ± 5800	9200 ± 4200

[a]TKN – total Kjeldahl nitrogen.

[b]One initial sample contained 0.10 mg N/L of ammonia, and one final sample contained 0.13 mg N/L. Ammonia levels were below reporting limits in the other 20 samples.

3.5 LABORATORY EXPERIMENTAL DESIGN

Twelve laboratory experiments were conducted with free chlorine and UV, and four were conducted with chloramines and UV. Experiments measured indigenous total coliforms and one or two of the following seeded organisms: MS2, poliovirus, and adenovirus. UV doses were supplied by a collimated beam device (ITT-Wedeco, Charlotte, NC) equipped with four parallel low-pressure high output lamps that emitted monochromatic radiation at a wavelength of 254 nm, and a 20-cm diameter collimating tube. A pneumatically operated

shutter controlled exposure time, which could be adjusted with a timer to a minimum of 0.1 seconds. UV doses were calculated according to the *Ultraviolet Disinfection Guidance Manual for the Final Long Term 2 Enhanced Surface Water Treatment Rule* (UVDGM, USEPA, 2006), and development of the dose-response curves followed the NWRI/AWWA Guidelines (Melin, 2003).

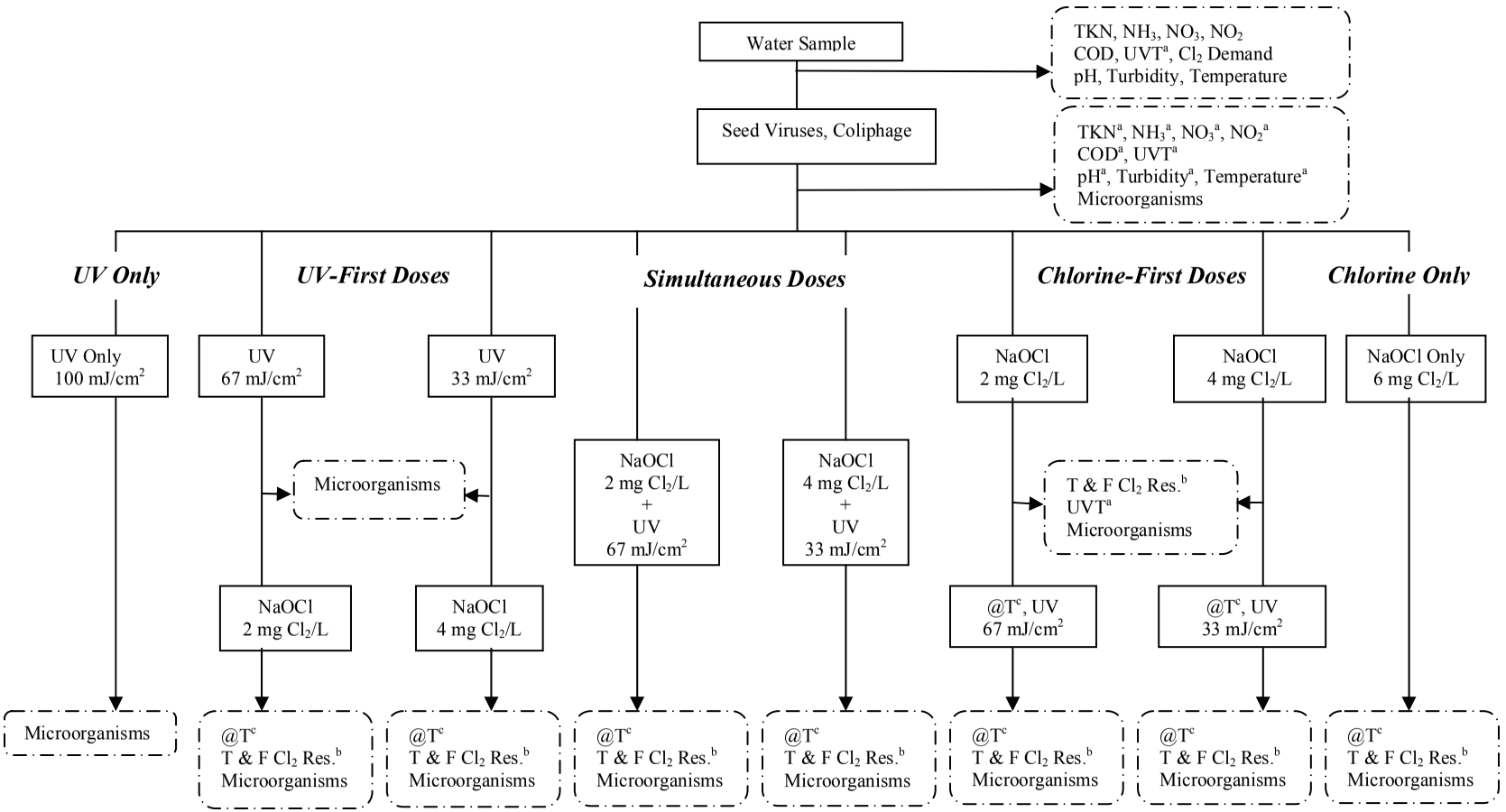
3.5.1 Experiments With Free Chlorine and UV

Twelve experiments were conducted with UV/free chlorine: one in DFB, seven in fully nitrified filtered effluent, and four in fully nitrified secondary effluent. Four microorganisms were analyzed: MS2, poliovirus, adenovirus, and indigenous total coliforms. Adenovirus was tested in two of the experiments with filtered effluent. Because of safety issues, no other microorganisms were seeded or monitored during the adenovirus experiments. In addition, total coliforms were not present in DFB and were not monitored in those experiments. A full list of the number of samples taken for each microorganism in each disinfection scheme is given in Table C3 of Appendix C.

Figure 3.1 shows a schematic of the UV/free chlorine experiments that includes the measured chemical and biological parameters. In a typical experiment, water quality samples were taken first. The effluent sample was then seeded with MS2 and poliovirus and was sampled again to identify changes in water quality from seeding (Table 3.3). The monitored water quality parameters varied by experiment (Table 3.6): UVT, TKN, ammonia, nitrate, nitrite, COD, pH, turbidity, and temperature were generally analyzed before and after seeding. In six experiments with filtered effluent, the effect of free chlorine on UVT was determined by measuring UVT before and after chlorine-only doses.

After water quality sampling, 250 mL aliquots of the water or effluent sample were added to petri dishes. UV and chlorine were dosed directly into these petri dishes. Each experiment tested UV doses of 33, 67, and 100 mJ/cm^2, chlorine doses of 2, 4, and 6 mg Cl_2/L, and combined UV/chlorine doses of 2*67 and 4*33. Combined UV/chlorine doses tested three disinfectant application orders: UV-first, simultaneous, and chlorine-first doses. Samples were taken at specified chlorine contact times (see detailed description of contact times in the following paragraph). For chlorine-only and combined UV/chlorine doses, a portion of the sample was analyzed for free and total chlorine residuals, and another portion of the sample was dechlorinated and analyzed for MS2, poliovirus, and indigenous total coliforms. For UV-only doses, samples were taken and analyzed for MS2, poliovirus, and indigenous total coliforms.

In most experiments, the chlorine contact time was 20 min, which was considered realistic for full-scale implementation and also allowed each experiment to be conducted on a single day. Most of the analyses in Chapter 4 use the data taken at this 20-min contact time. However, for the combined UV/chlorine doses, some samples were also taken at contact times of 10 or 30 min in DFB or secondary effluent. For the chlorine-only doses, some samples were taken at contact times of 1, 5, 10, or 30 min. These alternative contact times provided information on decay of chlorine residuals (Section 4.3) and the effect of contact time on disinfection (Section 4.6.2). Table C3 of Appendix C provides a complete list of the number of samples taken for each analyte under each disinfection scheme and contact time.



[a]Not measured in all experiments; see Table 3.6 for details.

[b]"T & F Cl_2 Res." refers to total and free chlorine residuals.

[c]"@T" refers to the chlorine contact time, which was generally 20 min; a full list of contact times is given in Table C3 of Appendix C.

Figure 3.1. Schematic of laboratory experiments with free chlorine and UV.

Table 3.6. Number of Samples Analyzed for Each Effluent Type: Water Quality Parameters

Parameter(s)	Measurement Point	DFB	Filtered Effluent	Secondary Effluent
TKN, Ammonia, Nitrate, Nitrite, COD, pH, Turbidity, Temperature	Before seeding	0	7	4
TKN, Ammonia, Nitrate, Nitrite, COD, pH, Turbidity, Temperature	After seeding	1	6	1
UVT	Before seeding	0	7	4
UVT	After seeding	1	7	3
UVT	After chlorine contact time	0	6	0

3.5.2 Experiments With Chloramines and UV

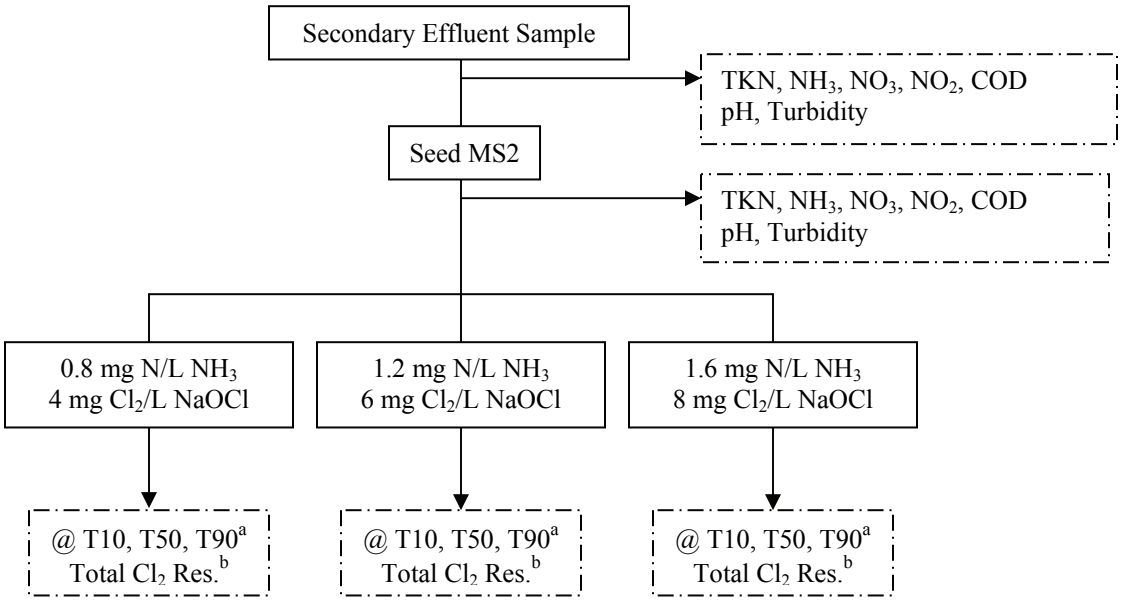
Two types of chloramination were tested at bench scale: the ammonia-chlorine and chlorine-ammonia processes. In the ammonia-chlorine process, ammonia was mixed into the effluent, followed by chlorine; this disinfection scheme simulated typical full-scale chloramination. At treatment plants without biological nitrogen removal, effluents contain ammonia, and chloramines are formed simply by adding chlorine. At treatment plants with biological nitrogen removal, chloramines are often formed by adding low doses of ammonia, followed by chlorine.

In the chlorine-ammonia process, the ammonia-free effluent was dosed with chlorine to produce a free chlorine residual. After 20 s of mixing, ammonia was added. The chlorine-ammonia process provided free chlorine disinfection for the first 20 s (until ammonia was added), and chloramine disinfection after ammonia addition.

Three sets of bench-scale experiments were conducted with chloramines. Each set was run twice, for a total of six experiments. The first set of experiments tested decay of chloramines, and the second and third sets of experiments tested UV in combination with the ammonia-chlorine and chlorine-ammonia processes, respectively.

3.5.2.1 Chloramine Decay Tests

Figure 3.2 shows a schematic for the chloramine decay tests, both of which used a single sample of fully nitrified secondary effluent. Total chlorine residuals were measured at doses of 4, 6, and 8 mg Cl_2/L. Ammonia doses of 0.8, 1.2, and 1.6 mg N/L were used to give a chlorine-dose-to-ammonia ratio of five; at the pH values in these experiments, these doses should yield predominantly monochloramines (Tchobanoglous et al., 2003). MS2 was seeded but not measured in these experiments.



[a]"@T" refers to the chlorine contact time in minutes.

[b]"T Cl. Res." refers to total chlorine residuals.

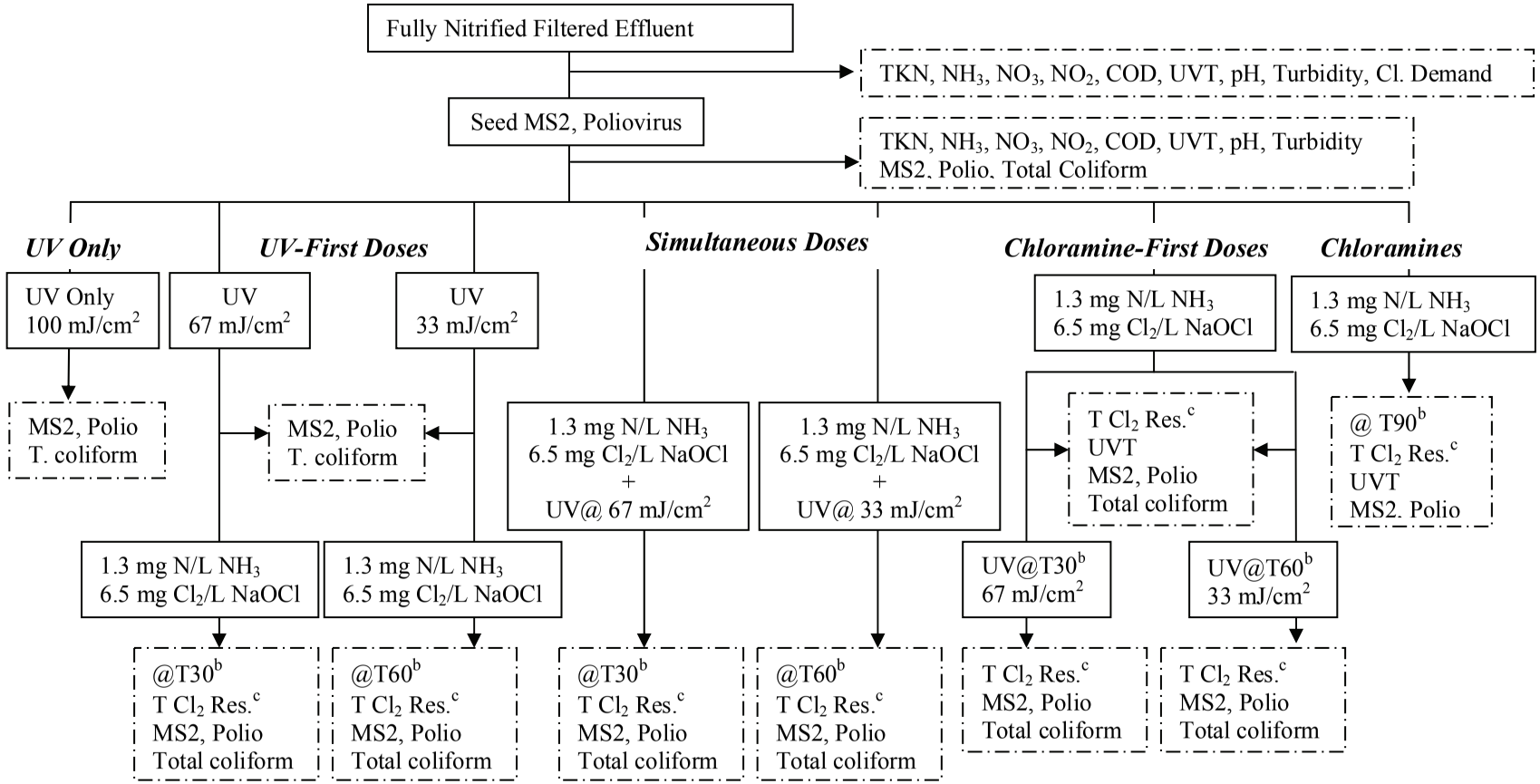
Figure 3.2. Schematic of the chloramine decay tests.

3.5.2.2 Experiments Combining UV With Ammonia-Chlorine and Chlorine-Ammonia Processes

Figure 3.3 shows a schematic of the experiments with UV/chloramines that includes the measured chemical and biological parameters. In the ammonia-chlorine experiments, ammonia was added before chlorine; in the chlorine-ammonia experiments, chlorine was mixed into the effluent sample for 20 s before ammonia was added. For both the ammonia-chlorine and chlorine-ammonia processes, the full chloramine CT value was 450 mg-min/L.

Both the ammonia-chlorine and chlorine-ammonia processes used filtered effluent and a contact time of 90 min for the full CT value. Results from the chloramine decay tests (Section 4.3.1.2) indicated that 6.5 mg Cl_2/L would yield a total chlorine residual of approximately 5 mg/L after 90 min. Therefore, the added chlorine dose was generally 6.5 mg Cl_2/L. As with the chloramine decay tests, the chlorine-dose-to-ammonia ratio was five, so the added ammonia dose was 1.3 mg N/L. The only exception to these conditions was the first ammonia-chlorine experiment, which used a chlorine dose of 8 mg Cl_2/L and an ammonia dose 1.6 mg N/L. Partial chloramine CT values of 150 and 300 mg-min/L were achieved by reducing the contact time.

Table 3.7 provides the average CT values for each of the ammonia-chlorine and chlorine-ammonia disinfection schemes, as calculated from the measured total chlorine residuals and contact times. Table E9 of Appendix E provides the measured total chlorine residual and CT value for each experiment. All average CT values in Table 3.7 were within 25% of the desired CT value, and individual CT values in Table E9 of Appendix E were within 30% of the desired CT value. In the data analysis (Chapter 4), all chloramine CT values are designated as CT150, 300, or 450, without accounting for variations on different dates.



[a]In the ammonia-chlorine process, ammonia was added before chlorine. In the chlorine-ammonia process, chlorine was added first, mixed for 20 s, then ammonia was added.

[b]"@T" refers to the chlorine contact time in minutes.

[c]"T Cl_2 Res." refers to total chlorine residuals.

Figure 3.3. Schematic of the UV/chloramine tests.[a]

Table 3.7. Average CT Values (mg-min/L) for Ammonia-Chlorine and Chlorine-Ammonia Experiments

	Chloramine CT (mg-min/L)	
Disinfection Scheme	Ammonia-Chlorine	Chlorine-Ammonia
67+150	171	123
150+67(sim)	162	113
150+67(seq)	177	116
33+300	351	240
300+33(sim)	333	231
300+33(seq)	351	231
CT150	173	123
CT300	354	240
CT450	504	338

In the ammonia-chlorine process, ammonia was added first, mixed well, then free chlorine was added. In the chlorine-ammonia process, free chlorine was added first and mixed well for 20 s, then ammonia was added. Contact times began with the addition of free chlorine.

3.6 PILOT PLANT EXPERIMENTAL DESIGN

The bench-scale experiments used relatively controlled conditions to investigate the combined UV/chlorine disinfection schemes. Following the bench-scale experiments, pilot-scale experiments were conducted to provide data at more realistic operating conditions that would better simulate full-scale systems. Eleven experiments tested UV and/or free chlorine in a flow-through pilot system. The same doses were used in the bench- and pilot-scale experiments: UV doses of 33, 67, and 100 mJ/cm^2, and free chlorine doses of 2, 4, and 6 mg Cl_2/L. Doses were tested with each disinfectant individually and also in combinations of 2*67 and 4*33. For combined UV/chlorine, "simultaneous" and "UV-first" dosing were tested; "chlorine-first" dosing was not tested because of practical constraints. Experiments measured indigenous total coliforms and seeded MS2; poliovirus and adenovirus could not be seeded because of safety concerns and cost, but indigenous adenovirus was measured in three experiments. DBPs were measured in seven experiments, and TrOCs were analyzed in three experiments (if analyzed by Aqwatec Laboratory) or seven experiments (if analyzed by SJCWQL).

Figure 3.4 shows a schematic of the pilot system, and Figures 3.5 through 3.8 show pictures of the constructed apparatus. Fully nitrified filtered secondary effluent was pumped from a wet well to a 1000-gal feed tank. A constant water level was maintained in the tank to provide constant head pressure and a steady flow rate to the pilot system. The influent pump withdrew water from the tank and pumped it to the system. MS2 was added with a diaphragm pump at the MS2 dosing point immediately downstream of the influent pump (Figures 3.4 and 3.6). A pulse dampener smoothed flow variations from the diaphragm pump, and a static mixer was used downstream of the MS2 dosing point to ensure effective mixing between the MS2 stock solution and the filtered effluent.

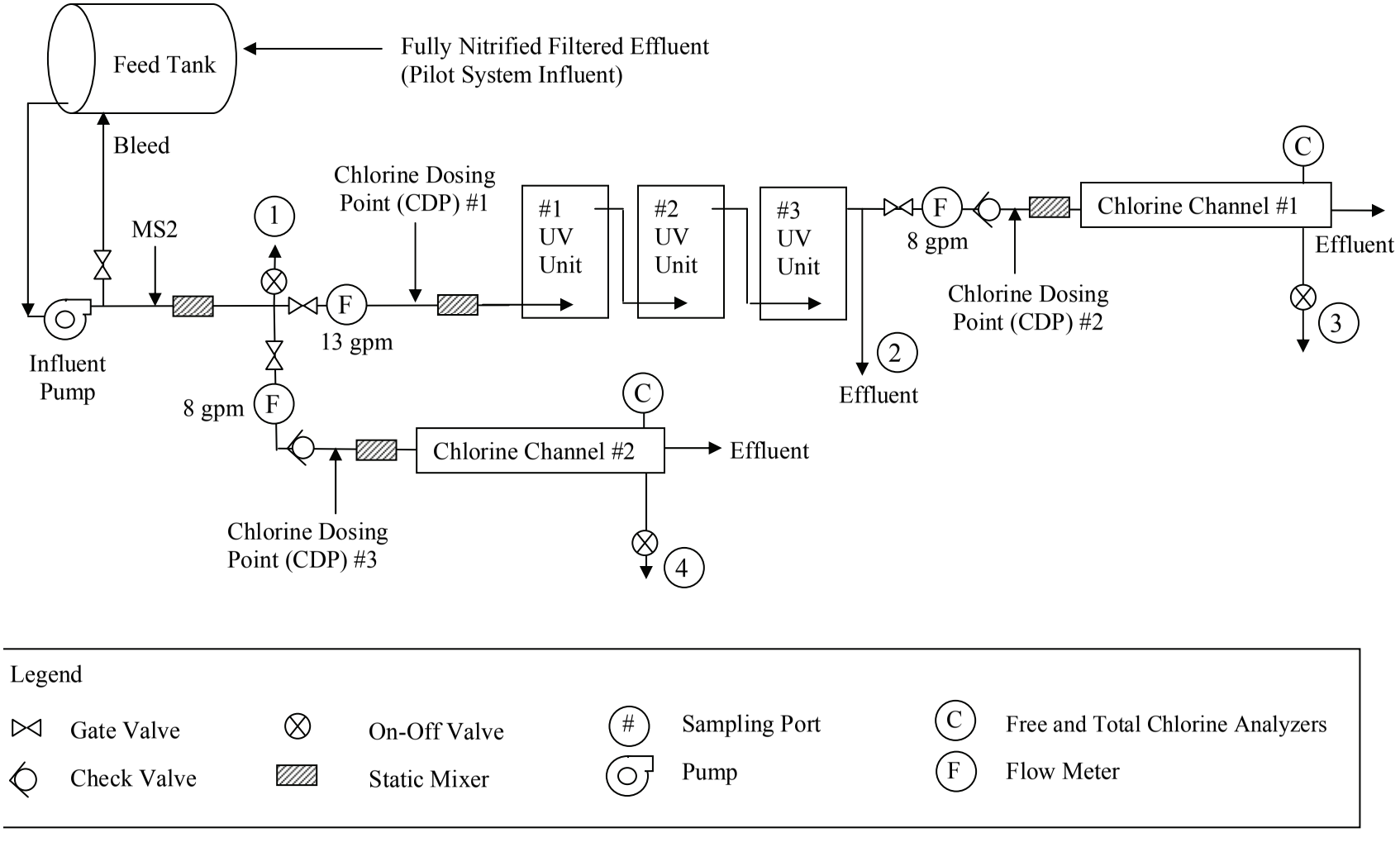


Figure 3.4. Pilot plant schematic.

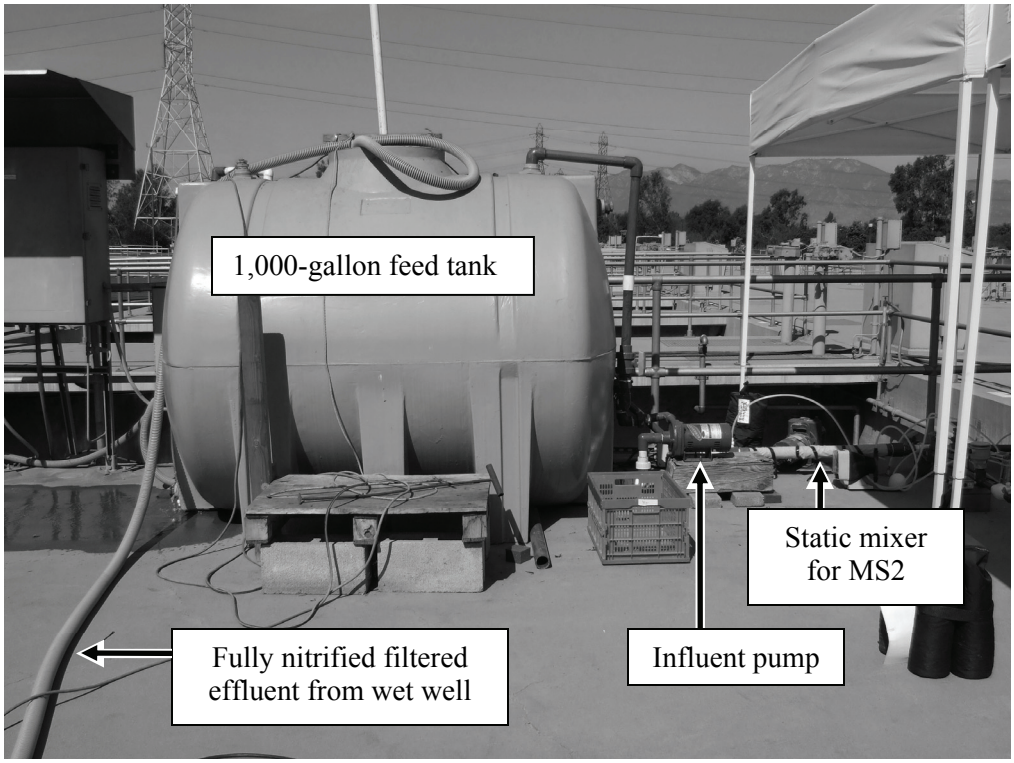


Figure 3.5. Equipment for the pilot system influent.

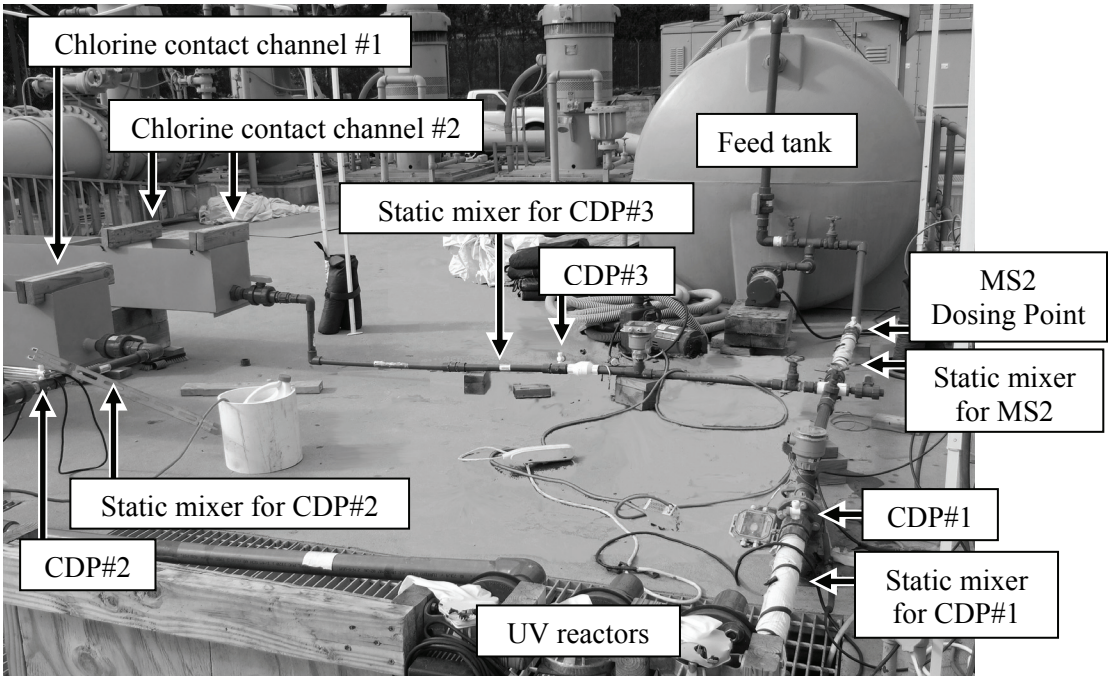


Figure 3.6 Dosing points, mixers, and flowmeters for the pilot system.
CDP = Chlorine dosing point.

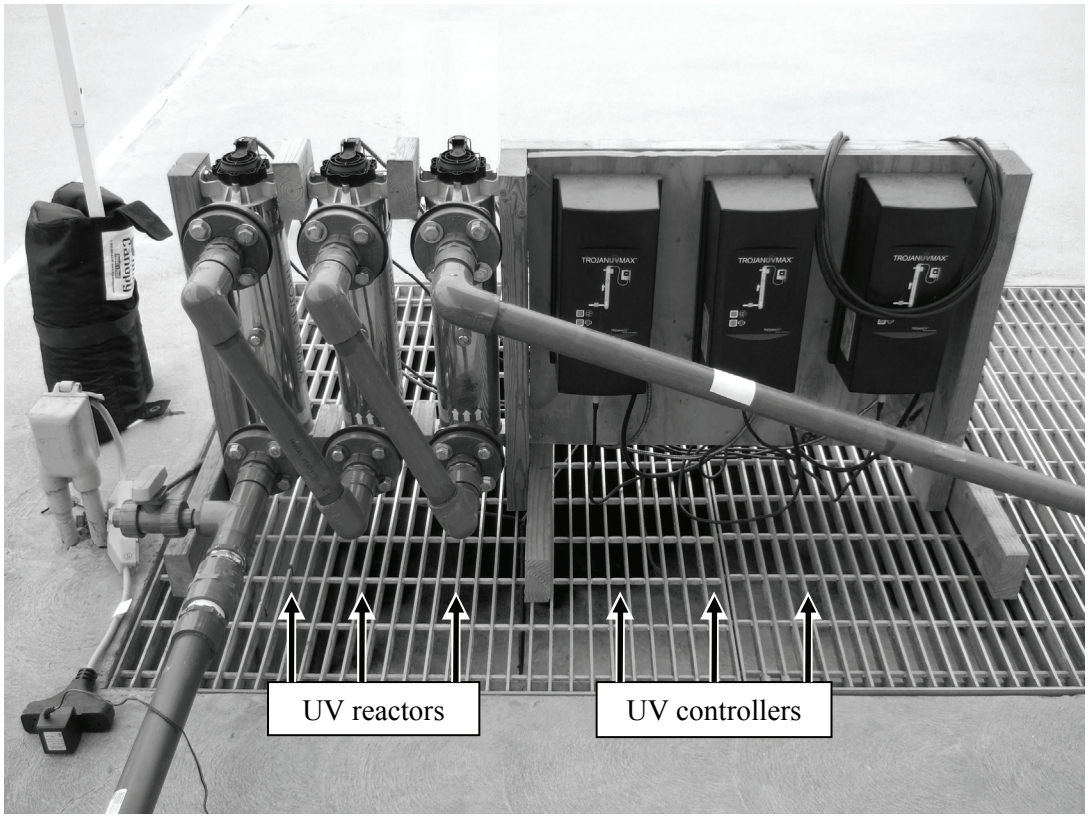


Figure 3.7. UV reactors and control boxes.

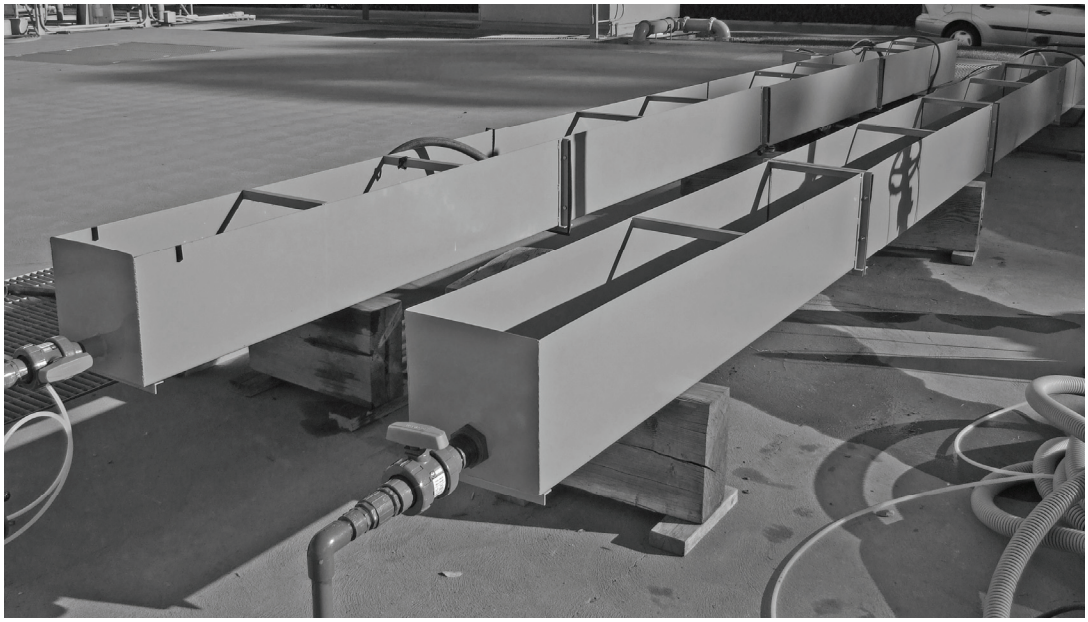


Figure 3.8. Two chlorine contact channels.

After the MS2 static mixer, the flow split into two streams. The first stream went directly to chlorine contact channel #2, and was used to test the chlorine-only doses of 2, 4, and 6 mg Cl_2/L. Chlorine-only doses were added at chlorine dosing point (CDP) #3. The second stream went to three Trojan UV Max G reactors in series, then to chlorine contact channel #1; this part of the system was used to test UV-only and combined UV/chlorine doses. For "simultaneous" dosing, chlorine was added immediately upstream of the UV reactors at CDP#1. For "UV-first" dosing, chlorine was added between the UV reactors and chlorine contact channel #1 at CDP#2. Static mixers were placed immediately downstream of each CDP to ensure effective mixing between the dosed chlorine and the effluent.

3.6.1 UV Reactors and Dosing

Figure 3.7 is a photograph of the three Trojan UV Max G reactors. These reactors consisted of pressurized UV vessels, each containing one LSI brand low pressure, high output lamp. Each reactor had a 90-degree bend at the inlet and outlet so that the ports were at right angles to the lamp axis. This design configuration suggests that the reactor was designed for turbulent rather than laminar flow; the Reynolds number was approximately 30,000 at the flow rates used. Preliminary experiments demonstrated that the three reactors provided similar disinfection results and could be used interchangeably (Appendix D). Experiments also yielded an operating equation (Equation 3.1), which was used to calculate the predicted UV doses, from the UVT and flow rate of the effluent. Eqn. 3.1 uses the following units: dose/reactor in mJ/cm^2, UVT as a percent, and flow in gpm. Appendix D gives full results and discussion of the dose tests, along with the derivation of Eqn. 3.1.

$$\text{Log(Dose/Reactor)} = -3.017 + 2.849 \times \log(\text{UVT}) - 0.760 \times \log(\text{Flow}) \qquad \text{(Eqn. 3.1)}$$

Because the effluent UVT was approximately 77%, most pilot plant experiments used a flow rate near 13 gpm, which yielded a predicted UV dose of 33 mJ/cm^2 with one lamp. One, two, or three lamps were used in series to achieve doses of 33, 67, and 100 mJ/cm^2, respectively.

Predicted UV doses for each experiment were calculated using Equation 3.1, the average flow rate recorded by flow meters (Figure 3.4), and the measured UVT values. For UV-only doses, the UVT values of the treated samples were used; however, chlorine altered the UVT of the effluent (Section 4.2), so UVT values of the chlorine-treated samples could not be used. Instead, dose predictions for the combined UV/free chlorine samples used the average UVT value of the daily initial and final influent samples.

During each week of experiments, part of an initial influent sample was treated with known UV doses from a collimated beam apparatus. The resulting MS2 concentrations were measured and used to generate a dose-response curve. For UV-only doses in the pilot experiments, delivered UV doses were calculated using the collimated beam dose-response curve and the MS2 inactivation data. For the combined UV/free chlorine doses, MS2 concentrations were only measured after both UV and chlorine were dosed (not after treatment with UV only), so delivered doses could not be calculated from collimated beam experiments.

Table 3.8 summarizes the average calculated doses and their standard deviations for the pilot plant experiments, including predicted and delivered UV doses and calculated chlorine doses (Section 3.6.2). Tables C7 and C8 of Appendix C list the flow rates and UVT values used to calculate the predicted UV doses, and Table C9 provides a full list of predicted and delivered UV doses for each day of the pilot experiments.

Table 3.8. UV and Free Chlorine Doses in the Pilot Experiments: Average and Standard Deviation Values

	UV Dose (mJ/cm^2)		Free Chlorine Dose (mg Cl_2/L)
Disinfection Scheme	Predicted	Delivered	Calculated
33 mJ/cm^2	35 ± 3	33 ± 8	—
67 mJ/cm^2	71 ± 5	75 ± 14	—
100 mJ/cm^2	106 ± 8	112 ± 17	—
67+2	72 ± 5	—	2.0 ± 0.2
2+67 (sim)	70 ± 5	—	2.0 ± 0.2
33+4	36 ± 2	—	4.0 ± 0.4
4+33 (sim)	35 ± 3	—	4.4 ± 0.3
2 mg Cl_2/L	—	—	1.8 ± 0.2
4 mg Cl_2/L	—	—	4.2 ± 0.4
6 mg Cl_2/L	—	—	6.2 ± 0.6

The average predicted and delivered UV doses were generally slightly higher than the target doses of 33, 67, and 100 mJ/cm^2, but were within 12% of the target values (Table 3.8). Because these elevated UV doses caused relatively small changes in MS2 log inactivation, the analysis of the data (Chapter 5) designates all UV doses from the pilot plant experiments as 33, 67, or 100 mJ/cm^2, without accounting for the slight variations on different dates.

3.6.2 Free Chlorine Reactors and Dosing

Figure 3.8 is a photograph of the two chlorine contact channels. Both were 1 ft wide by 1 ft high by 24 ft long and were constructed from painted sheet metal. Perforated baffles were placed approximately 2 and 18 inches downstream of the channel inlets to help provide uniform flow distribution throughout the channel. The tops of the baffles can be seen in Figure 3.6. A fixed 7-inch weir was placed 1 ft from the channel effluent to control water depth.

Although the bench-scale experiments used a contact time of 20 min, practical constraints necessitated shorter contact times for the pilot experiments. The chlorine contactors were operated to provide a modal chlorine contact time of appproximately 10 min. To satisfy these conditions, the pilot plant experiments used a flow rate of 8 gpm (Appendix D).

Chlorine was dosed using sodium hypochlorite stock solutions with concentrations between 750 and 2000 mg Cl_2/L. Diaphragm pumps fed the stock solutions from carboys to the pilot system at the chlorine dosing points (Figures 3.4 and 3.6). To smooth flow variations, a pulse dampener was placed between each pump and dosing point. The average flow rate of the stock solution was calculated from the time duration of each disinfection scheme and the corresponding volume of stock solution used. This average flow rate of the stock solution, the chlorine stock concentration, and the average effluent flow rate (as measured on the flow meters shown in Figure 3.4) were used to calculate the average chlorine dose for each disinfection scheme. Table 3.8 presents the calculated chlorine dose for each of the disinfection schemes; Tables C10 through C13 in Appendix C provide full data for the concentrations of the hypochlorite stock solutions, the flow rates of the stock solutions and effluent, and the calculated doses for each disinfection scheme.

Table 3.8 shows that average calculated chlorine doses were within 10% of the target doses of 2, 4, and 6 mg Cl_2/L. Because these deviations from the target chlorine doses caused relatively small changes in MS2 log inactivation, the analysis of the data (Chapter 5) designates all chlorine doses from the pilot plant experiments as 2, 4, or 6 mg Cl_2/L, without accounting for the slight variations on different dates.

3.6.3 Operating Protocols

In preparation for the pilot plant experiments, the system was cleaned the day before each experiment to remove biofilms that may have accumulated in the pilot system between experiments. When experiments were run on consecutive days, the system was only cleaned before the first day's experiment. To clean the system, the feed tank, UV lamps, and chlorine contact channels were soaked in a hypochlorite solution at concentrations of 50 to 100 mg Cl_2/L. The contact channels were also scrubbed and flushed with the hypochlorite solution to remove biofilms and particles. At the start of each experiment, the system was flushed with filtered effluent, and samples were taken to ensure that no chlorine residual remained in the system.

The pilot plant experiments used fully nitrified filtered effluent taken from a wet well at the treatment plant. Under normal plant operations, free chlorine is added to the secondary effluent at a point upstream of the filters, in a step called "pre-chlorination." Normal operations were interrupted for the pilot plant experiments, and pre-chlorination was stopped approximately 15 to 20 h before the experiments began to ensure that the effluent in the wet well contained no chlorine residual. The lack of chlorine residuals was verified before the start of each day's experiment. In addition to stopping pre-chlorination, filter backwashing (cleaning) was postponed until each day's experiment was finished, to provide relatively consistent water quality.

These changes helped to maintain the integrity of the pilot plant experiments, but also caused time constraints, because normal plant operations could not be postponed indefinitely. Additional time constraints occurred because sample preparation for some analytes (such as total coliforms) was time-consuming and time-sensitive. As a result, the experiments needed to end early enough on each day to allow for sample processing. Finally, minimizing the run time helped to minimize variations in water quality parameters (Table 3.5), although some TrOC concentrations decreased over the course of the experiments (Table 5.4).

Several steps were taken to minimize the time required to conduct the experiments, although the desire to minimize run time was balanced against the need to ensure the quality of the data. Figure 3.4, shows that the chlorine-only and combined UV/free chlorine disinfection schemes were run simultaneously, to reduce the total run time for each day. In addition, all three UV lamps were warmed up at the start of each experiment, and UV doses were run in decreasing order (100, then 67, then 33 mJ/cm^2), to minimize the waiting time for lamp warm-up. A display light on the control panel indicated when the lamps were ready for use. The display light typically turned off after 2–4 min, but at least 5 min of warm-up time were used to provide a margin of safety.

On a typical day, the feed tank was first filled with water from the filter effluent wet well, and flow rates throughout the system were set. The concentrated MS2 solution from GAP Enviromicrobial Services was mixed with 40 L effluent to form the MS2 stock solution for the pilot experiment, then split into two 20-L carboys that were placed in an icebox filled with ice. All three UV lamps were turned on and warmed up, and the MS2 flow was started.

Samples on the combined UV/free chlorine side of the pilot system were typically taken in the following order: 100 mJ/cm^2, 67 mJ/cm^2, 67+2, 2+67(sim), 33 mJ/cm^2, 33+4, 4+33(sim). To provide analogous samples, the chlorine-only side of the pilot system also tested doses in the following order: 2 mg Cl_2/L, 4 mg Cl_2/L, 6 mg Cl_2/L. Influent samples were generally taken after the 100 mJ/cm^2 sample and after the last effluent sample. The 100 mJ/cm^2 sample was taken first because sampling had little impact on the flow, so the influent sample could be taken immediately afterward. Taking the influent sample disrupted the flow to the system, so at least 5 min were provided to reach steady state before the subsequent sample (generally the 67 mJ/cm^2 sample) was taken. Calculations indicate that the residence time between the MS2 dosing point and the UV sampling point was less than 30 s. Based on the results of the hydraulic tests (Appendix D), 30 min were allowed to achieve steady state in the chlorine contact channel before the 2*67 and 4*33 samples were taken. Sampling times for each experiment are given in Table C6 of Appendix C.

Samples containing chlorine were dechlorinated with sodium thiosulfate immediately after sampling. All samples were placed on ice immediately after being taken, and almost all remained on ice until being processed. The only exceptions were the TrOC samples shipped to the Aqwatec Laboratory at the Colorado School of Mines (Golden, CO; Appendix B). These samples were refrigerated overnight, packed in ice, and shipped for next-day delivery. They were then refrigerated until they were processed for analysis.

3.7 DATA ANALYSIS

3.7.1 Predicted Disinfection and Removal

The laboratory and pilot-scale data were analyzed for synergistic and antagonistic effects by comparing measured MS2 inactivation or TrOC removal values to predicted values. The first step in the analysis was to calculate inactivation or removal to the detection limit (i.e., the maximum value that could be observed) for each measured MS2 or TrOC concentration. These values were averaged for each disinfection scheme. If a predicted inactivation or removal value was greater than the maximum value that could be observed, the maximum observable value was instead used for analysis.

For MS2 disinfection, predicted inactivation was assumed to be additive, that is, the predicted inactivation was the sum of the average log inactivation values for the individual disinfectants (Equation 3.2). This sum is mathematically equivalent to calculating the set of additive inactivation values for every possible combination of measured inactivation values with free chlorine (or chloramines) alone and UV alone, and then averaging the values in that set. In other words, "n" measured values with free chlorine (or chloramines) and "m" measured values with UV yield a set of "m × n" predicted inactivation values that can be averaged to yield the predicted average inactivation. Standard deviations were calculated on this set of predicted values.

$$\textit{Predicted Log Inactivation} = LI_C + LI_{UV} \qquad \text{(Eqn. 3.2)}$$

where LI_C = average log inactivation with the corresponding dose of chlorine only

LI_{UV} = average log inactivation with the corresponding dose of UV only

Similarly, predicted removals of TrOCs in the pilot-scale experiments were calculated using Equation 3.3, which assumes that individual removals by UV and chlorine are additive. The predicted average removal in Equation 3.3 is mathematically equivalent to calculating the set of predicted removal values for every possible combination of measured removals with chlorine alone and UV alone, and then averaging the values in that set. In other words, "n" measured removals with free chlorine and "m" measured removals with UV yield a set of "m × n" predicted removal values that can be averaged to yield the predicted average removal in Equation 3.3. Standard deviation values were calculated on this set of predicted removal values.

$$\textit{Predicted Average Removal} = 1 - (1 - R_C)(1 - R_{UV}) \qquad \text{(Eqn. 3.3)}$$

where R_C = average removal with the corresponding dose of chlorine only

R_{UV} = average removal with the corresponding dose of UV only

3.7.2 Statistical Analysis

Statistical tests were used to analyze the data in several cases. For each test, a null hypothesis was formed, and the probability (*p*-value) that the null hypothesis was true was determined. The acceptance level was set at α of 0.05, and the null hypothesis was rejected if the *p*-value was 0.05 or less, that is, if the probability that the null hypothesis was true was 5% or less.

For example, effects of relative dose were analyzed by comparing MS2 disinfection at "mostly UV" and "mostly chlorine" doses. The null hypothesis in this case was that MS2 inactivation was the same at both doses, that is, the measured inactivation values came from the same population of values. If the calculated *p*-value was 0.05 or less, there was 5% or less chance that this null hypothesis was true. The null hypothesis was then rejected and MS2 disinfection was considered significantly different at the two doses. Note that *p*-values greater than 0.05 only indicate that no significant differences could be observed; there may still be differences in the true inactivation values that could not be observed because of a small number of samples or large variability in measurements.

Three types of statistical tests were used to analyze the data collected for this project: an independent one-sample *t*-test, Wilcoxon-Mann-Whitney test, and Welch's *t*-test. Table 3.9 summarizes the applications of each of the tests to the data from this study. The one-sample *t*-test was used to compare a single set of data to a specified value, for example, whether TrOC removals were significantly different from zero. This test assumes normally distributed data.

The other two tests compared two sets of data with each other. The Wilcoxon-Mann-Whitney test makes the fewest assumptions about the data and was used where possible; it is non-parametric, that is, it assumes no specified distribution to the data. This test can be used to analyze data sets containing 2 to 20 samples. For the acceptance criteria used, a minimum of eight points between the two data sets was generally required; however, if one set contained only two points, the other needed to contain at least eight points (minimum of 10 points total). For data sets with too many or too few samples, Welch's *t*-test was used. This test assumes that the two sets of data being compared are normally distributed with unequal variances.

Table 3.9. Application of Statistical Tests to the Data

Test	Application
One-sample *t*-test	Significance test for losses in total chlorine residual after UV treatment
	Significance test for TrOC removals
	Significance test for DBP concentrations after disinfection
Wilcoxon-Mann-Whitney test	Comparison of lab and pilot MS2 disinfection
	Effect of relative dose on MS2 disinfection and DBP formation at pilot scale
	Effect of disinfectant application order on MS2 disinfection and DBP formation at pilot scale
Welch's *t*-test	Comparisons of MS2 disinfection at bench scale
	Effects of relative dose and disinfectant application order on TrOC removal at pilot-scale
	Synergistic and antagonistic effects on MS2 disinfection, DBP formation, and TrOC removal at bench and pilot-scale

CHAPTER 4

BENCH-SCALE RESULTS FROM EXPERIMENTS COMBINING UV WITH FREE CHLORINE AND CHLORAMINES

4.1 BACKGROUND

The following sections describe the results from the bench-scale experiments testing disinfection with UV in combination with free chlorine or chloramines. The effects of UV and chlorine species on each other are first analyzed. Disinfection of MS2, poliovirus, adenovirus, and total coliforms by UV, chlorine, combined UV/chlorine, and combined UV/chloramines is then discussed. Finally, disinfection efficacies are analyzed as a function of water quality (DFB, filtered effluent, or secondary effluent), application order of the disinfectants (UV before, simultaneously with, or after chlorine), and relative doses (100% UV to 100% chlorine, and intermediate combinations of UV and chlorine). DBPs were not measured in these bench-scale experiments, because sample volumes were too small.

4.2 EFFECTS OF FREE CHLORINE AND CHLORAMINES ON UVT

The effects of free chlorine and chloramines on UVT were measured during some of the bench-scale experiments on filtered effluent. Table E1 in Appendix E provides complete UVT data from the free chlorine experiments, and Table E2 provides complete UVT data from the chloramine experiments.

Figure 4.1a shows data for the six experiments in which UVT values were measured after 20 min of free chlorine contact time. A dose of 2 mg Cl_2/L had no significant effect on UVT. Once the chlorine demand was satisfied (between doses of 2 and 4 mg Cl_2/L), free chlorine addition generally raised the UVT, probably because of reactions with UV-absorbing compounds. Average UVT increased by 1.7 ± 1.4 percentage points between doses of 2 and 4 mg Cl_2/L, and by 2.2 ± 0.9 percentage points between doses of 2 and 6 mg Cl_2/L. This slight increase in UVT had little impact (<2% change) on the UV dose calculated for the collimated beam. However, the increase in UVT may have a larger impact on the calculated UV dose in a flow-through system; for example, the operating equation (Eqn. D2) for the pilot system used in this study predicts that the increase in UVT would increase delivered UV dose by 7–8%.

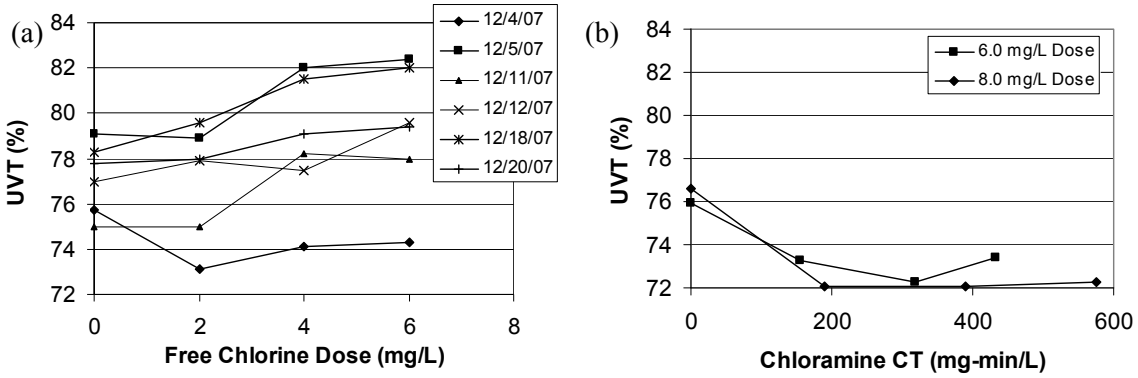


Figure 4.1. Effect of (a) free chlorine dose and (b) chloramine CT on UVT of filtered effluent.

Chloramines decreased UVT values by an average of 3.7 ± 0.9 percentage points (Figure 4.1b), possibly because of UV absorption by chloramines; the molar absorption coefficient at 254 nm is much higher for chloramines than for hypochlorous acid or hypochlorite ions (Watts and Linden, 2007). This decrease in UVT decreased the UV dose calculated for the collimated beam by approximately 3%, but would likely have a larger impact on the delivered UV dose in a flow-through system; for the pilot system in this study, the operating equation (Eqn. D2) predicts that the decrease in UVT would decrease UV dose by approximately 14%.

4.3 CHLORINE DECAY

This section analyzes decay of free chlorine and chloramines in secondary and/or filtered effluents in the presence and absence of UV radiation. Literature suggests that UV can increase the rate of chlorine degradation by photolyzing it to species such as the hydroxyl and chlorine radicals (Cassan et al., 2006; Watts and Linden, 2007).

4.3.1 Chlorine Decay in the Absence of UV Radiation

4.3.1.1 Decay of Free Chlorine Residuals

Free chlorine residuals were only monitored during the experiments with free chlorine. Tables E3 through E5 in Appendix E provide all of the measured free chlorine residual data. Figures 4.2a, 4.2c, and 4.2e show that free chlorine residual initially decreased rapidly, probably because of constituents that exerted chlorine demand. The free chlorine residual also decreased rapidly in the DFB suggesting that the MS2 stock solution seeded into the buffer may exert a chlorine demand.

Figures 4.2a and 4.2c show that free chlorine residual decreased rapidly and approached the reporting limit within the first minute after chlorine addition at a dose of 2 mg Cl_2/L, and within the first 5 min at a dose of 4 mg Cl_2/L. At 6 mg Cl_2/L of free chlorine dose (Figure 4.2e), chlorine residual concentrations in DFB leveled off at approximately 3.5 mg Cl_2/L within 10 min, while concentrations in filtered and secondary effluents continued to decrease toward the reporting limit of 0.05 mg Cl_2/L during the 30-min experiments. The DFB had the lowest chlorine demand and the highest free chlorine residual, followed by the filtered effluent, followed very closely by the secondary effluent.

4.3.1.2 Decay of Total Chlorine Residuals With Free Chlorine or Chloramines

Total chlorine residuals in the absence of UV radiation were measured during experiments with free chlorine and chloramines; complete data are given in Tables E6 through E8 of Appendix E. Results for the experiments with free chlorine are shown in Figures 4.2b, 4.2d, and 4.2f. Total chlorine residual concentrations were higher than free chlorine residual concentrations and leveled off or decreased very slowly after approximately 10 min for all doses and water types. The DFB had the lowest chlorine demand and the highest total chlorine residual concentrations.

The fact that total chlorine residuals were higher than free chlorine residuals indicates the presence of combined chlorine and suggests that free chlorine reacted with constituents in the water. Ammonia concentrations (<0.10 mg N/L in DFB and filtered effluent, and an average of 0.15 mg N/L in secondary effluent) were too low to form the observed total chlorine residual concentrations; the most likely reactive constituents were organic nitrogen, which was present in all water samples, or components of the COD, which was present at the highest concentrations in the DFB.

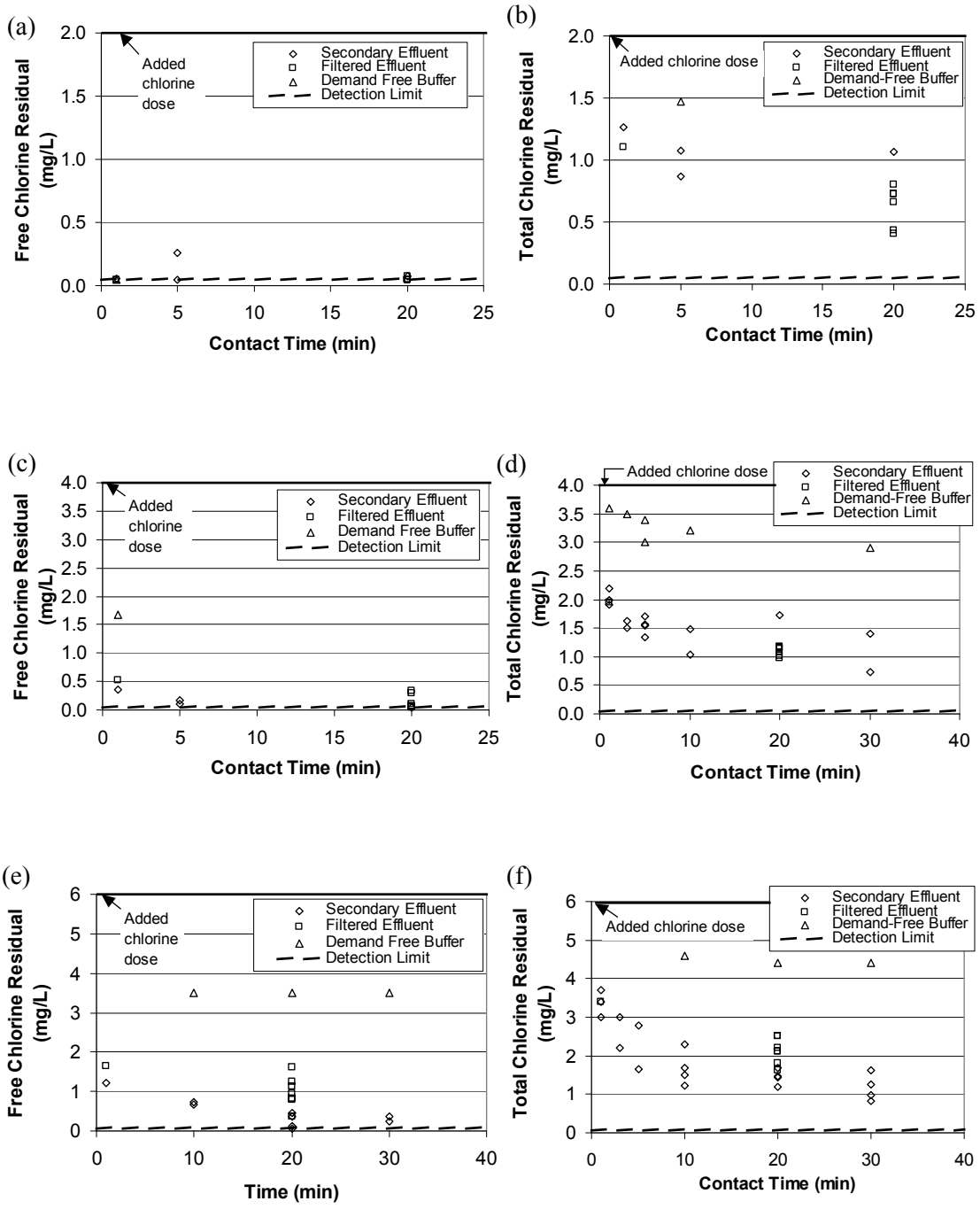


Figure 4.2. Free and total chlorine residuals in bench-scale experiemtns. (a) Free chlorine residuals and (b) Total chlorine residuals after doses of 2 mg Cl_2/L, (c) Free chlorine residuals and (d) Total chlorine residuals after doses of 4 mg Cl_2/L, and (e) Free chlorine residuals and (f) Total chlorine residuals after doses of 6 mg Cl_2/L.

Two tests were conducted to determine the decay of total chlorine residuals during chloramine disinfection in the absence of UV. Figure 4.3 shows that total chlorine residual concentrations initially decreased by approximately 1 mg Cl_2/L because of chlorine demand, then decreased slowly over time. As expected, chloramines yielded higher total chlorine residual concentrations and less chlorine demand than the highly reactive free chlorine.

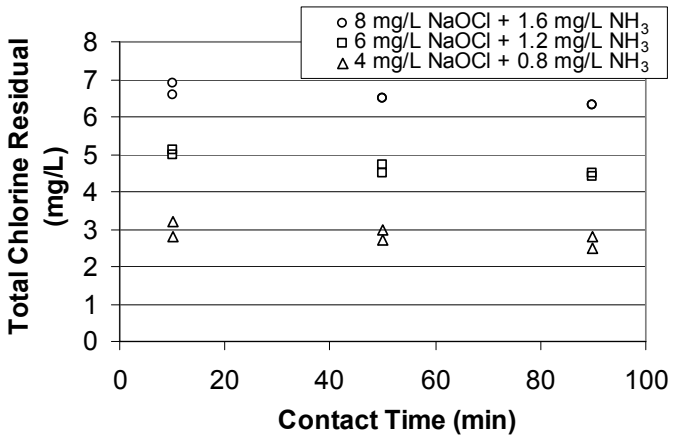


Figure 4.3. Chloramine decay in secondary effluent.

4.3.1.3 Implications for Disinfection Dose Calculations

In theory, a chlorine disinfection dose is the integral of the residual concentration (C) over contact time (T). In practice, disinfection doses are usually approximated using a CT value, which is the product of the chlorine contact time (T) and the total chlorine residual (C) at that contact time.

Figure 4.3 shows that chloramines are relatively stable, so that the total chlorine residual concentrations throughout a chlorine contact tank should be fairly constant. In this case, the CT value is a reasonable estimate of disinfection dose, and has been used to determine the chloramine disinfection dose throughout this report.

Data from the free chlorine decay experiments (Section 4.3.1.2) suggest that the measured total chlorine residuals may contain organochloramines, which have little or no disinfecting power. Consequently, using total chlorine residual concentrations may overestimate the disinfection dose, and the use of the free chlorine residual seems more appropriate than the use of the total chlorine residual in CT calculations for free chlorine disinfection.

However, it is difficult to determine appropriate values for either the free chlorine residual concentration or the contact time. Figure 4.2 indicates that free chlorine residuals typically decay rapidly. Using the low residual concentrations at the end of the contact time would underestimate the disinfection dose. Figure 4.2 also shows that the free chlorine residual concentration often falls rapidly below the reporting limit; in this case, the exact chlorine residual concentration and chlorine contact time cannot be determined. Therefore, an appropriate CT value could not be calculated using the chlorine residual in free chlorine experiments. Instead, the applied free chlorine dose concentration was used throughout this report as a measure of free chlorine disinfectant doses.

4.3.2 Decay of Total Chlorine Residuals in the Presence of UV Radiation

UV-induced decay of free chlorine residuals was not analyzed because their concentrations were too low for meaningful interpretation. UV-induced decay of total chlorine residuals was analyzed using data from the free chlorine and chloramine experiments; full data are given in Tables E7 and E9 of Appendix E. Because total chlorine residual concentrations varied from day to day and decreased over time even in the absence of UV radiation, the analysis compared only residuals that were measured using the same effluent sample on the same day at the same contact time (20 min). The loss of residuals was calculated as the percent change in residual concentration after combined UV/chlorine treatment, relative to chlorine alone. One-sample *t*-tests with $\alpha \leq 0.05$ were applied to determine whether the percent changes in residual concentrations were significantly different from zero.

Table 4.1 compares the percent change values for UV-first, simultaneous, and chlorine-first doses. A negative value indicates that UV reduced the total chlorine residual concentrations. When UV radiation was applied before chlorine (UV-first doses), it generally had no significant effect on the subsequent chlorine addition and the resulting total chlorine residuals, regardless of the dose or effluent quality; the only exception was the 33+4 dose in filtered effluent. In contrast, when UV radiation was applied directly to chlorine (chlorine-first or simultaneous dosing), average total chlorine residuals decreased by 7 to 15% in filtered effluent and total chlorine residuals decreased by 1 to 15% in secondary effluent; these decreases were statistically significant in all filtered effluents, and the 2+67(seq) dose in secondary effluent. These results with simultaneous and chlorine-first doses suggest that UV radiation from low-pressure, high-output lamps can transform total chlorine residuals, particularly in filtered effluents.

The impact of the loss of these total chlorine residuals on disinfection is unclear. Data (Section 4.3.1.2) suggest that these total chlorine residuals may be organochloramines, which have little disinfecting power. Consequently, the loss of these compounds may have little effect on disinfection; however, if the UV-induced decay forms radicals, disinfection may improve.

Table 4.1. Free Chlorine Experiments: Percent Change in Total Chlorine Residuals That Is Due to UV Radiation

	Secondary Effluent (2 Data Points)		Filtered Effluent (6 Data Points)	
Disinfectant Application Order	2*67	4*33	2*67	4*33
UV before chlorine	0 to 5	2 to 4	0 ± 12	-5 ± 4
Simultaneous dosing	-15 to -9	-4 to -1	-15 ± 7	-7 ± 5
Chlorine before UV	-11[*]	-7 to -4	-13 ± 2	-13 ± 6

[*]Both measurements at this dose yielded the same percent change in total chlorine residual.

The loss of residuals was calculated for combined UV/chloramine treatment, relative to chloramines alone. Table 4.2 compares the percent change values for UV+chloramines, chloramines +UV (simultaneous), and chloramines +UV (sequential). A negative value indicates that UV reduced total chlorine residual concentrations. A two-tailed statistical *t*-test with $\alpha \leq 0.05$ indicates that most of the changes in total chlorine residual concentrations were not significantly different from zero; the only exception was the dose of 300+33(sim). These results are consistent with the findings of Watts and Linden (2007), who observed little photodegradation of chloramines.

Table 4.2. Chloramine Experiments: Percent Change in Total Chlorine Residuals That Is Due to UV Radiation

	Filtered Effluent (2 Data Points)	
Disinfectant Application Order	67 mJ/cm^2 UV CT150	33 mJ/cm^2 UV CT300
UV+chloramines	-6 to 3	-2 to 0
Chloramines +UV (simultaneous)	-10 to -3%	-8 to -5
Chloramines +UV (sequential)	-6*	-2 to 0

*Only one measurement was taken at this dose.

4.4 DISINFECTION RESULTS WITH FREE CHLORINE AND UV

Complete disinfection data for MS2, poliovirus, adenovirus, and total coliforms are provided in Appendix E, Tables E11 through E17. Figures 4.4 through 4.6 summarize the disinfection results for MS2, poliovirus, and adenovirus in DFB, filtered effluent, and secondary effluent, at a chlorine contact time of 20 min for each of the disinfection schemes tested. Solid or patterned bars show the average disinfection efficacies achieved, whereas "error bars" indicate 75% confidence intervals. No "error bars" are shown when only one sample was taken, and no data are shown for DFB at partial chlorine doses of 2 or 4 mg Cl_2/L because no samples were taken at a contact time of 20 min. In some cases, microorganism concentrations were below detection after treatment, so average inactivation values were calculated using conservative estimates of disinfection, that is, by assigning non-detections the value of the reporting limit (Section 3.4). Average log inactivation values that include these samples are shown with dashed arrows in Figures 4.4 through 4.6, to signify that actual inactivation may be higher than indicated by the solid or patterned bars.

Average MS2 inactivation values achieved the 4-log benchmark (Section 3.4) for all full doses (Figure 4.4a) and for the chlorine-only dose of 4 mg Cl_2/L in filtered effluent (Figure 4.4b). The dose of 4 mg Cl_2/L in secondary effluent and other partial doses (2 mg Cl_2/L, 33 or 67 mJ/cm^2) did not achieve a 4-log inactivation of MS2.

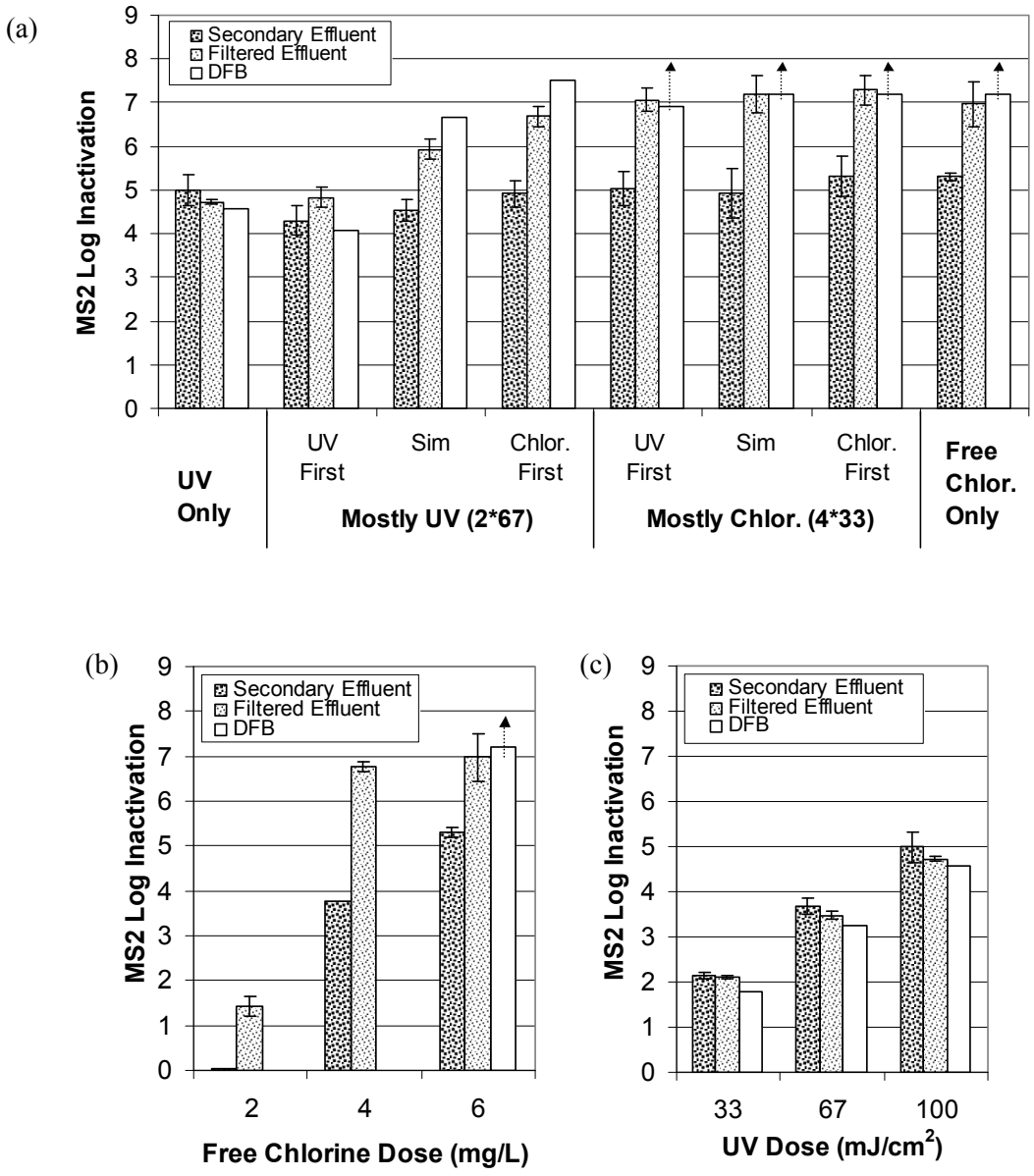


Figure 4.4. MS2 disinfection in DFB, filtered effluent, and secondary effluent after 20 min of chlorine contact time. (a) Full disinfectant doses, (b) Chlorine-only doses, (c) UV-only doses. Dashed arrows indicate that some samples had MS2 concentrations below detection, so actual log inactivation may be higher than shown by the solid or patterned bars. MS2 was not measured at a contact time of 20 min and doses of 2 or 4 mg Cl_2/L in DFB.

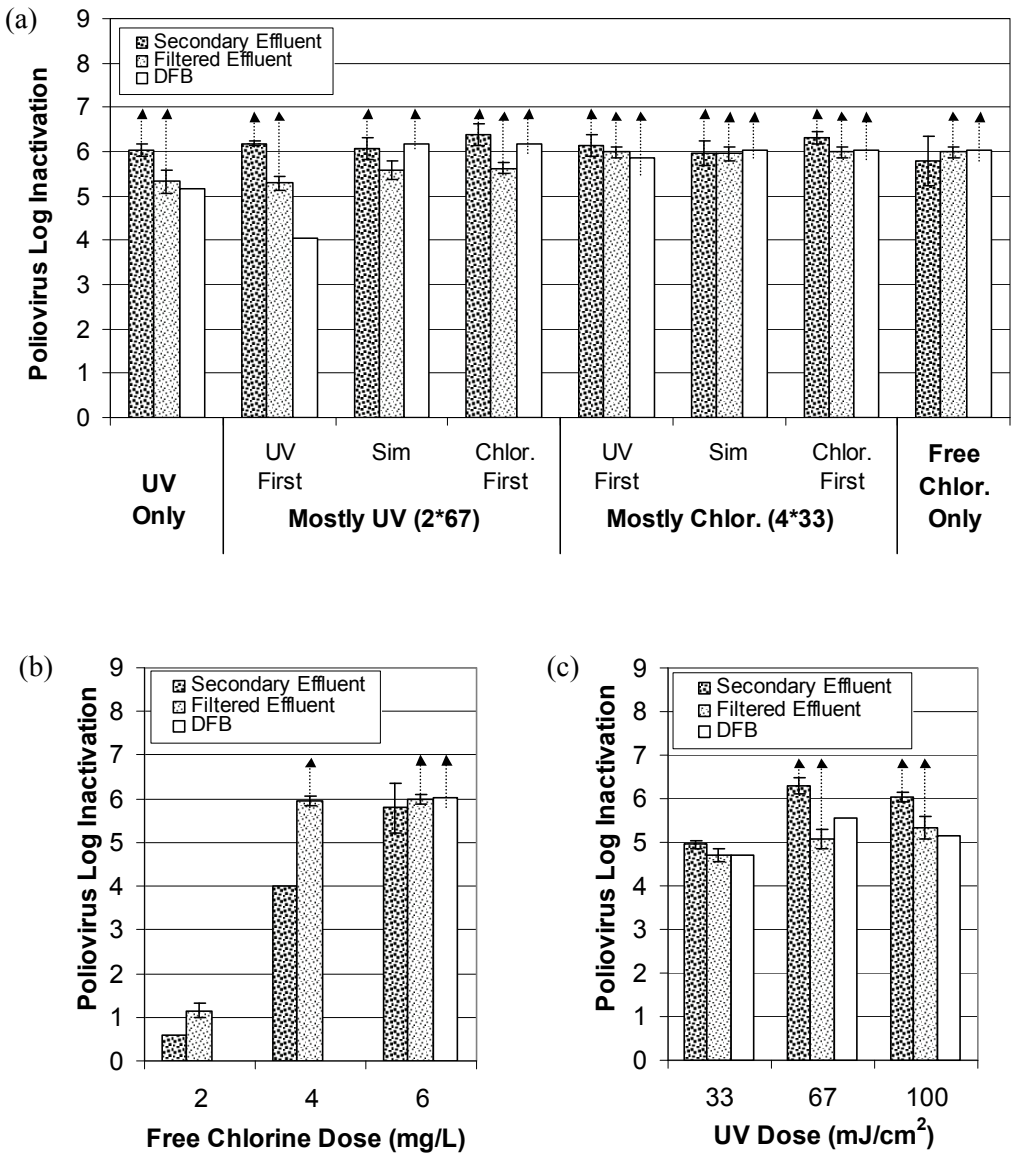


Figure 4.5. Poliovirus disinfection in DFB, filtered effluent, and secondary effluent after 20 min of chlorine contact time. (a) Full disinfectant doses, (b) Chlorine-only doses, (c) UV-only doses. Dashed arrows indicate that some samples had poliovirus concentrations below detection, so actual log inactivation may be higher than shown by the solid or patterned bars. Poliovirus was not measured at a contact time of 20 min and doses of 2 or 4 mg Cl_2/L in DFB.

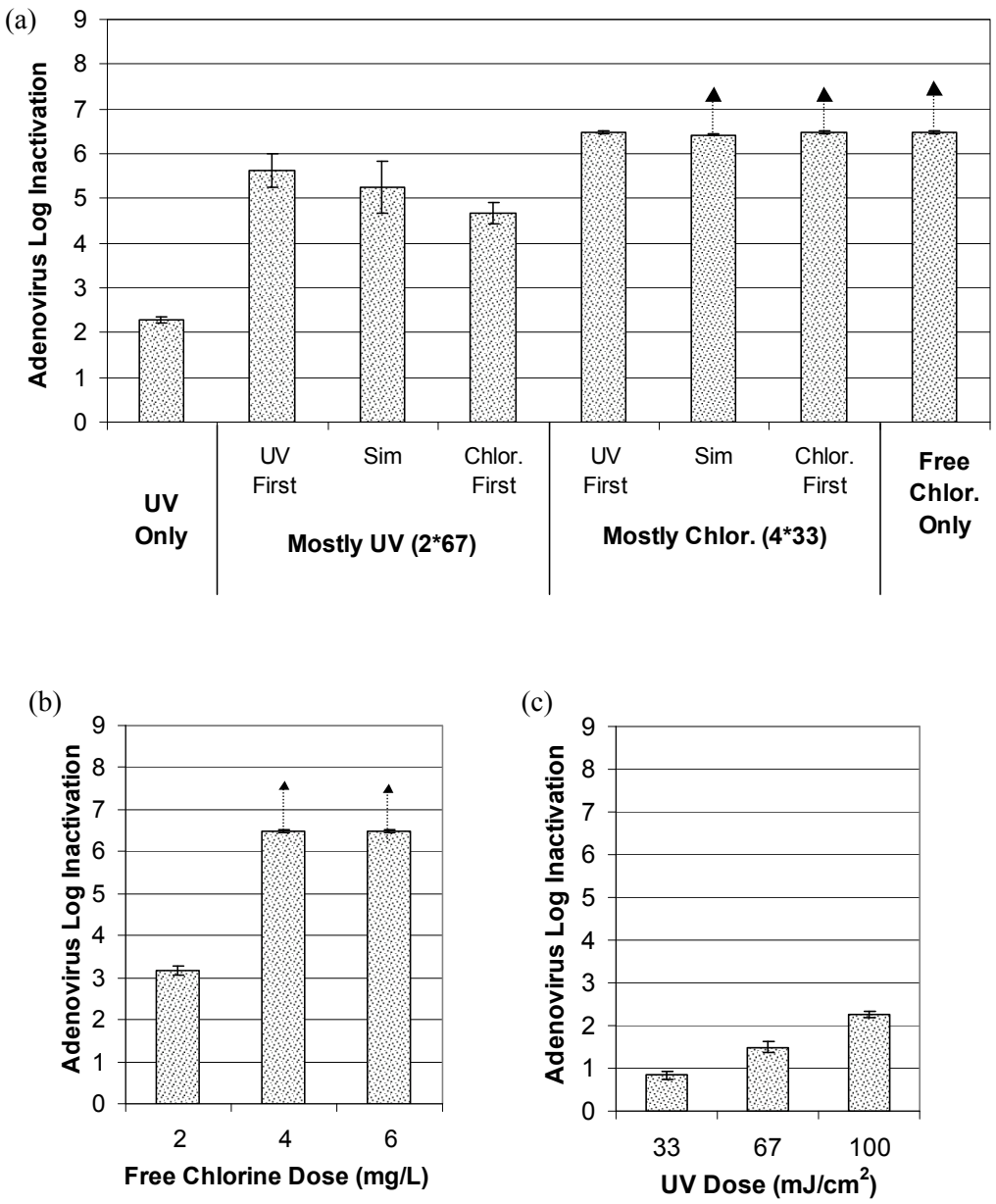


Figure 4.6. Adenovirus disinfection in filtered effluent after 20 min of chlorine contact time. (a) Full disinfectant doses, (b) Chlorine-only doses, (c) UV-only doses. Dashed arrows indicate that some samples had adenovirus concentrations below detection, so actual log inactivation may be higher than shown by the patterned bars.

Poliovirus results are shown in Figure 4.5. Disinfection efficacies were greater for poliovirus than for MS2, with almost half (46%) of the samples below detection after treatment. Average inactivation values and 75% confidence intervals met the benchmark of 5-log inactivation for all full doses in both secondary and filtered effluent samples (Figure 4.5a). Partial doses yielded mixed results. An average of 5-log inactivation was achieved by the UV-only dose of 67 mJ/cm^2 in all tested waters, and by the chlorine-only dose of 4 mg Cl_2/L in filtered effluent, but not by the UV-only dose of 33 mJ/cm^2 or the chlorine-only dose of 2 mg Cl_2/L.

Adenovirus results are shown in Figure 4.6. UV disinfection of adenovirus was poorer than for MS2 or poliovirus. Even the full UV dose of 100 mJ/cm^2 provided less than a 3-log inactivation. Chlorine was more effective than UV and inactivated adenovirus to below detection limits at doses of 4 and 6 mg Cl_2/L. A dose of 2 mg Cl_2/L chlorine (below the chlorine demand level) provided slightly more than 3-log inactivation. All combinations of UV and free chlorine achieved at least 4-log inactivation, with more disinfection of adenovirus at higher relative chlorine doses.

Total coliform concentrations after disinfection were less than or equal to the reporting limit of 2 CFU/100 mL in all samples exposed to UV doses of 33, 67, or 100 mJ/cm^2, either alone or in combination with chlorine. In effluent exposed to chlorine only for a contact time of 20 min, the results were mixed (Table 4.3). Higher doses generally provided more disinfection, and filtered effluents yielded more disinfection than secondary effluents. Filtered effluent exposed to 6 mg Cl_2/L had coliform levels at or below 2 CFU/100 mL; doses of 4 mg Cl_2/L yielded median coliform levels below the benchmark of 2.2 CFU/100 mL, but values were as high as 170 CFU/100 mL. Secondary effluent at all doses and filtered effluent at doses of 2 mg Cl_2/L resulted in total coliform levels that exceeded the benchmark of 2.2 CFU/100 mL.

Table 4.3. Total Coliform Concentrations After 20 Min of Contact Time With Free Chlorine

Free Chlorine Dose (mg Cl_2/L)	Filtered Effluent Total Coliform (CFU/100 mL) Median	Range	No. of Samples	Secondary Effluent Total Coliform (CFU/100 mL) Median	Range	No. of Samples
2	49	26 to 56	5	470	—	1
4	<2	<2 to 170	5	14	—	1
6	<2	<2 to 2	5	6	2 to 40	3

4.5 DISINFECTION RESULTS WITH CHLORAMINES AND UV

UV disinfection was tested in combination with the ammonia-chlorine and chlorine-ammonia processes. In the ammonia-chlorine process, ammonia was mixed into the effluent, followed by free chlorine; this disinfection scheme simulated typical full-scale chloramination. The chlorine-ammonia process was tested in an attempt to mitigate the issues with the ammonia-chlorine process, which are discussed in Section 4.5.1. In the chlorine-ammonia process, free chlorine was added to the effluent, followed by 20 s of mixing, then by addition of ammonia. The chlorine-ammonia process provided free chlorine disinfection for the first 20 s (until ammonia was added), and chloramine disinfection thereafter.

Filtered effluents were used in two tests combining UV with the ammonia-chlorine process and in two tests combining UV with the chlorine-ammonia process. MS2, poliovirus, and total coliforms were measured in each experiment. Because of the limited number of samples, no statistical analysis of the results was carried out. Tables E18 and E19 in Appendix E provide the complete data from the ammonia-chlorine and chlorine-ammonia experiments, respectively.

4.5.1 Ammonia-Chlorine Process

Figure 4.7 summarizes MS2 and poliovirus data for each of the ammonia-chlorine disinfection schemes. Patterned bars show average disinfection efficacies, whereas "error bars" represent the standard deviations. Average log inactivation values that include samples below detection are shown with dashed arrows, to signify that actual inactivation may be higher than indicated by the patterned bars. As Figure 4.7b shows, MS2 was very resistant to chloramines. Average MS2 inactivation values were less than the 4-log benchmark for all combined UV/chloramine doses and were slightly less than zero for all tested chloramine only doses. These negative inactivation values likely resulted from the variability in the microbial analysis, rather than from any MS2 growth or regrowth.

Inactivation levels were much higher for poliovirus than for MS2. More than half of the poliovirus samples were below detection, so conservative estimates of disinfection were used to calculate average inactivation values (Chapter 3). Poliovirus disinfection by combined UV/chloramine doses exceeded the benchmark of 5-log inactivation under all six combined disinfection schemes. The full chloramine CT value of 450 mg-min/L achieved an average poliovirus inactivation of 4.8-log, which was slightly lower than the 5-log inactivation benchmark.

Final total coliform levels achieved the benchmark of 2.2 MPN/100 mL. Levels after disinfection were below the detection limit of 2 CFU/100 mL in all samples exposed to the three tested doses of UV alone and to the three tested doses of chloramines alone. Total coliform levels were below detection in five of the six samples exposed to combined UV/chloramines; one sample exposed to a dose of 67+150 had a concentration of 4 CFU/100 mL.

Overall, these results indicate that the combined UV/chloramine disinfection scheme is effective against poliovirus and total coliforms. Although the combined UV/chloramine disinfection schemes did not meet the MS2 benchmark, the addition of UV to the chloramine-only scheme improved MS2 disinfection.

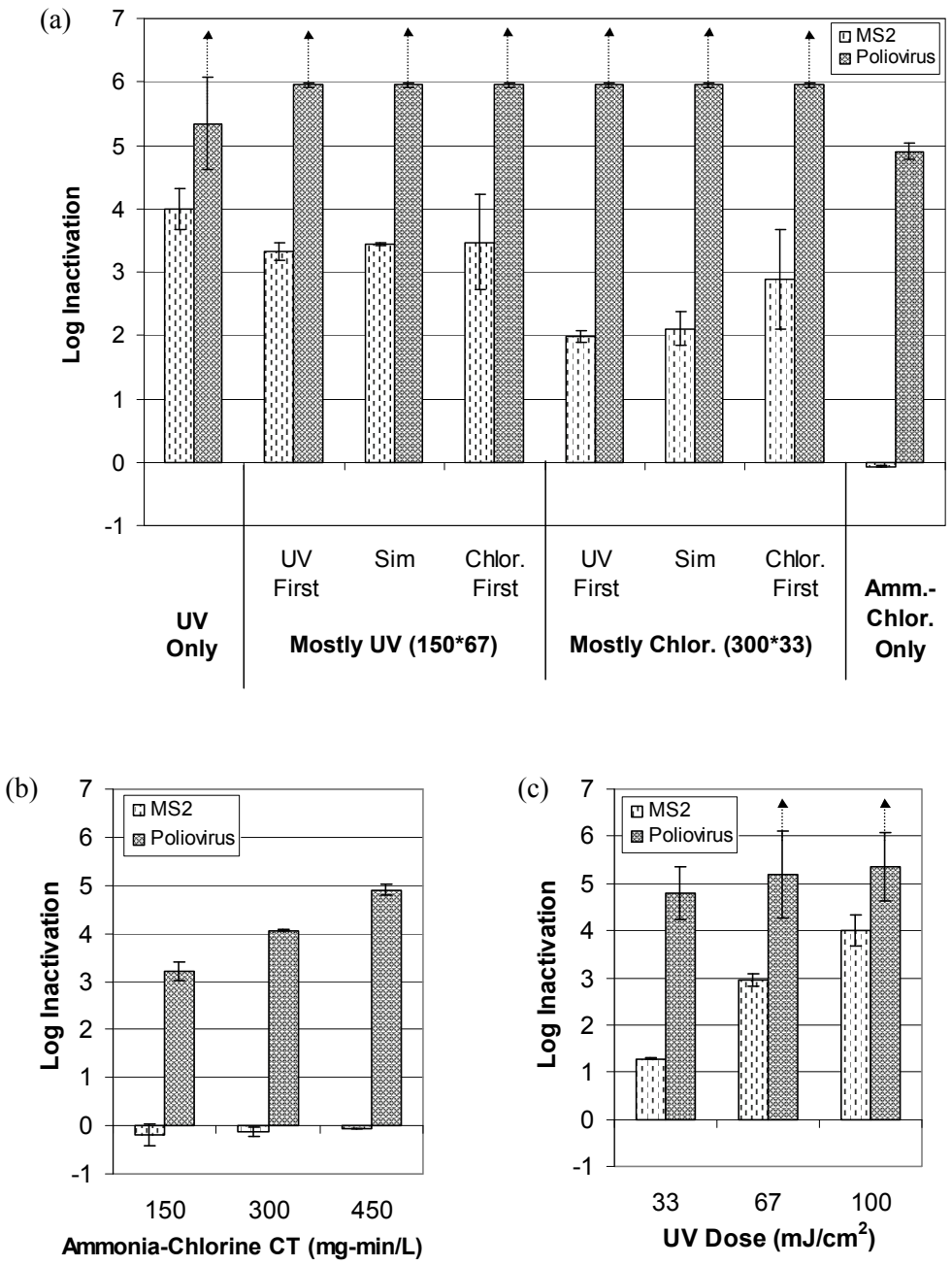


Figure 4.7. MS2 and poliovirus disinfection in filtered effluent with UV and/or the ammonia-chlorine process. (a) Full disinfectant doses, (b) Ammonia-chlorine-only CT values, (c) UV-only doses. Dashed arrows indicate that some samples had concentrations below detection, so actual log inactivation may be higher than shown by the patterned bars.

4.5.2 Chlorine-Ammonia Process

Sections 4.4 and 4.5.1 indicate that chloramines are ineffective against MS2, but that free chlorine can effectively disinfect MS2. These results suggested that the chlorine-ammonia process should be evaluated. In the chlorine-ammonia process, free chlorine is added first, and then ammonia is added. Free chlorine should be present during the initial period after chlorine addition and should provide effective disinfection of MS2. The subsequent addition of ammonia could reduce DBP formation and provide a more stable chlorine residual for distribution of recycled water.

Figure 4.8 summarizes MS2 and poliovirus data for each of the chlorine-ammonia disinfection schemes. Patterned bars show average disinfection efficacies, whereas "error bars" represent the standard deviations. Average log inactivation values that include samples below detection are shown with dashed arrows, to signify that actual inactivation may be higher than indicated by the patterned bars.

Figure 4.8a shows that average poliovirus disinfection met the 5-log inactivation benchmark for all full doses with the chlorine-ammonia process. For MS2, the chlorine-ammonia process alone did not meet the 4-log benchmark, but the addition of UV improved disinfection. Average MS2 disinfection exceeded the 4-log benchmark for all combined UV/chloramines doses. Total coliform concentrations were below detection in most of the 24 samples (Table E19 of Appendix E), although total coliform levels were 4 CFU/100 mL in four samples: one sample each at doses of 67 mJ/cm^2, 150+67(sim), and chloramine-only CT values of 150 and 300 mg-min/L.

The three chloramine-only CT values produced similar levels of disinfection (Figure 4.8b). All three chloramine-only CT values used 6.5 mg Cl_2/L of free chlorine, followed by 20 s of mixing, then ammonia addition. These results suggest that free chlorine caused most of the disinfection, and the subsequent 30, 60, or 90 min of contact time with chloramines did not cause much further inactivation. These results also suggest that disinfection with the chlorine-ammonia process might be improved by extending the free chlorine contact time before ammonia addition; this hypothesis was not tested.

4.5.3 Comparing Free Chlorine, the Ammonia-Chlorine Process, and the Chlorine-Ammonia Process

Figures 4.9 and 4.10 summarize the MS2 and poliovirus disinfection data, respectively, for each of the disinfection schemes. The UV-only doses provided comparable disinfection in all experiments with MS2 (Figure 4.9c) or poliovirus (Figure 4.10c). The chlorine-ammonia process provided as much or more MS2 and poliovirus disinfection than the ammonia-chlorine process under all chloramine-only or combined UV/chloramine disinfection schemes, presumably because of the 20 s of exposure to free chlorine prior to ammonia addition.

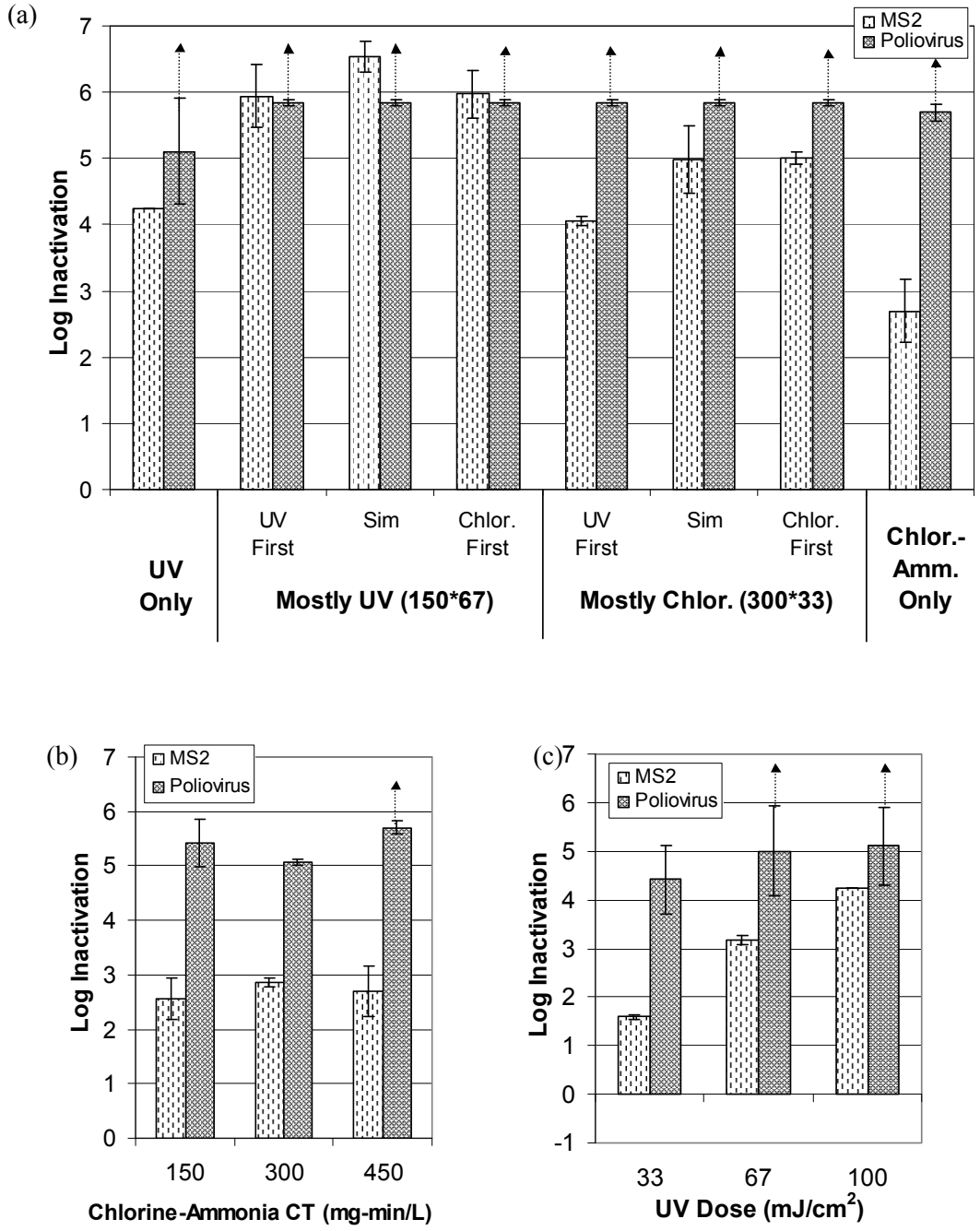


Figure 4.8. MS2 and poliovirus disinfection in filtered effluent with UV and/or the chlorine-ammonia process. (a) Full disinfectant doses, (b) Chlorine-ammonia-only doses, (c) UV-only doses. Dashed arrows indicate that some samples had concentrations below detection, so actual log inactivation may be higher than shown by the patterned bars.

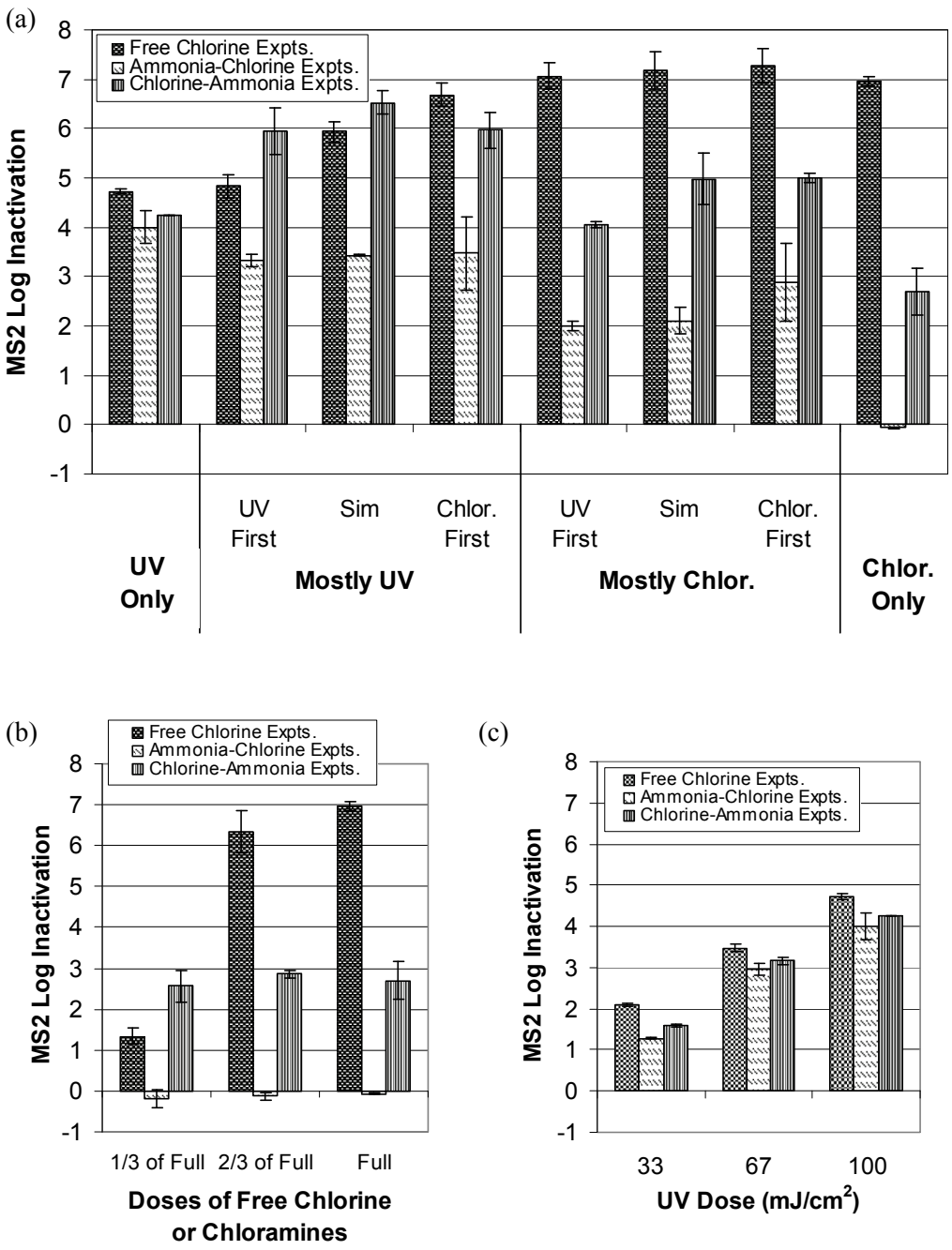


Figure 4.9. MS2 disinfection in filtered effluent. (a) Full disinfectant doses, (b) Free chlorine or chloramine only doses, (c) UV-only doses. Full doses were 6 mg Cl_2/L for free chlorine and CT of 450 mg-min/L for chloramines.

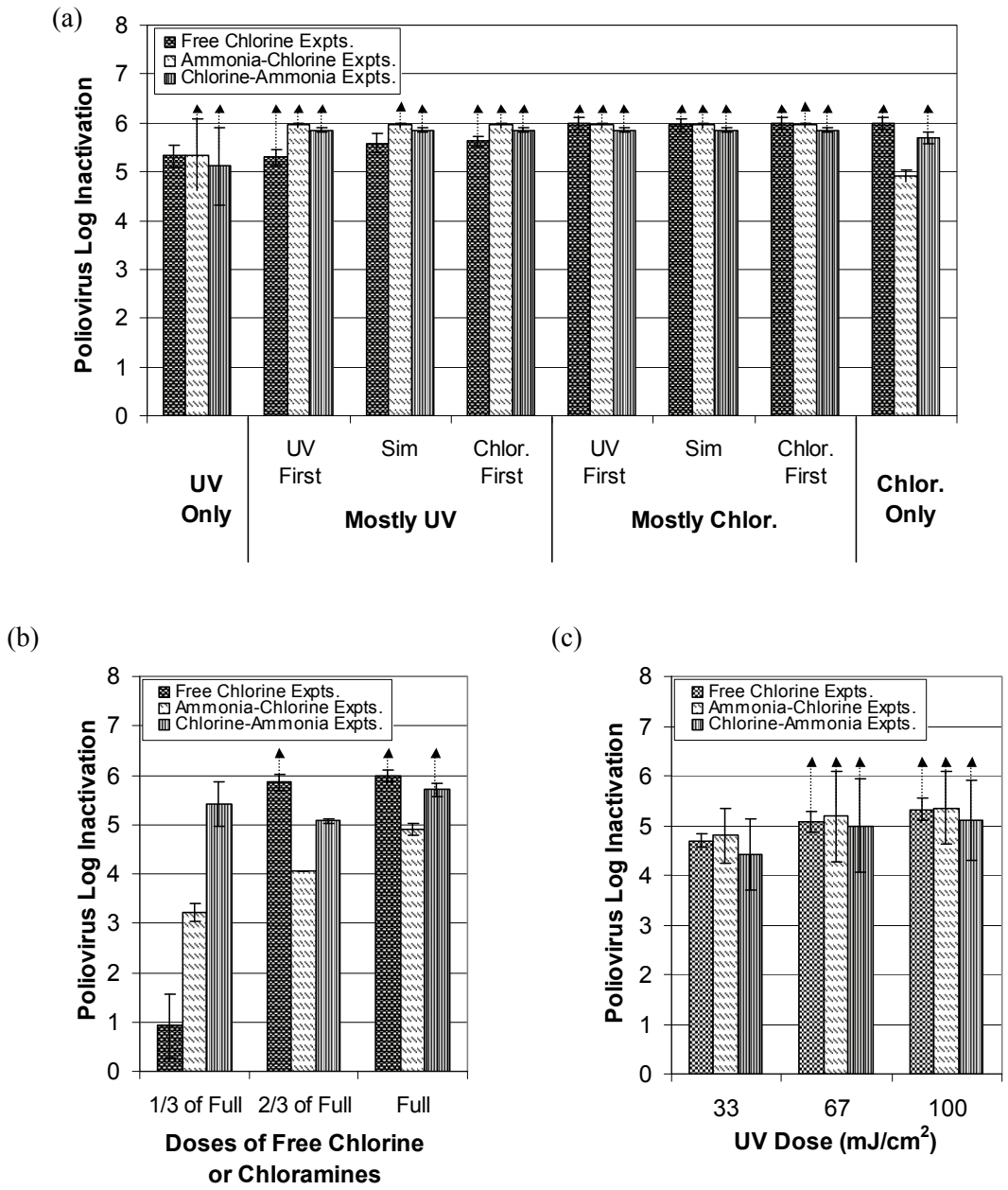


Figure 4.10. Poliovirus disinfection in filtered effluent. (a) Full disinfectant doses, (b) Free chlorine or chloramine only doses, (c) UV-only doses. Full doses were 6 mg Cl_2/L for free chlorine and CT of 450 mg-min/L for chloramines. Dashed arrows indicate that some samples had concentrations below detection, so actual log inactivation may be higher than shown by the patterned bars.

Free chlorine generally provided comparable or more disinfection of MS2 and poliovirus than the ammonia-chlorine or chlorine-ammonia process. The only exception was for the 1/3 dose of free chlorine (2 mg Cl_2/L), which produced less poliovirus inactivation than the ammonia-chlorine or chlorine-ammonia process alone at a dose of CT150. Similarly, the free chlorine dose of 2 mg Cl_2/L, alone or in combination with UV, yielded less MS2 inactivation than the corresponding doses with the chlorine-ammonia process. These discrepancies are probably caused by differences in the added chlorine doses; the free chlorine dose of 2 mg Cl_2/L was below the chlorine demand of the effluent, whereas for the CT150 values, the added free chlorine of 6.5 mg Cl_2/L was much higher than the chorine demand.

The chlorine-ammonia process provided more MS2 and poliovirus disinfection than the ammonia-chlorine process but did not meet MS2 disinfection benchmarks when used alone. Free chlorine generally provided more disinfection than either the ammonia-chlorine or chlorine-ammonia process. In practice, the chlorine-ammonia process could only be used for fully nitrified effluents. However, for such effluents, disinfection with free chlorine would use less chlorine and no ammonia, be less expensive, and be less complex than the chlorine-ammonia process. Because the chlorine-ammonia process showed few advantages relative to free chlorine, the pilot experiments focus on the use of UV in combination with free chlorine.

4.6 EFFECTS OF OPERATING CONDITIONS ON DISINFECTION

This section discusses the effects of water quality, chlorine contact time, relative UV/chlorine dose, and disinfectant application order on inactivation of MS2, poliovirus, adenovirus, and total coliforms. Data taken with DFB were not analyzed statistically, because there was only one sample for each disinfection scheme.

Poliovirus, adenovirus, and total coliform data had samples below detection, so log inactivation values could not be quantitatively calculated and compared. For these microorganisms, "better" disinfection was defined as a higher percentage of samples at or below detection limits. Tables 4.4 through 4.7 show the percentages of samples at or below detection limits for the tested microorganisms with UV (Table 4.4), free chlorine (Table 4.4), the ammonia-chlorine process (Table 4.5), the chlorine-ammonia process (Table 4.5), combined UV/free chlorine (Table 4.6), and combined UV/chloramines (Table 4.7). These percentages provide an indication of the effectiveness of disinfection and were used to compare different operating conditions. However, this approach does not account for measurement variability and is less robust than the statistical *t*-test analysis of the measured inactivation values that was performed when all samples were above detection limits.

4.6.1 Effects of Water Quality

The effects of water quality were tested by comparing disinfection in secondary and filtered effluent samples. The two types of effluent samples had similar levels of most measured parameters, although the secondary effluent samples had lower levels of nitrate and higher levels of particles, chlorine demand, ammonia, and TKN (Tables 3.3 and 3.4). Because adenovirus and chloramines were only tested in filtered effluent samples, the effect of water quality could not be evaluated. UV and/or free chlorine disinfection was evaluated for MS2, poliovirus, and total coliforms. Some poliovirus and total coliform samples were below detection; in these cases, comparisons were made using the percentage of samples at or below detection (Tables 4.4 and 4.6). When all samples yielded detectable concentrations, comparisons were made using Welch's *t*-test with α of 0.05 or less to define significance. The *p*-values from these tests are given in Table E20 of Appendix E.

Table 4.4. Percentage of Samples at or Below Detection Limits After Treatment With UV or Free Chlorine

		UV (mJ/cm^2)			Free Chlorine (mg Cl_2/L)		
Microorganism	**Effluent Type**	**33**	**67**	**100**	**2**	**4**	**6**
MS2	Secondary	0	0	0	0	0	0
	Filtered	0	0	0	0	0	0
Adenovirus[a]	Filtered	0	0	0	0	100	100
Poliovirus	Secondary	0	67	50	0	0	33
	Filtered	0	20	20	0	80	100
Total Coliform	Secondary	100	100	100	0	0	33
	Filtered	100	100	100	0	60	100

[a] Adenovirus was not tested in secondary effluent, and was only tested twice in filtered effluent.

Table 4.5. Percentage of Samples at or Below Detection Limits After Treatment With the Ammonia-Chlorine or Chlorine-Ammonia Process in Filtered Effluent[a]

	Ammonia-Chlorine			Chlorine-Ammonia		
Microorganism	**CT150**	**CT300**	**CT450**	**CT150**	**CT300**	**CT450**
MS2	0	0	0	0	0	0
Poliovirus	0	0	0	0	0	50
Total Coliform	100	100	100	50	50	100

[a] Chloramination was not tested in secondary effluent, and was only tested twice in filtered effluent.

Table 4.6. Percentage of Samples at or Below Detection Limits After Treatment With UV Combined with Free Chlorine

Microorganism	**Effluent Type**	**67+2**	**2+67 (sim)**	**2+67 (seq)**	**33+4**	**4+33 (sim)**	**4+33 (seq)**
MS2	Secondary	0	0	0	0	0	0
	Filtered	0	0	0	0	0	0
Adenovirus[a]	Filtered	0[b]	0[b]	0[b]	100[b]	50[b]	100[b]
Poliovirus	Secondary	33	50[b]	67	33	50[b]	67
	Filtered	20	50	40	100	100	100
Total Coliform	Secondary	100	100[c]	100	100	100[c]	100
	Filtered	100	100	100	100	100	100

[a] Adenovirus was not tested in secondary effluent.

[b] Only two samples were analyzed under this disinfection scheme.

[c] Only one sample was analyzed under this disinfection scheme.

Table 4.7. Percentage of Samples at or Below Detection Limits After Treatment With UV Combined With the Ammonia-Chlorine or Chlorine-Ammonia Process in Filtered Effluent[a]

Disinfectants	Microorganism	67+150	150+67 (sim)	150+67 (seq)	33+300	300+33 (sim)	300+33 (seq)
UV with Ammonia-Chlorine	MS2	0	0	0	0	0	0
	Poliovirus	100	100	100	100	100	100
	Total Coliform	50	100	100	100	100	100
UV with Chlorine-Ammonia	MS2	0	0	0	0	0	0
	Poliovirus	100	100	100	100	100	100
	Total Coliform	100	50	100	100	100	100

[a] Chloramination was not tested with secondary effluent or adenovirus. All disinfection schemes were only tested twice.

4.6.1.1 Free Chlorine Disinfection

After disinfection with chlorine alone, average microorganism concentrations were lower (and log inactivation values were higher) in filtered effluent than in secondary effluent for all three microorganisms. At chlorine-only doses of 4 or 6 mg Cl_2/L, a higher percentage of total coliform and poliovirus samples were below detection in filtered effluent than in secondary effluent (Table 4.4). Welch's *t*-test was applied for the data at a chlorine-only dose of 2 mg Cl_2/L, because no poliovirus or total coliform samples were below detection. Average inactivation of total coliforms was significantly higher in filtered effluent than in secondary effluent. The differences were not statistically significant for poliovirus (Figure 4.5). For MS2 (Figure 4.4), inactivation was significantly higher in filtered effluent than in secondary effluent at chlorine-only doses of 4 and 6 mg Cl_2/L, but there was no significant difference at 2 mg Cl_2/L. The higher levels of disinfection in filtered effluent samples at higher chlorine doses may be due to factors such as lower chlorine demand, ammonia levels, and particle concentrations in the filtered effluent samples (Tables 3.3 and 3.4).

4.6.1.2 UV Disinfection

The effects of water quality on the disinfection efficacy of total coliforms could not be determined, because the total coliform levels were at or below detection after UV treatment in all of the filtered and secondary effluent samples (Table 4.4). For MS2 disinfection, Welch's *t*-test indicated no statistically significant difference between secondary and filtered effluents (Figure 4.4c). Welch's *t*-test also indicated no statistically significant difference between secondary and filtered effluents for poliovirus disinfection with a UV-only dose of 33 mJ/cm^2 (Figure 4.5c). With UV-only doses of 67 and 100 mJ/cm^2, some secondary and filtered effluent samples were below detection, so Welch's *t*-test could not be used to assess statistical significance of differences in poliovirus disinfection; however, a higher percentage of samples were below detection in secondary effluent than in the filtered effluent. These results suggest that UV disinfection may be more effective in secondary effluent than in filtered effluent; however, more testing is needed to confirm this finding because of the limited number of samples and the similar water qualities of the secondary and filtered effluent samples in these experiments.

4.6.1.3 Combined UV/Free Chlorine Disinfection

The data from combined UV/free chlorine were generally consistent with UV-only or chlorine-only disinfection results: Total coliforms were at or below detection levels in all filtered and secondary effluent samples, so that the disinfection efficacy in the two effluents could not be compared statistically. For MS2 (Figure 4.4), combined UV/free chlorine doses achieved significantly higher average disinfection levels in filtered effluent than in secondary effluent at doses of 2+67(sim), 2+67(seq), and 33+4. These results are consistent with results with the individual disinfectants: MS2 disinfection by free chlorine was better in filtered effluent than in secondary effluent, whereas UV showed no effects. For poliovirus at doses of 4*33, filtered effluents had a higher percentage of samples below detection than secondary effluents (Tables 4.4 and 4.6). Doses of 2*67 yielded a higher percentage of samples below detection in secondary effluent. Thus, doses of 4*33 behaved like the chlorine-only doses and yielded more disinfection in filtered effluent, whereas doses of 2*67 behaved like the UV-only doses and yielded more disinfection in secondary effluent.

4.6.2 Effects of Chlorine Contact Time in Secondary Effluent

To assess the effects of chlorine contact time on disinfection, two sets of MS2 inactivation data in secondary effluent were compared at contact times of 10, 20, and 30 min, and at doses of 2*67, 4*33, and 6 mg Cl_2/L. Figure 4.11 shows the average inactivation and standard deviations at each contact time and dose. Welch's *t*-tests with α of 0.05 were performed to determine whether increasing the contact time (from 10 to 20 min, 10 to 30 min, or 20 to 30 min) had a statistically significant impact on disinfection; a complete list of *p*-values is given in Table E21 of Appendix E. Results of the analysis indicated that increasing the contact time beyond 10 min generally had no significant effect on disinfection in secondary effluent. This observation is consistent with the free chlorine residual data (Figure 4.2), which showed that no free chlorine residuals remained in secondary effluent after 10 min and suggests that the remaining total chlorine residual has limited value as a disinfectant.

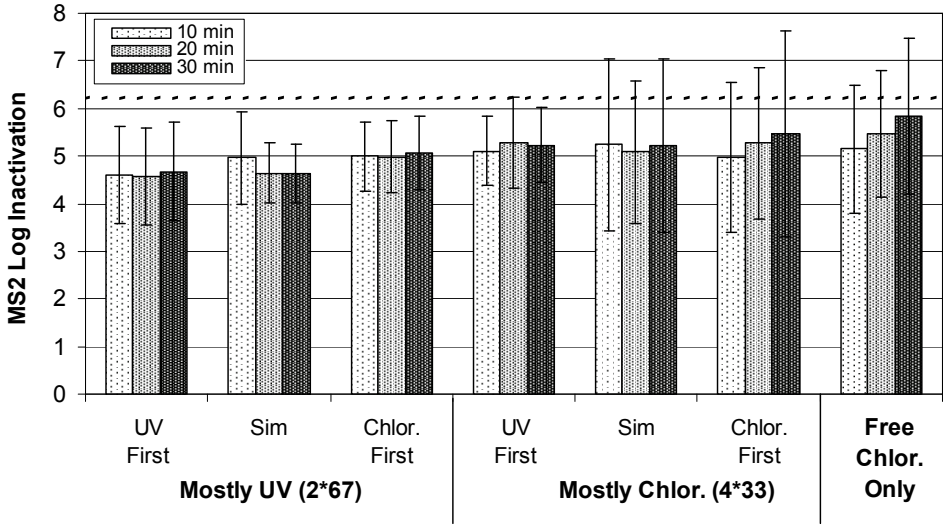


Figure 4.11. MS2 disinfection performance in secondary effluent with combined UV/free chlorine at contact times of 10, 20, and 30 min. Dotted line represents average inactivation to the detection limit, i.e., the maximum removal that could be detected.

4.6.3 Effects of Disinfectant Application Order

The effects of disinfectant application order (i.e., the order in which the disinfectants were applied) were assessed by comparing inactivation when UV was dosed first, UV and chlorine were dosed simultaneously, and chlorine was dosed first. Figures 4.12 and 4.13 compare MS2 inactivation for the different orders of addition with free chlorine and chloramines, respectively. Statistical analysis of the disinfection differences used Welch's *t*-test with α of 0.05. Table E22 of Appendix E provides the *p*-values for all comparisons of inactivation values. For poliovirus, adenovirus, and total coliforms, comparisons used the percentage of samples at or below detection (Tables 4.6 and 4.7).

Almost all total coliform samples were below detection in both secondary and filtered effluents, so no trends could be seen. For inactivation of MS2, poliovirus, and adenovirus, disinfectant application order generally had no observable effect, with two exceptions. Average MS2 inactivation (Figure 4.12) in filtered effluent was significantly lower at a dose of 67+2 (UV-first) than at doses of either 2+67(sim) or 2+67(seq). For poliovirus in secondary effluent, the highest percentage of samples below detection occurred when chlorine was dosed before UV, followed by simultaneous dosing, and UV dosed before chlorine (Table 4.6). Although MS2 log inactivation with combined UV/chloramines at a dose of 300*33 appears to be lower when UV was dosed first than when chlorine was dosed first (Figure 4.13), only two data points were taken, and the statistical analysis showed no significant difference. The effects of disinfectant application order were investigated further in the pilot experiments (Sections 5.5.1 and 5.5.3).

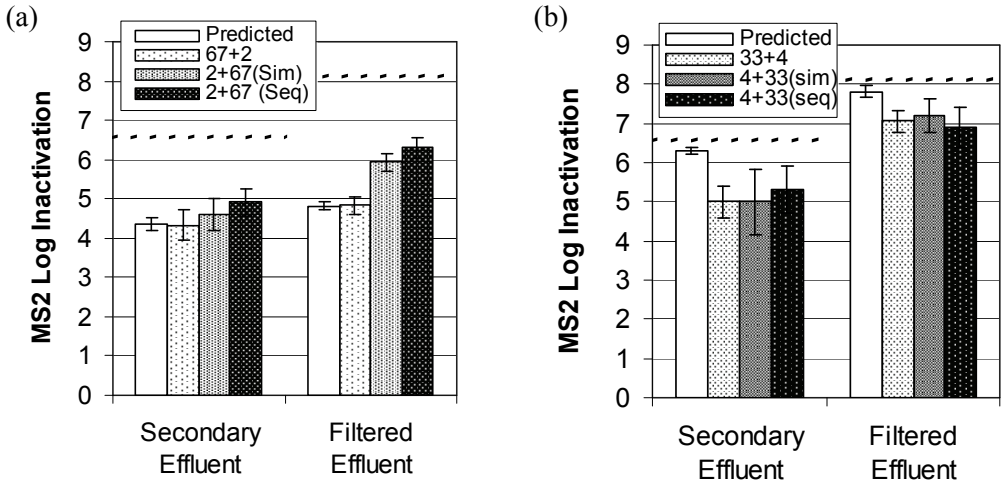


Figure 4.12. Predicted and measured MS2 disinfection performance with combined UV/free chlorine for (a) doses of 2*67, (b) doses of 4*33. Dotted lines represent average inactivation to the detection limit, i.e., the maximum removal that could be detected.

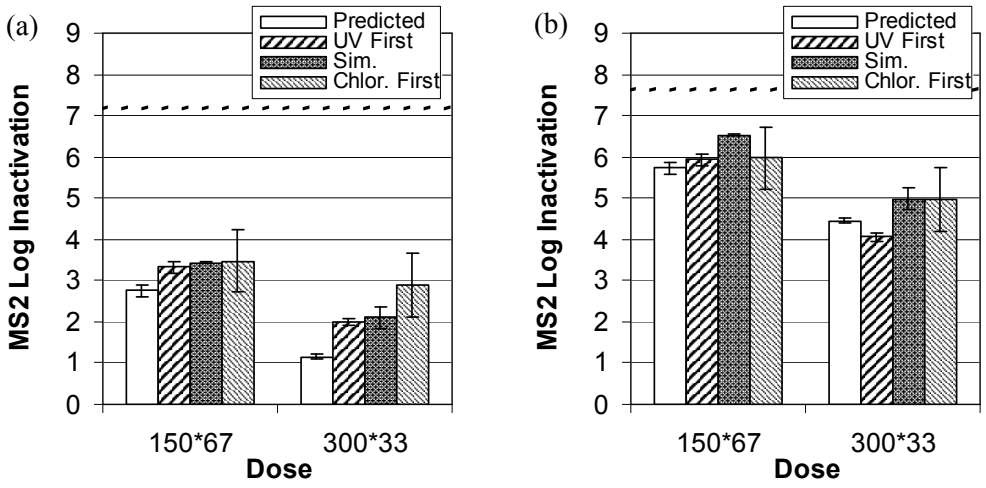


Figure 4.13. Predicted and measured MS2 disinfection performance with (a) combined UV/ammonia-chlorine and (b) combined UV/chlorine-ammonia. Dotted lines represent average inactivation to the detection limit, i.e., the maximum removal that could be detected.

4.6.4 Effects of Relative UV/Chlorine Dose

The effects of relative UV and chlorine dose on disinfection efficacy were assessed by using Welch's *t*-test to compare inactivation at "mostly chlorine" and "mostly UV" doses. Poliovirus, adenovirus, and total coliforms were compared using the percentage of samples at or below detection (Tables 4.6 and 4.7). Figure 4.14 compares the doses for MS2 disinfection. Figure 4.14a compares UV/free chlorine at doses of 2*67 and 4*33. Figures 4.14b and 4.14c compare UV/chloramines at doses of 150*67 and 300*33 for the ammonia-chlorine and chlorine-ammonia processes, respectively. Patterned bars represent average inactivation values, whereas "error" bars are the 75% confidence intervals. *P*-values from the statistical comparisons of MS2 disinfection are presented in Table E23, Appendix E.

Table 4.6 indicates that for combined UV/free chlorine dosing, higher relative doses of chlorine (4*33 vs. 2*67) provided more poliovirus and adenovirus disinfection in filtered effluent. No such trend was observed for poliovirus in secondary effluent, or for total coliforms in secondary or filtered effluent. Average MS2 inactivation values in filtered effluent were significantly higher at doses of 4*33 than 2*67 when UV was applied first or when UV and chlorine were applied simultaneously (Figure 4.14a). These results are consistent with the individual disinfectant data, which showed that the highest chlorine dose provided more MS2, poliovirus, and adenovirus inactivation in filtered effluents than the highest UV dose (Figures 4.4, 4.5, and 4.6).

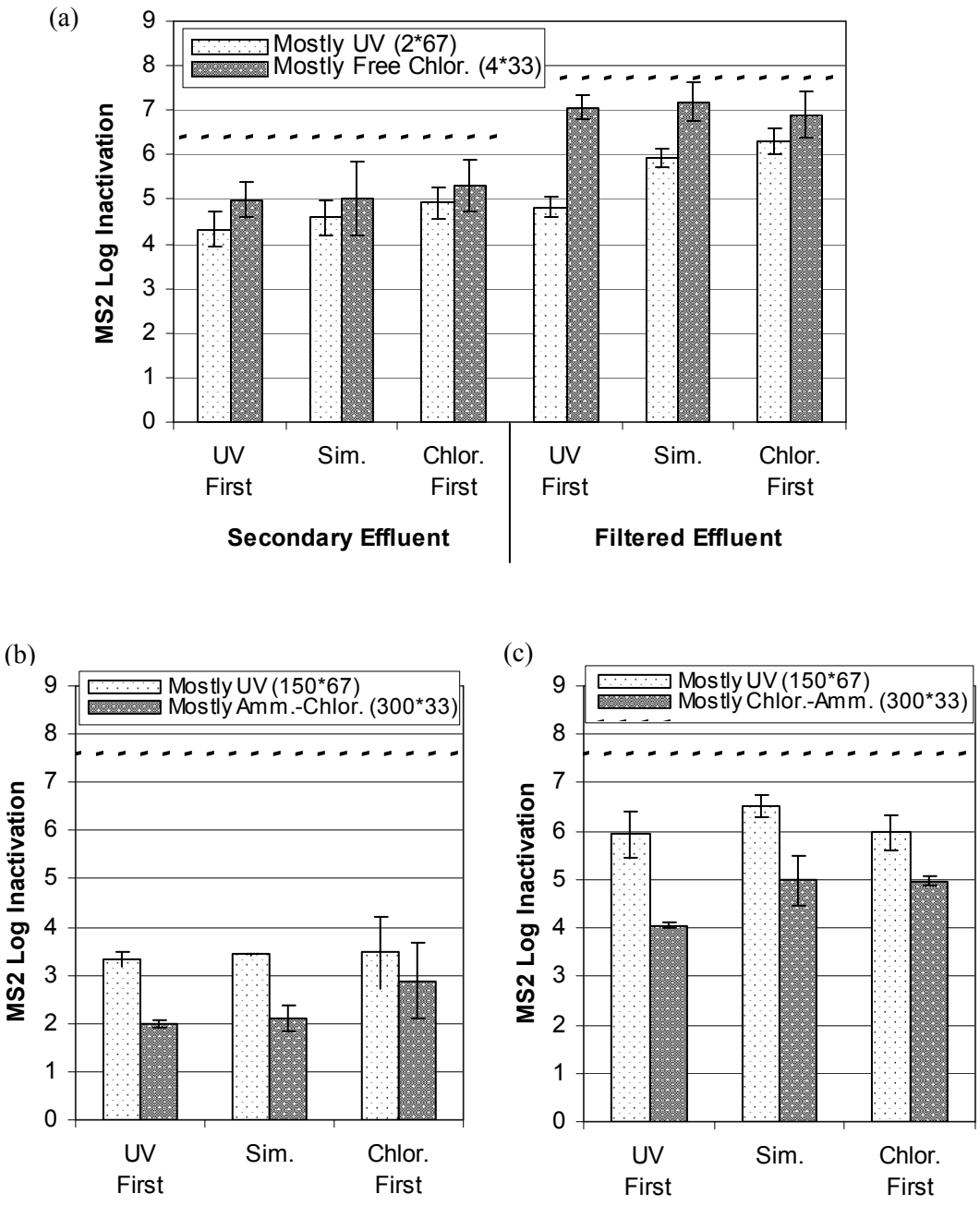


Figure 4.14. MS2 disinfection: Comparison of "mostly UV" and "mostly chlorine" doses. (a) Combined UV/free chlorine doses of 2*67 and 4*33 in secondary and filtered effluent, (b) combined UV/ammonia-chlorine doses of 150*67 and 300*33 in filtered effluent, (c) combined UV/chlorine-ammonia doses of 150*67 and 300*33 in filtered effluent. Dotted lines represent average inactivation to the detection limit, i.e., the maximum removal that could be detected.

Effects of relative dose were difficult to assess for poliovirus and total coliform disinfection with combined UV/chloramines, because only two samples were taken for each disinfection scheme, and most disinfected samples were below detection (Table 4.7); consequently, statistical comparisons were not conducted. Average MS2 inactivation values were higher at doses of 150*67 than at doses of 300*33 (i.e., higher relative doses of UV provided more disinfection) for all three disinfectant application orders with both combined UV/ammonia-chlorine and combined UV/chlorine-ammonia. These results are consistent with the individual disinfectant data, which showed that the highest UV dose provided more MS2 inactivation than the highest chloramine dose (Figures 4.7 and 4.8).

4.6.5 Synergistic and Antagonistic Effects With Combined UV/Chlorine

Synergistic and antagonistic effects were analyzed for MS2 disinfection; disinfection of other organisms could not be evaluated because some samples had concentrations below detection. For free chlorine disinfection schemes, effects were identified using Welch's *t*-test with α of 0.05, as described in Section 3.7.2; Table E24 of Appendix E provides the *p*-values for all comparisons of inactivation values. Statistical analyses were not conducted for the chloramine disinfection tests because of the limited number of samples.

Figures 4.12a and 4.12b compare the measured and predicted MS2 inactivation values for combined UV/free chlorine in secondary and filtered effluent for the 2*67 and 4*33 doses, respectively. Average inactivation values were significantly higher than predicted (synergistic effects) in filtered effluent at doses of 2+67(sim) and 2+67(seq). These two disinfection schemes also yielded significantly more disinfection than UV-first dosing in filtered effluents (Section 4.6.3.1). These effects and their potential causes are discussed further in Sections 5.5.2 and 5.5.3.

Average disinfection was significantly worse than predicted (antagonistic effects) at doses of 33+4 in filtered and secondary effluents. This result may be because inactivation levels were very high, that is, the predicted inactivation values are close to the detection limit. The MS2 that remained after disinfection may represent a fraction of the coliphage that is difficult to inactivate, for example, because of association with particles. This hypothesis is consistent with the observation that the difference between predicted and measured inactivation was greater in secondary effluent than in filtered effluent (approximately 1.2-log vs 0.7-log). In addition, secondary effluents had higher particle concentrations than filtered effluents in all measured particle size ranges (see Appendix A for details).

Figure 4.13 compares the measured and predicted MS2 inactivation values with combined UV/chloramines in filtered effluent for the 150*67 and 300*33 doses. Average inactivation values were generally higher than predicted at both doses (synergistic effects). However, only two samples were taken for each disinfection scheme; more data would be needed to confirm that this trend is significant.

4.7 SUMMARY

Overall, the results from the bench-scale tests indicate that combining UV and free chlorine can provide effective disinfection of pathogens and indicator organisms. Chloramines were effective against total coliforms and poliovirus, but not MS2. The results also underscore the value of using multiple disinfectants for microbial inactivation. UV disinfection of MS2 and poliovirus was less affected by water quality (secondary effluent vs. filtered effluent) than free chlorine disinfection. In addition, UV was more effective than free chlorine against total coliforms in both filtered and secondary effluents. However, free chlorine was generally more effective than UV against adenovirus, poliovirus, and MS2. Thus, combining the two disinfectants may provide effective inactivation of a wider range of organisms.

More specifically, investigation of free chlorine, chloramines, and UV found:

- Free chlorine residuals decayed rapidly, particularly at free chlorine doses of 4 mg Cl_2/L or less. Total chlorine residuals decayed much more slowly. Total chlorine residual decay was slower when the added disinfectant was chloramines than when free chlorine was added.

- Free chlorine doses of 4 or 6 mg Cl_2/L increased UVT by approximately 2 percentage points, which increased the calculated UV dose for the collimated beam by approximately 1.5% for a given radiation exposure.

- Chloramines at CT values between 150 and 450 mg-min/L decreased UVT by an average of 3.7 percentage points, which decreased the calculated UV dose for the collimated beam by approximately 2% for a given radiation exposure.

- In free chlorine experiments, UV at a dose of 67 mJ/cm^2 caused approximately 10 to 15% loss of total chlorine residuals; losses were smaller at a dose of 33 mJ/cm^2. In chloramine experiments, UV also reduced total chlorine residual concentrations, but most of the losses were not statistically significant.

For disinfection:

- Total coliforms were effectively inactivated to levels at or below detection by UV at any of the tested doses (33 to 100 mJ/cm^2), alone or in combination with free chlorine. Chloramines also yielded total coliform levels at or below detection with all tested CT values (150 to 450 mg-min/L). Combined UV/chloramines yielded total coliform levels at or below detection in five out of six samples.

- Poliovirus inactivation was greater than the benchmark of 5-log inactivation for all combined UV/free chlorine disinfection schemes in both secondary effluent and filtered effluent, and for all combined UV/chloramine disinfection schemes in filtered effluent.

- MS2 was more difficult to inactivate than poliovirus by UV, free chlorine, or chloramines. For the chlorine-only disinfection schemes, free chlorine generally yielded the highest levels of inactivation, followed by the chlorine-ammonia process; the ammonia-chlorine process was ineffective against MS2. Results followed the same trend when UV was combined with free chlorine or chloramines:

    - In filtered effluent, combined UV/free chlorine doses achieved the benchmark of 4-log inactivation and often exceeded 6-log inactivation. Average inactivation in secondary effluent was lower than in filtered effluent, but met the 4-log benchmark at all doses.

    - Combined UV/chlorine-ammonia yielded average MS2 inactivation greater than 4-log.

    - Combined UV/ammonia-chlorine generally yielded less than 4-log inactivation of MS2.

For the effects of operating conditions on disinfection:

- Free chlorine generally provided more disinfection in filtered effluent than in secondary effluent.

- In most cases, disinfectant application order had no observable effect, with two exceptions. Average MS2 inactivation in filtered effluent was significantly lower at the UV-first dose of 67+2 than at doses of either 2+67(sim) or 2+67(seq). For poliovirus in secondary effluent, the highest percentage of samples below detection occurred when chlorine was dosed before UV, followed by simultaneous dosing, and UV dosed before chlorine.

- The effects of the relative UV/chlorine dose depended on the effects of the individual disinfectants. When free chlorine (or chloramines) was the stronger disinfectant, increasing the relative free chlorine (or chloramine) dose yielded more disinfection. Organisms that were more susceptible to UV disinfection yielded higher levels of inactivation with higher relative UV doses.

- With UV/free chlorine and MS2, doses of 2*67 showed statistically significant synergistic effects in filtered effluent for the chlorine-first and simultaneous doses. Doses of 4*33 showed antagonistic effects, which may reflect residual levels of particle-bound MS2 or other coliphage that are difficult to inactivate.

CHAPTER 5

PILOT-SCALE RESULTS FROM EXPERIMENTS COMBINING UV WITH FREE CHLORINE

5.1 BACKGROUND

The following sections describe the results from the pilot-scale experiments that used filtered effluent to test UV in combination with free chlorine. Filtered effluent was used as the influent to the pilot system for all pilot-scale experiments and is referred to as the "influent" throughout this chapter. Disinfection performance was analyzed as a function of relative dose (100% UV to 100% chlorine, and intermediate combinations of UV and chlorine) and disinfectant application order (UV-first or simultaneous dosing of UV and chlorine). This chapter also discusses the effect of the disinfection schemes on DBPs, hormones/endocrine disrupting compounds, pharmaceuticals, and personal care products.

5.2 DISINFECTION RESULTS

Figure 5.1 compares MS2 disinfection efficacy during the pilot and laboratory experiments; full data are given in Table F2 of Appendix F. Disinfection with the full doses (Figure 5.1a) met the MS2 benchmark of 4-log inactivation. Statistical analysis of the disinfection data using the Wilcoxon-Mann-Whitney nonparametric test indicated no significant differences in disinfection between the pilot and laboratory tests.

Figure 5.2 compares median total coliform levels after disinfection in the pilot and laboratory experiments (complete data are in Table F3 of Appendix F). Final coliform levels were often below the detection limits of 1 colony-forming unit (CFU)/100 mL in the pilot experiments and 2 CFU/100 mL in the laboratory experiments. For comparison purposes, samples below detection were assigned a coliform concentration of 1 CFU/100 mL. Figure 5.2 indicates that median total coliform levels generally met the disinfection benchmark of 2.2 CFU/100 mL, and were similar between the pilot and laboratory experiments. The only median values higher than 2.2CFU/100mL occurred at the chlorine dose of 2 mg Cl_2/L, and the 67+2 dose. The only significant discrepancy between the pilot and laboratory tests occurred at the dose of 67+2, which had a median coliform level of 8 CFU/100 mL. Because the UV-only dose of 67 mJ/cm^2 achieved a median value of 1 CFU/100 mL (Figure 5.2c), and there is no reason to suspect that the adding 2 mg Cl_2/L would reduce disinfection, it is likely that the high effluent coliform levels at the dose of 67+2 in the pilot experiments were due to contamination.

Table 5.1 summarizes the pilot plant data for indigenous adenovirus. Influent adenovirus levels were not analyzed, because the sample preparation process is laborious and limited the number of analyses to two samples per day. Both the full UV dose of 100 mJ/cm^2 and the combined dose of 2*67 generally inactivated adenovirus to below detection. However, the results of the first experiment on November 4, 2008, suggested that combined UV/chlorine provided more disinfection than UV alone, which is consistent with literature indicating that adenovirus is more susceptible to chlorine than to UV (Jackson and Thompson, 2008).

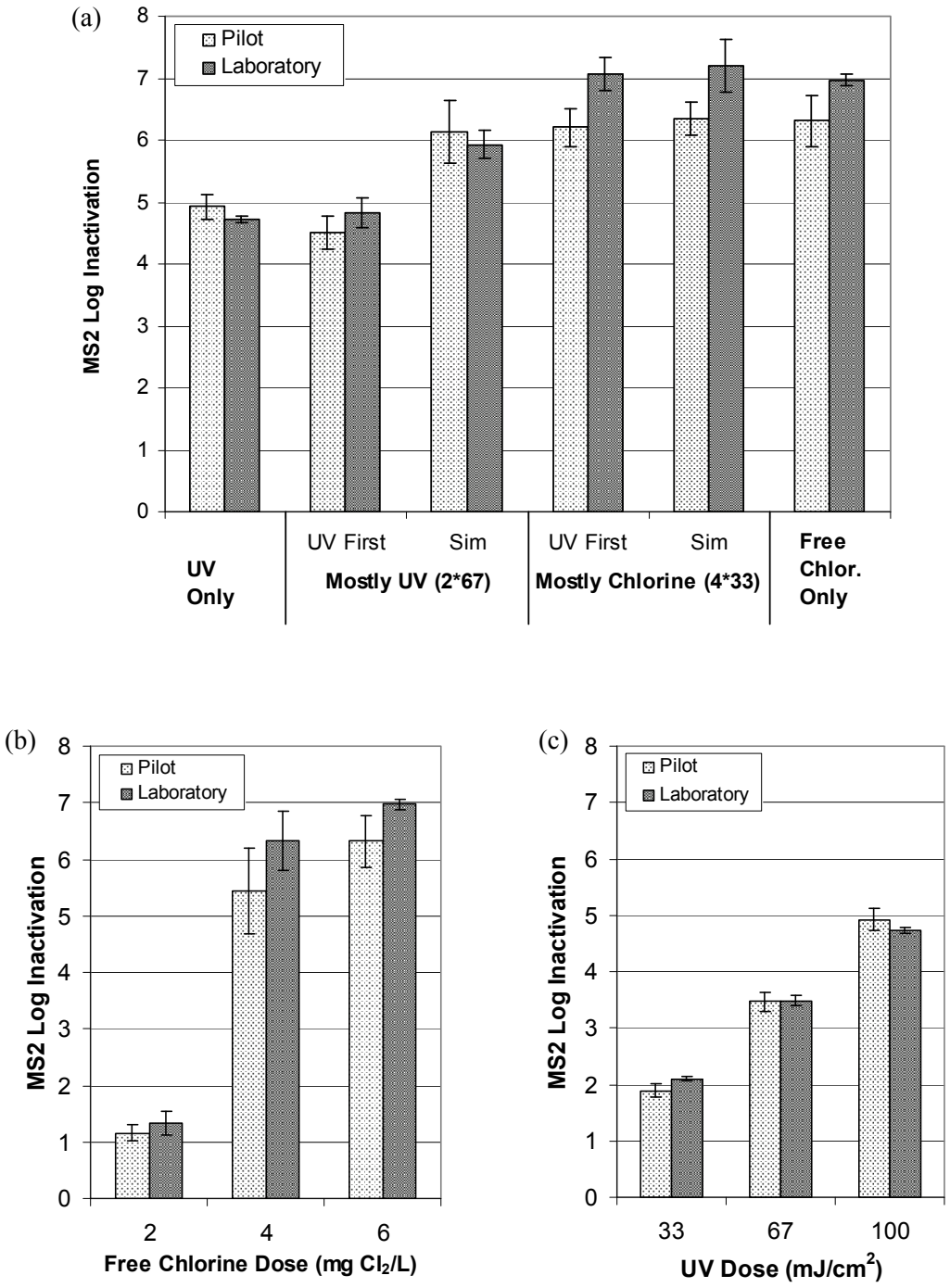


Figure 5.1. MS2 disinfection performance in pilot and laboratory experiments. (a) Full doses, (b) Free chlorine-only doses, (c) UV-only doses.

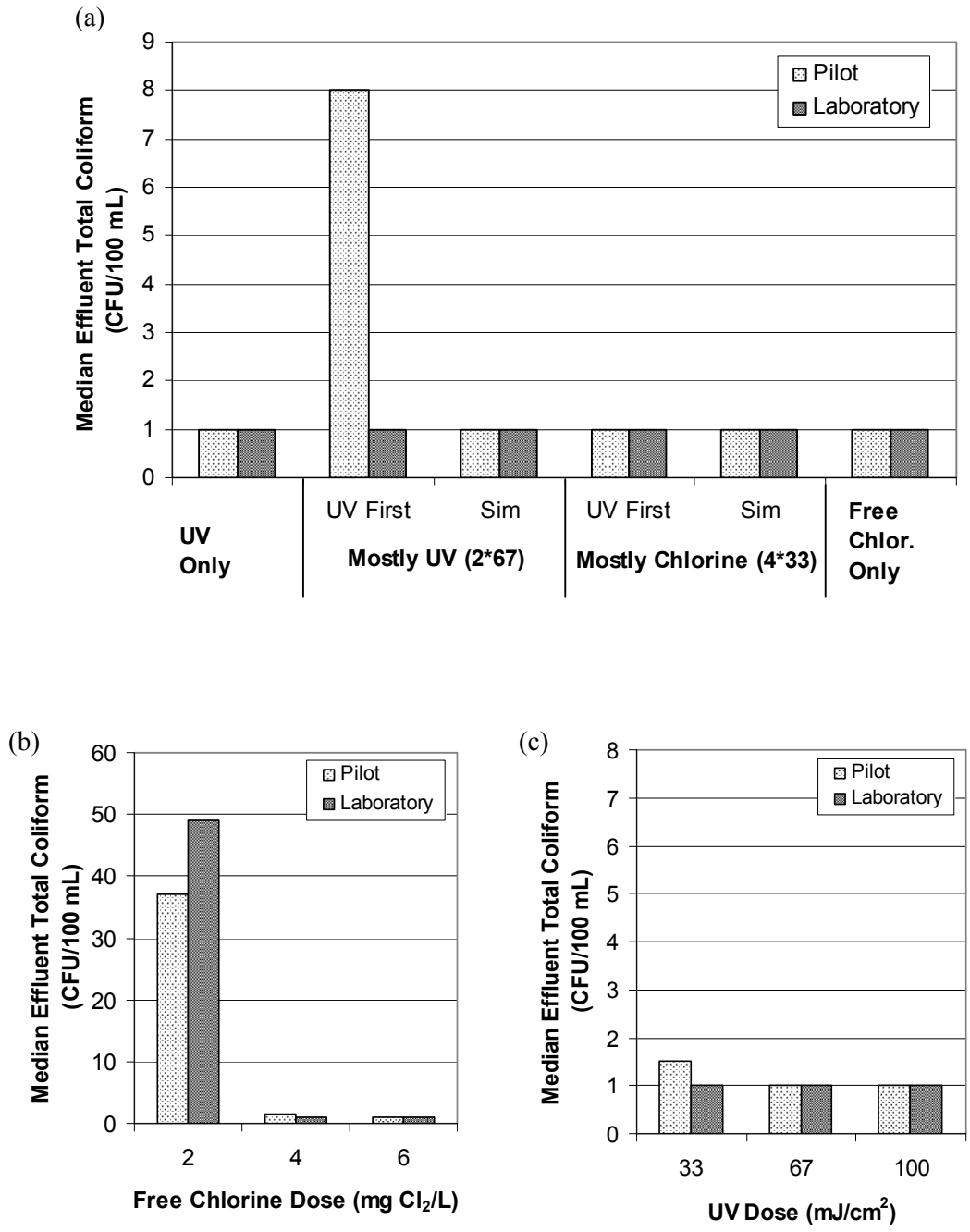


Figure 5.2. Total coliform levels after disinfection in pilot and laboratory experiments. (a) Full doses, (b) Free chlorine-only doses, (c) UV-only doses.

Table 5.1. Effluent Adenovirus Concentrations in Pilot-Scale Experiments

Date	Dose 1	Adenovirus (MPN IU/L)*	Dose 2	Adenovirus (MPN IU/L)
11/04/2008	100	0.0015	67+2	< 0.0009
01/14/2008	100	< 0.0014	2+67	< 0.0015
01/29/2008	100	< 0.0011	2+67	< 0.0011

*MPN IU = most probable number of infectious units

5.3 DISINFECTION BYPRODUCTS

TTHM, NDMA, cyanide, and cyanogen chloride were analyzed during the pilot experiments. Complete data are in Tables F4 through F11 of Appendix F. The results are summarized in Figures 5.3 through 5.5.

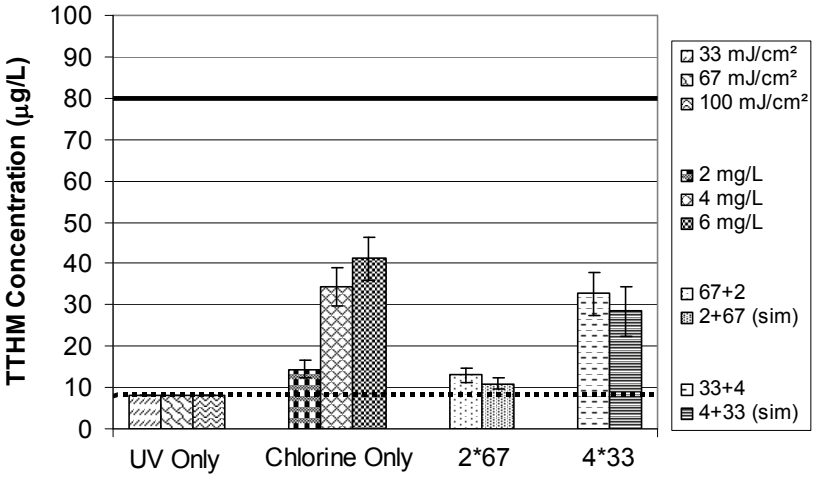


Figure 5.3. TTHM concentrations after disinfection in pilot experiments. Solid line represents the USEPA drinking water standard of 80 µg/L, dotted line represents the reporting limit of 8 µg/L. Sample concentrations below this limit were assigned values of 8 µg/L.

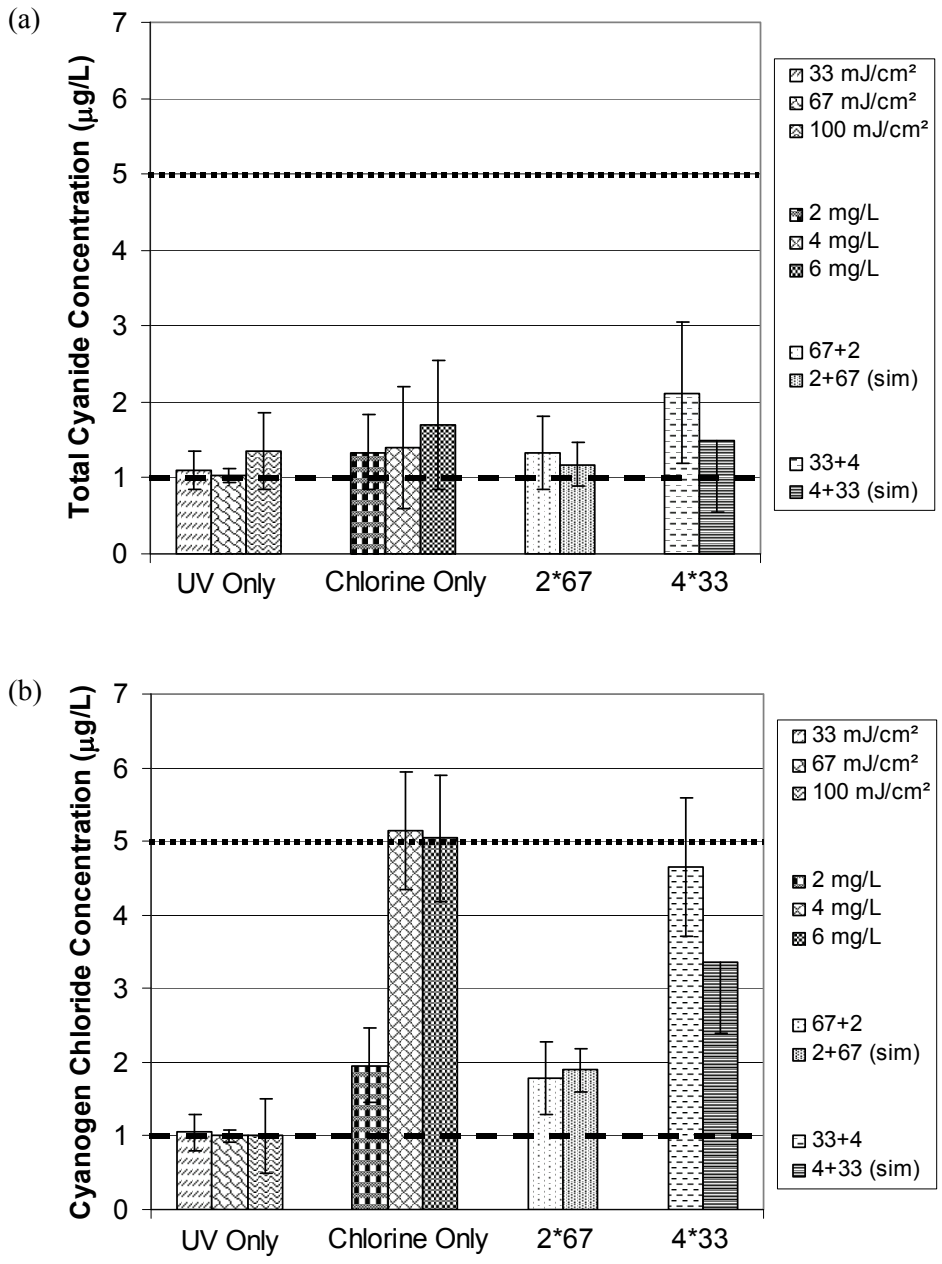
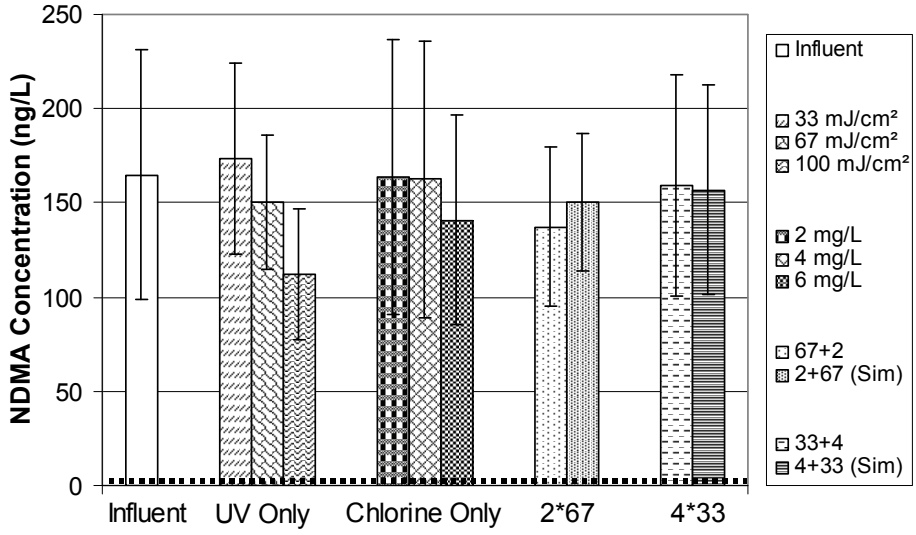


Figure 5.4. (a) Total cyanide and (b) cyanogen chloride concentrations after disinfection in pilot experiments. Dotted line represents the reporting limit of 5.0 µg/L, dashed line represents the method detection limit of 1.0 µg L. Concentrations between 1.0 and 5.0 µg L were estimated; sample concentrations below the method detection limit were assigned values of 1.0 µg L.

(a)



(b)

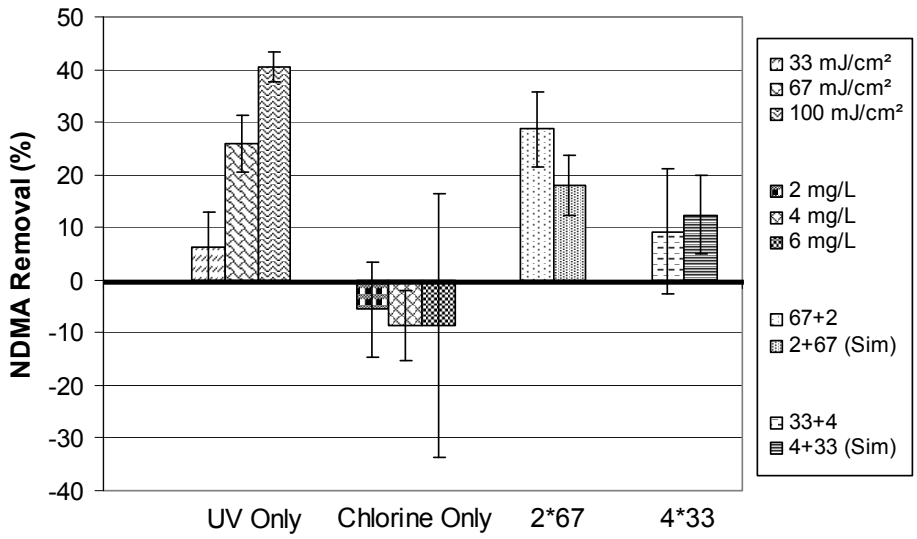


Figure 5.5. NDMA levels in pilot experiments. (a) Concentrations, (b) Percent removals. Dotted line in (a) represents the reporting limit of 2 ng/L; solid line in (b) marks zero on the y-axis.

Influent concentrations of THMs, cyanide, and cyanogen chloride were generally below reporting limits; NDMA levels were above the reporting limit of 2 ng/L in all samples. The reporting limit for each of the four individual THMs was 2 μg/L, so the overall reporting limit for TTHMs was assumed to be 8 μg/L. For cyanide and cyanogen chloride, reporting limits were 5.0 μg/L, and detection limits were 1.0 μg/L. For data analysis, concentrations below reporting (or detection) limits were assigned the value of the reporting (or detection) limit.

TTHM levels remained well below the USEPA drinking water standard of 80 μg/L under all disinfection schemes. No THMs were detected after UV disinfection, but TTHM levels increased as free chlorine doses increased from 2 to 4 to 6 mg Cl_2/L. There was no significant effect of disinfectant application order on the effluent concentration of TTHMs.

Total cyanide levels were below the reporting limit after all disinfection schemes. Cyanogen chloride concentrations were also low, but some samples dosed with 4 or 6 mg Cl_2/L yielded concentrations of 5 to 7 μg/L, slightly higher than the reporting limit of 5 μg/L. Disinfectant application order had no significant effect on total cyanide and cyanogen chloride concentrations.

Influent NDMA concentrations varied across experiments and also varied between samples taken at the beginning and end of each pilot plant experiment. Because NDMA concentrations varied across days of experiments, it is difficult to draw conclusions about the effects of UV and chlorine on NDMA, based on the average measured concentrations (Figure 5.5a). Consequently, percent removal values were calculated (Figure 5.5b). To account for the daily variability in influent NDMA concentrations, influent concentrations corresponding to each effluent sample were estimated by linearly interpolating between the initial and final measurements. Effluent sampling times (Table C6 of Appendix C) were used for the interpolation.

Consistent with literature (Drewes et al., 2008), free chlorine did not significantly increase NDMA concentrations. Also consistent with literature, increasing UV doses decreased NDMA levels. As shown in Table 5.2, the range of the removals observed during these pilot experiments is consistent with removals observed during previous laboratory and pilot plant experiments that used effluent from another water reclamation plant operated by the Districts (Jalali et al., 2005). Disinfectant application order had no significant effect on NDMA removal.

Table 5.2. NDMA Removals by UV Radiation

	NDMA Removals (%)		
UV Dose (mJ/cm^2)	Current Study	Previous Pilot Study*	Previous Laboratory Work*
33	5 to 15	11	15
67	15 to 30	21	29
100	40	29	40

* Jalali et al. (2005).

5.4 TRACE ORGANIC CONSTITUENTS

Over the course of six days of pilot experiments, 43 hormones, pharmaceuticals, personal care products, and other chemicals were analyzed. Compounds were analyzed by one of two laboratories: the Advanced Water Technology Center (Aqwatec, Golden, CO) or the Districts' San Jose Creek Water Quality Laboratory (SJCWQL, Whittier, CA). Samples sent to Aqwatec included one initial influent sample taken at the start of each day's experiment, whereas samples sent to SJCWQL included two influent samples taken at the start and end of each day.

Of the 43 compounds, 16 were generally below reporting limits in the influent and three (o-hydroxy atorvastatin, caffeine, and salicylic acid) were detected in the influent on only one day; data for these compounds were limited and were not analyzed further. Table 5.3 lists these compounds, along with their class and the laboratory that performed the analysis. Table 5.4 lists the 24 compounds that were above reporting limits in the influent, their class, and the laboratory that performed the analysis. For the nine compounds analyzed by both laboratories, agreement was generally good (Appendix G). Results for tris(chloroisopropyl)phosphate (TCPP) and tris(2,3-dichloropropyl)phosphate (TDCPP) should be viewed with caution, because only initial influent samples were taken, that is, changes in influent concentrations were not monitored over each day's experiment.

Table 5.3. TrOCs Generally Below Reporting Limits in Pilot-Scale Experiments

Compound	Class	Analysis Laboratory
Acetaminophen	Analgesic	SJCWQL
Atorvastatin	Cholesterol lowering	SJCWQL
o-Hydroxy atorvastatin	Cholesterol lowering	SJCWQL
p-Hydroxy atorvastatin	Cholesterol lowering	SJCWQL
Bisphenol A	Plasticizer	Both
Caffeine	Diuretic/stimulant	SJCWQL
Clofibric acid	Cholesterol lowering	Aqwatec
Dichlorprop	Herbicide/insecticide	Aqwatec
Estradiol	Hormone	SJCWQL
Ethynylestradiol	Synthetic hormone	SJCWQL
Fenofibrate	Cholesterol lowering	Aqwatec
Ibuprofen	Analgesic	Both
Ketoprofen	Analgesic	Both
Mecoprop	Herbicide/insecticide	Aqwatec
Naproxen	Analgesic	Both
Phenacetine	Analgesic	Aqwatec
Progesterone	Hormone	SJCWQL
Salicylic acid	Analgesic	Aqwatec
Simvastatin OH acid	Cholesterol lowering	SJCWQL

Table 5.4 also provides the average percent change between the initial and final influent samples, relative to the initial level. A positive percent change value indicates that influent concentrations rose from the beginning to the end of sampling. Most of the analyzed compounds had relatively constant concentrations; the average change for all compounds was a decrease of 19% between the initial and final influent samples. Influent concentrations of five compounds (DEET, furosemide, gemfibrozil, octylphenol, and trimethoprim) decreased by more than 30% over each day's experiment. Reasons for the large decreases in the influent concentrations of these five compounds are unknown.

Table 5.4. TrOCs Detected During Pilot-Scale Experiments

Compound	Class	Analysis Laboratory	Average % Change, Initial and Final Influent Concentrations
Atenolol	Beta-blocker	SJCWQL	-25
Azithromycin	Antibiotic/antimicrobial	SJCWQL	-21
Carbamazepine	Anticonvulsant	Both	2
DEET	Herbicide/insecticide	SJCWQL	-62
Diclofenac	Analgesic	Both	4
Dilantin	Anticonvulsant	SJCWQL	-3
Erythromycin[-H_2O]	Antibiotic/antimicrobial	SJCWQL	-17
Estrone	Hormone	SJCWQL	-8
Fluoxetine	Anti-depressant	SJCWQL	-6
Furosemide	Diuretic	SJCWQL	-53
Gemfibrozil	Cholesterol lowering	Both	-72
Iopromide	Contrast agent	SJCWQL	10
Metoprolol	Beta-blocker	SJCWQL	-22
Nonylphenol	Industrial chemical	SJCWQL	-17
Octylphenol	Industrial chemical	SJCWQL	-34
Primidone	Anticonvulsant	Both	-10
Propranolol	Beta-blocker	SJCWQL	6
Sulfamethoxazole	Antibiotic/antimicrobial	SJCWQL	-20
TCEP*	Flame retardant	Both	11
TCPP*	Flame retardant	Aqwatec	Not available
TDCPP*	Flame retardant	Aqwatec	Not available
Triclocarban	Antibiotic/antimicrobial	SJCWQL	1
Triclosan	Antibiotic/antimicrobial	SJCWQL	-13
Trimethoprim	Antibiotic/antimicrobial	SJCWQL	-44

*TCEP = tris(2-carboxyethyl)phosphine; TCPP = tris(chloroisopropyl)phosphate; TDCPP = tris(2,3-dichloropropyl)phosphate.

5.4.1 Determining Effects of Free Chlorine and UV on Compounds

Full influent and effluent concentration data for all compounds are given in Tables F12 through F51 of Appendix F. For data analysis, effluent concentrations below reporting limits were assigned the value of the reporting limits. Percent removals were calculated for each effluent sample and then averaged across all experiments for each dose. For each compound, maximum observable removal values, that is, removals to the reporting limit, were also determined for each influent concentration and averaged across all doses and experiments. For this report, "removal" is defined as the decrease in concentration across the pilot system; end products were not analyzed, so "removal" may simply indicate transformation of the TrOCs to daughter compounds.

Influent concentrations varied between the beginning and end of each day's experiment. Prior to this project, hourly concentrations were measured over 24 h for a subset of the compounds in Table 5.4. Concentrations of azithromycin, erythromycin[-H_2O], gemfibrozil, sulfamethoxazole, and trimethoprim generally decreased continuously during the morning hours, that is, the time period during which the pilot experiments were conducted. These results suggested that influent concentration values in the pilot experiments could be estimated by linearly interpolating between the initial and final measurements. Effluent sampling times were used for the interpolation, and the resulting influent concentration values were used to calculate percent removal values. Average removal values were analyzed statistically to determine whether they were greater than zero using Welch's *t*-test with α of 0.05 (Tables F52 and F53 of Appendix F).

Table 5.5 summarizes the three criteria used to evaluate the reactivity of compounds with UV or free chlorine. First, as the dose increased, reactive compounds showed a trend of increasing removal or increasing formation. Second, for reactive compounds, average removal at the highest UV or chlorine dose was statistically significant (i.e., greater than zero). Finally, the average removal at the maximum dose was used as an indication of the strength of the effect or reactivity.

Table 5.5. Criteria for Determining Reactivity of Compounds With Free Chlorine and UV

Reactivity	Trend With Increasing Dose	Significant Removal at Maximum Dose	Average Removal at Maximum Dose (%)
Strong	Yes	Yes	> 50
Moderate	Yes	Yes	> 20 to 50
Inconclusive	Yes	Yes	> 10 to 20
Inconclusive	1 of these criteria met		> 10
Inconclusive	0 of these criteria met		> 20
Insignificant	0 of these criteria met		> 10 to 20
Insignificant	0, 1, or both of these criteria met		≤ 10

If the first two criteria were met (i.e., there was a trend with increasing dose and removal was significant at the maximum dose), the effect was considered "strong" if average removal at the maximum dose was > 50%, "moderate" if the average removal was 20 to 50%, and "inconclusive" if the average removal was 10 to 20%. If only one of the first two criteria were met, the effect was considered "inconclusive" if the average removal was greater than 10%. If neither criterion was met, the effect was considered "inconclusive" if the average removal was greater than 20% and "insignificant" if the average removal was 20% or less. If the average removal was 10% or less, the effect was considered "insignificant," regardless of whether the other two criteria were met. Note that a designation of "insignificant" does not necessarily mean that the disinfectant has no effect; rather, it means that any effect was too small to be observed in these experiments.

Tables 5.6 and 5.7 provide the data for each of the compounds treated with UV or free chlorine, respectively. The "Trend With Dose" was considered positive if removals increased with an increasing dose, and negative if removals decreased with an increasing dose or if formation increased with an increasing dose. "None" indicates that no trend was observed.

Table 5.6. Effect of UV Radiation on TrOCs

Compound	Effect	Trend With Dose	Significant Removal ($p \leq 0.05$) at 100 mJ/cm^2 (%)	Average Removal ± Standard Deviation at 100 mJ/cm^2 (%)
Nonylphenol	Strong	Negative	Yes	-55 ± 24
Octylphenol	Strong	Negative	Yes	-102 ± 24
Diclofenac	Moderate	Positive	Yes	46 ± 21
Iopromide	Moderate	Positive	Yes	49 ± 1
Sulfamethoxazole	Moderate	Positive	Yes	31 ± 14
Triclocarban	Moderate	Positive	Yes	35 ± 6
Triclosan	Moderate	Positive	Yes	45 ± 8
Dilantin	Inconclusive	Positive	No	18 ± 15
Estrone	Inconclusive	None	Yes	29 ± 20
Fluoxetine	Inconclusive	Positive	No	16 ± 13
Atenolol	Insignificant	Negative	No	-1 ± 2
Azithromycin	Insignificant	Negative	No	1 ± 3
Carbamazepine	Insignificant	Negative	No	-2 ± 18
DEET	Insignificant	None	No	4 ± 3
Erythromycin[-H_2O]	Insignificant	None	No	-3 ± 8
Furosemide	Insignificant	None	Yes	10 ± 2
Gemfibrozil	Insignificant	Negative	Yes	-10 ± 5
Metoprolol	Insignificant	Positive	No	1 ± 1
Primidone	Insignificant	Negative	No	-6 ± 12
Propranolol	Insignificant	Positive	No	4 ± 6
TCEP	Insignificant	None	No	-5 ± 11
TCPP	Insignificant	None	No	0 ± 14
TDCPP	Insignificant	None	No	-16 ± 22
Trimethoprim	Insignificant	None	No	-3 ± 4

Table 5.7. Effect of Free Chlorine on TrOCs

Compound	Effect	Trend With Dose	Significant Removal ($p \leq 0.05$) at 6 mg Cl_2/L	Average Removal ± Standard Deviation at 6 mg Cl_2/L (%)
Azithromycin	Strong	Positive	Yes	78 ± 8
Diclofenac	Strong	Positive	Yes	85 ± 16
Erythromycin[-H_2O]	Strong	Positive	Yes	84 ± 5
Estrone	Strong	Positive	Yes	71 ± 7
Furosemide	Strong	Positive	Yes	90 ± 3
Gemfibrozil	Strong	Positive	Yes	52 ± 19
Octylphenol	Strong	Positive	Yes	58 ± 14
Propranolol	Strong	Positive	Yes	62 ± 12
Sulfamethoxazole	Strong	Positive	Yes	98 ± 0.7
Triclosan	Strong	Positive	Yes	69 ± 7
Trimethoprim	Strong	Positive	Yes	94 ± 0.1
Fluoxetine	Inconclusive	Positive	No	13 ± 9
Nonylphenol	Inconclusive	None	No	25 ± 23
TCPP	Inconclusive	Positive	No	13 ± 18
Triclocarban	Inconclusive	Positive	Yes	17 ± 2
Atenolol	Insignificant	Positive	No	2 ± 5
Carbamazepine	Insignificant	Positive	No	-3 ± 10
DEET	Insignificant	Positive	No	4 ± 22
Dilantin	Insignificant	None	No	-7 ± 21
Iopromide	Insignificant	None	No	20 ± 39
Metoprolol	Insignificant	None	No	6 ± 6
Primidone	Insignificant	None	No	-1 ± 8
TCEP	Insignificant	Positive	No	9 ± 12
TDCPP	Insignificant	Positive	No	-4 ± 6

Table 5.8 summarizes the effects of free chlorine and UV on the compounds. Results generally agree with literature findings (Drewes et al., 2006; Snyder et al., 2007; Drewes et al., 2008). In all studies, chlorine removed diclofenac, erythromycin[-H_2O], estrone, gemfibrozil, sulfamethoxazole, triclosan, and trimethoprim; but provided low removal of carbamazepine, DEET, dilantin, iopromide, metoprolol, and TCEP. UV removed diclofenac, sulfamethoxazole, and triclosan; but provided low removal of DEET, erythromycin[-H_2O], gemfibrozil, TCEP, TCPP, TDCPP, and trimethoprim. Only three compounds showed inconsistencies: carbamazepine, iopromide, and nonylphenol. Drewes et al. (2008) reported moderate removal of carbamazepine, whereas this study and Snyder et al. (2007) reported low removals; the cause of this discrepancy is unknown. Snyder and coworkers observed low removal of iopromide with UV, whereas this study yielded moderate removal; these differences may be because Snyder and coworkers used 40 mJ/cm^2 of UV, whereas this study used UV doses of up to 100 mJ/cm^2. Finally, Drewes et al. (2006) reported low removal of

nonylphenol with UV, whereas UV increased concentrations of nonylphenol in this study; these increased concentrations are likely attributable to the breakdown of parent compounds that may have been absent from the effluents tested by Drewes and coworkers.

Table 5.8. Summary: Reactivity of TrOCs With UV or Free Chlorine

		Free Chlorine Effect			
		Strong	Moderate	Inconclusive	Insignificant
UV Effect	Strong	Octylphenol*	-	Nonylphenol*	-
	Moderate	Diclofenac Sulfamethoxazole Triclosan	-	Triclocarban	Iopromide
	Inconclusive	Estrone	-	Fluoxetine	Dilantin
	Insignificant	Azithromycin Erythromycin[-H_2O] Furosemide Gemfibrozil Propranolol Trimethoprim	-	TCPP	Atenolol Carbamazepine DEET Metoprolol Primidone TCEP TDCPP

*UV increased concentrations of octylphenol and nonylphenol; concentrations of all other affected compounds decreased or showed no significant trend with UV and/or chlorine treatment.

The following sections provide more detailed data on the effects of UV and free chlorine on each of the hormones, pharmaceuticals, and other measured compounds. The statistical methods used to analyze the data are described in Section 3.7.2.

5.4.2 Compounds Strongly Affected by UV

Figure 5.6 shows results for octylphenol and nonylphenol, the two compounds that were strongly affected by UV. The lowest doses of 33 mJ/cm^2 of UV alone or 2 mg Cl_2/L of free chlorine alone had little impact on concentrations. The UV dose of 67 mJ/cm^2, alone or in combination with 2 mg Cl_2/L of free chlorine, and the UV dose of 100 mJ/cm^2 increased octylphenol levels by approximately 70 to 100%, and increased nonylphenol levels by approximately 50%. The chlorine dose of 4 mg Cl_2/L, alone or in combination with 33 mJ/cm^2 of UV, and the chlorine dose of 6 mg Cl_2/L reduced octylphenol concentrations to the reporting limit and reduced nonylphenol concentrations by 25 to 50%. These results indicate that chlorine reacts with alkylphenols and reduces their concentrations, whereas UV increases concentrations of alkylphenols, which is possibly due to the breakdown of precursor compounds.

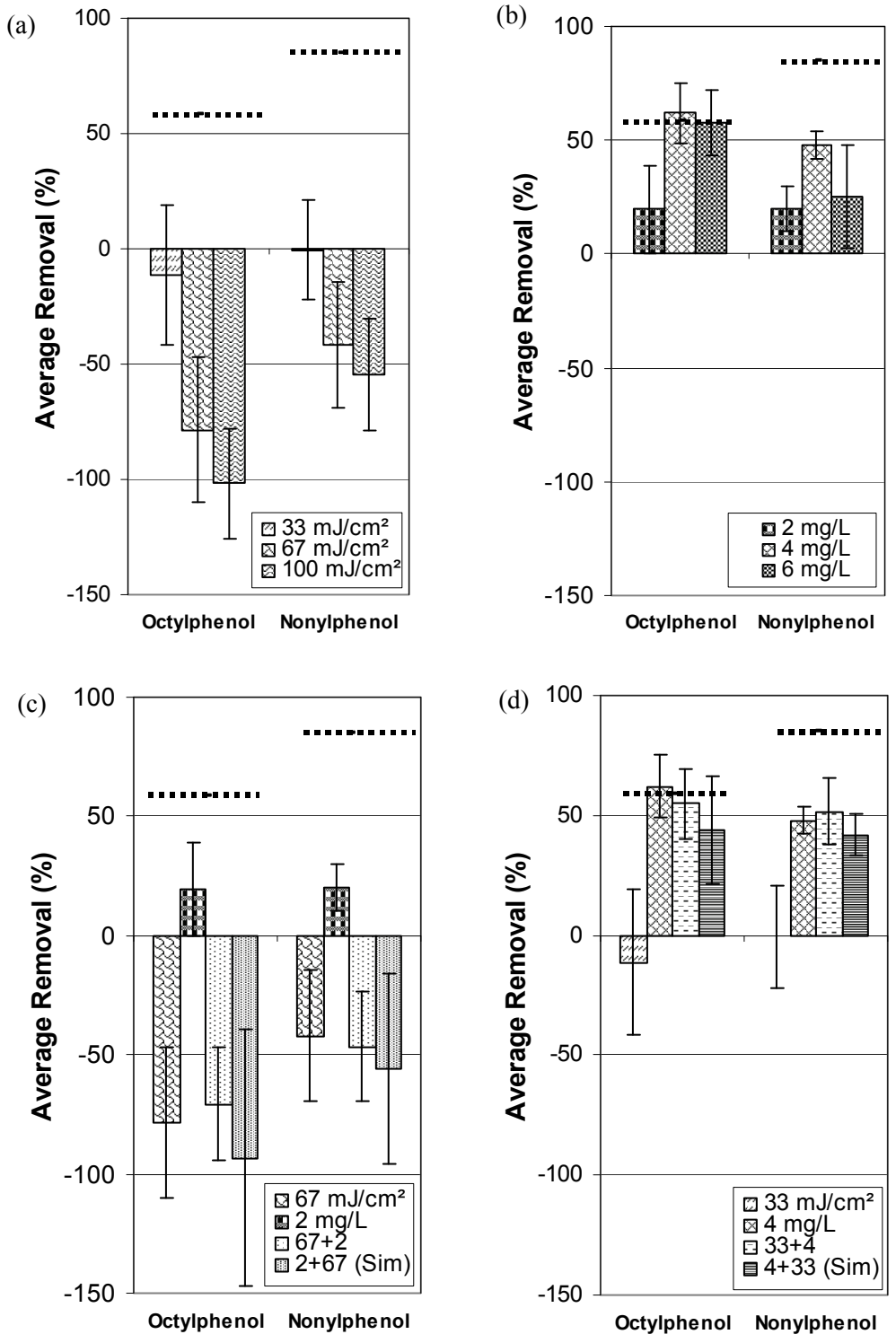


Figure 5.6. Pilot experiments: Removal of compounds that were strongly affected by UV and free chlorine. (a) UV, (b) Free chlorine, (c) UV and/or free chlorine at a dose of 2*67, (d) UV and/or free chlorine at a dose of 4*33. Dotted lines represent average removal to reporting limits, i.e., the maximum removal that could be detected (Section 5.4.1).

5.4.3 Compounds Moderately Affected by UV

Figure 5.7 shows results for the three compounds that were moderately affected by UV and strongly affected by free chlorine (diclofenac, sulfamethoxazole, and triclosan). Removal of all three compounds was greater with increasing UV or chlorine dose (Figures 5.7a and 5.7b). Free chlorine almost completely removed all three compounds to the reporting limit at doses of 4 or 6 mg Cl_2/L. A free chlorine dose of 2 mg Cl_2/L almost completely removed triclosan to the reporting limit, but had little effect on diclofenac or sulfamethoxazole.

The results with combined UV/chlorine (Figures 5.7c and 5.7d) are consistent with the results from the individual disinfectants. Triclosan was completely removed at doses of 2 or 4 mg Cl_2/L of chlorine alone, and also at combined doses of 2*67 and 4*33. For the other compounds, the lowest UV and chlorine doses yielded no significant removal and did not significantly affect removals in the combined UV/chlorine schemes. Adding 2 mg Cl_2/L of free chlorine to the UV-only dose of 67 mJ/cm^2 did not significantly improve removal, and adding 33 mJ/cm^2 of UV to the chlorine-only dose of 4 mg Cl_2/L did not significantly improve removal.

Figure 5.8 shows results for the two other compounds that were moderately affected by UV: triclocarban (which was inconclusively affected by free chlorine), and iopromide (which was insignificantly affected by free chlorine). As shown in Figure 5.8a, removal increased with increasing UV dose for both compounds. Figure 5.8b suggests that free chlorine alone may react with these compounds, but that the removals are relatively low. Data with combined UV/chlorine (Figures 5.8c and 5.8d) suggest that free chlorine had little impact. Adding 2 mg Cl_2/L of free chlorine to the UV-only dose of 67 mJ/cm^2 did not significantly improve removals, whereas addition of 4 mg Cl_2/L of free chlorine to the UV dose of 33 mJ/cm^2 generally did not significantly improve removals. The only exception was for iopromide at a dose of 4+33(sim), which yielded removals that were significantly higher than with doses of 33 mJ/cm^2 alone or 33+4.

5.4.4 Compounds Inconclusively Affected by UV

Figure 5.9 shows results for the three compounds where UV effects were inconclusive (estrone, fluoxetine, and dilantin). Average removals of estrone were significantly greater than zero for all three UV doses, but there was no trend with increasing dose. Chlorine reacted strongly with estrone and almost completely removed it at doses of 4 and 6 mg Cl_2/L. For combined UV/chlorine doses, the addition of UV did not significantly improve removals, relative to the chlorine-only doses. The strong chlorine effect masked any removal by UV, so the results are inconclusive on the effects of UV on estrone.

The effects of UV and free chlorine on fluoxetine were inconclusive. Removals increased with increasing UV or free chlorine dose and were significant at the highest doses, but removal levels were relatively low (less than 20%). Removals with combined UV/chlorine were not significantly greater than zero for "UV-first" doses (when UV was applied upstream of the chlorine addition point), but were significantly greater than zero for simultaneous dosing (when chlorine was applied immediately upstream of the UV reactors).

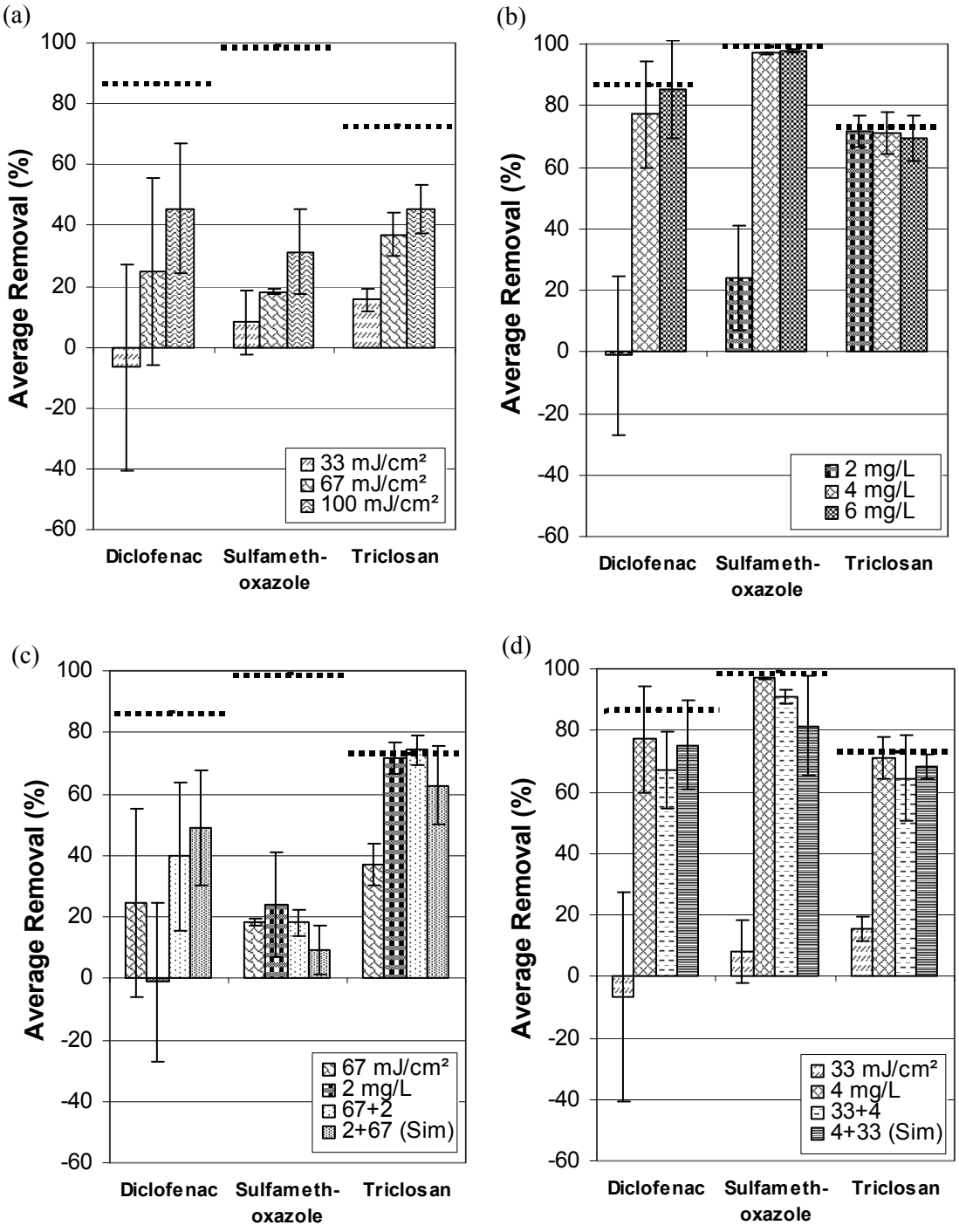


Figure 5.7. Pilot experiments: Removal of compounds that were moderately affected by UV and strongly affected by free chlorine. (a) UV, (b) Free chlorine, (c) UV and/or free chlorine at a dose of 2*67, (d) UV and/or free chlorine at a dose of 4*33. Dotted lines represent average removal to reporting limits, i.e., the maximum removal that could be detected (Section 5.4.1).

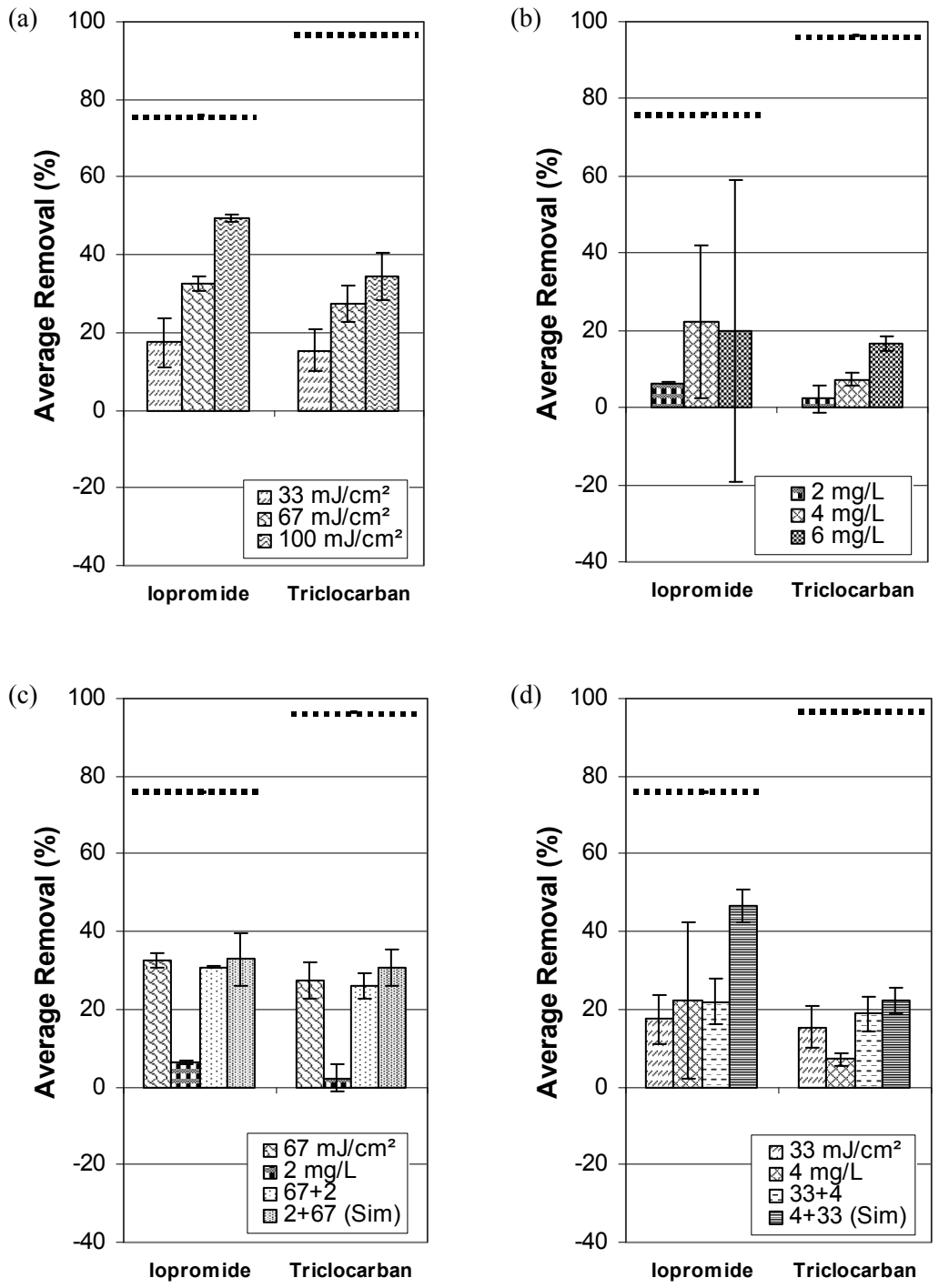


Figure 5.8. Pilot experiments: Removal of compounds that were moderately affected by UV and inconclusively or insignificantly affected by free chlorine. (a) UV, (b) Free chlorine, (c) UV and/or free chlorine at a dose of 2*67, (d) UV and/or free chlorine at a dose of 4*33. Dotted lines represent average removal to reporting limits, i.e., the maximum removal that could be detected (Section 5.4.1).

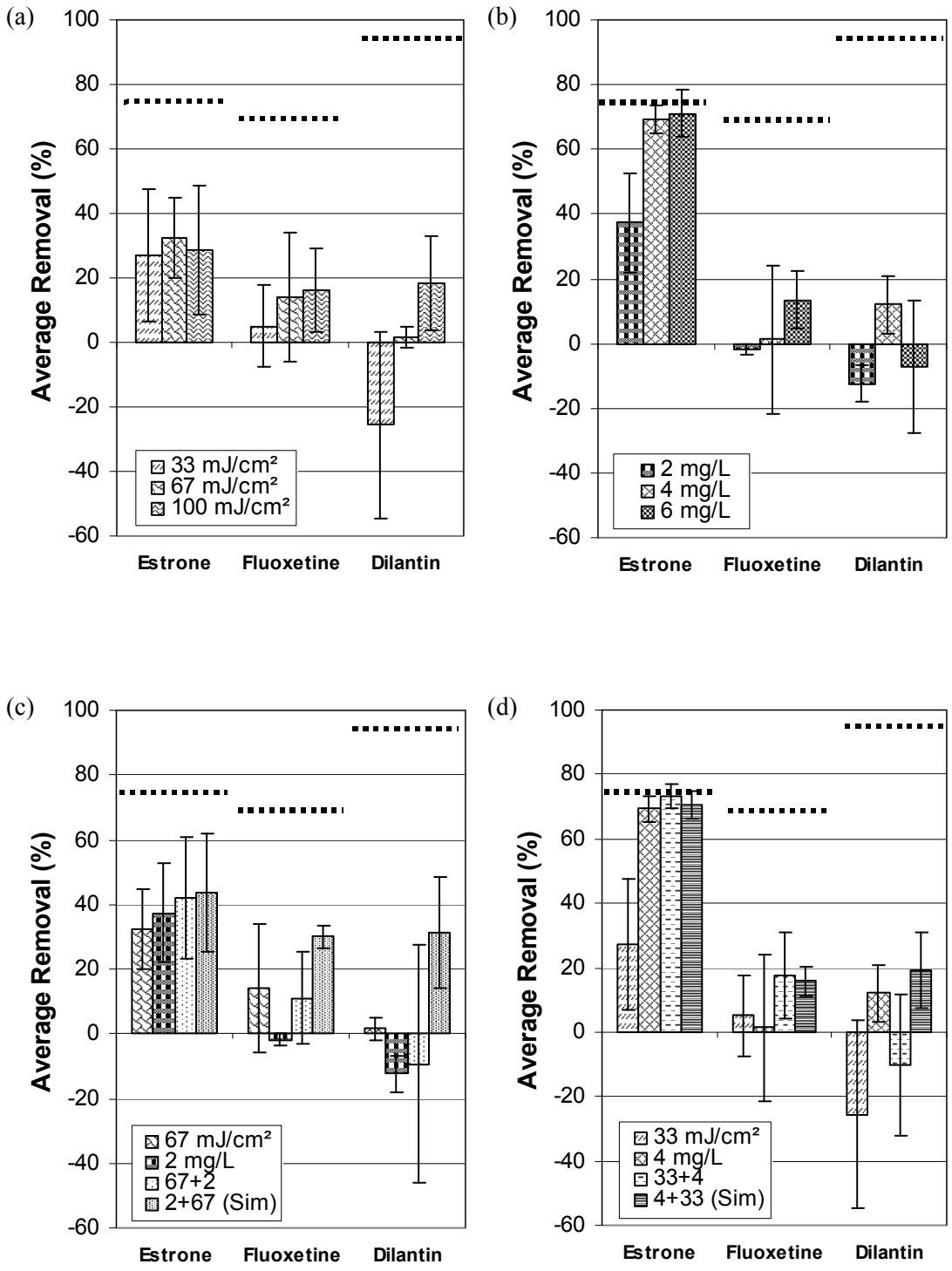


Figure 5.9. Pilot experiments: Removal of compounds that were inconclusively affected by UV. (a) UV, (b) Free chlorine, (c) UV and/or free chlorine at a dose of 2*67, (d) UV and/or free chlorine at a dose of 4*33. Dotted lines represent average removal to reporting limits, i.e., the maximum removal that could be detected (Section 5.4.1).

Dilantin removals were greater with increasing UV, but removal at 100 mJ/cm^2 was low (<20%) and was not statistically significant. Free chlorine yielded no trend with dose, and insignificant removal at a dose of 6 mg Cl_2/L. Like fluoxetine, removals with combined UV/chlorine were not significantly greater than zero for UV-first doses but were significantly greater than zero for simultaneous dosing.

5.4.5 Compounds Insignificantly Affected by UV

Figures 5.10 and 5.11 show removals of the six compounds (azithromycin, erythromycin[-H_2O], furosemide, gemfibrozil, propranolol, and trimethoprim) where UV effects were insignificant, and free chlorine effects were strong. As shown in Figure 5.10a, average removals by UV were generally low (less than 20%). Average removals with free chlorine were greater with increasing dose for all compounds (Figure 5.10b). Doses of 4 or 6 mg Cl_2/L yielded relatively high removals of furosemide and trimethoprim, with removals near the reporting limit for trimethoprim.

The results with combined UV/chlorine (Figure 5.11) suggest that any effect of UV on these compounds is small and/or masked by the strong chlorine response. For most combined UV/chlorine doses, the addition of UV to the chlorine-only doses did not significantly alter removals. There were only two exceptions: azithromycin at a dose of 33+4, where removal decreased significantly relative to the chlorine-only dose; and propranolol at doses of 2+67(sim) and 4+33(sim), where removals increased significantly relative to the chlorine-only dose.

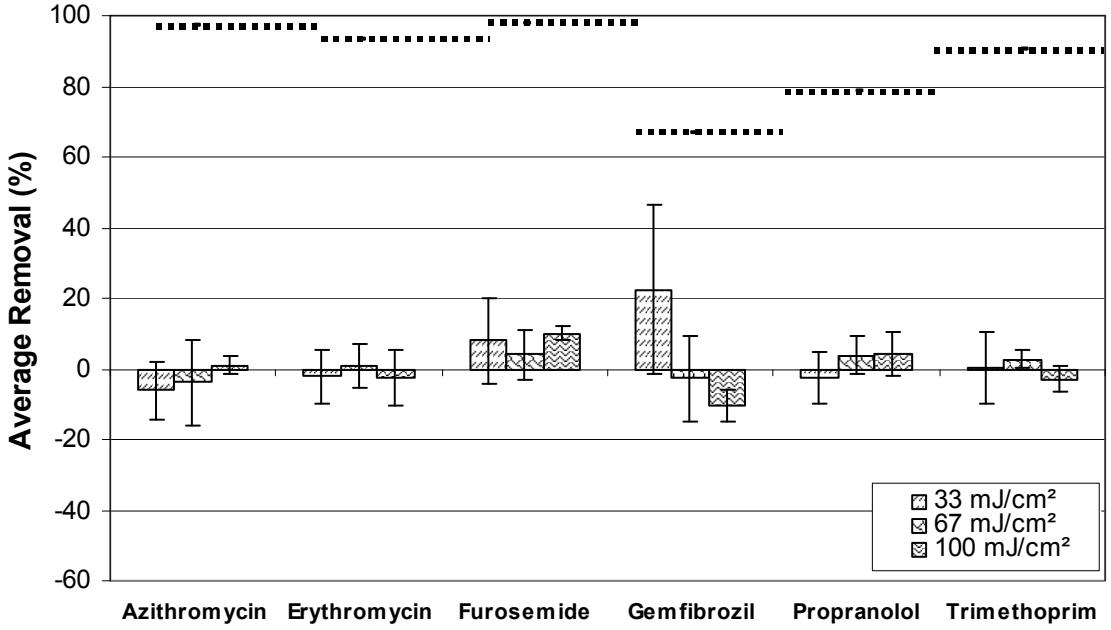
Figure 5.12 shows removals of the eight compounds with insignificant effects from UV and inconclusive or insignificant effects from free chlorine. Average removals were <20% for all compounds under all doses. Removals of atenolol and metoprolol were significantly higher with simultaneous dosing than with UV-first doses.

5.5 DISINFECTANT APPLICATION ORDER AND SYNERGISTIC EFFECTS

This section discusses the effects caused by the order in which disinfectants were applied or by synergism between the disinfectants. TCPP and TDCPP at doses of 2*67 were excluded from the analysis, because the limited number of samples at the chlorine-only dose of 2 mg Cl_2/L did not allow for reliable conclusions.

5.5.1 Effects of Disinfectant Application Order

As described in Section 3.7.2, Welch's *t*-test with α of 0.05 was used to determine whether disinfectant application order affected removals. MS2 disinfection results (Figure 5.13) were consistent with laboratory results: At doses of 2*67, UV-first doses provided significantly less disinfection than simultaneous dosing, and no effects of disinfectant application order were observed at doses of 4*33. For most of the compounds analyzed in the pilot experiments, disinfectant application order had no significant effect on removals. The exceptions were for atenolol, metoprolol, and propranolol at doses of 2*67 and 4*33, and iopromide at a dose of 4*33 (Figure 5.14). In all cases, removals were significantly greater with simultaneous dosing than with the UV-first dose.



(b)

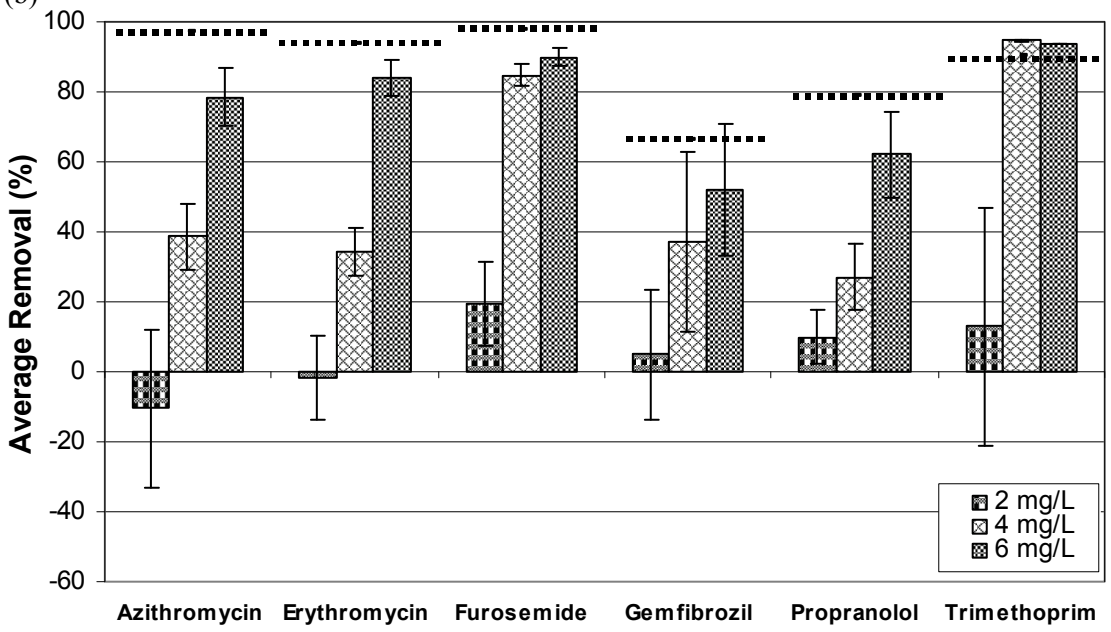


Figure 5.10 Pilot experiments: Removal of compounds that were insignificantly affected by UV and strongly affected by free chlorine. (a) UV alone, (b) Free chlorine alone. Dotted lines represent average removal to reporting limits, i.e., the maximum removal that could be detected (Section 5.4.1).

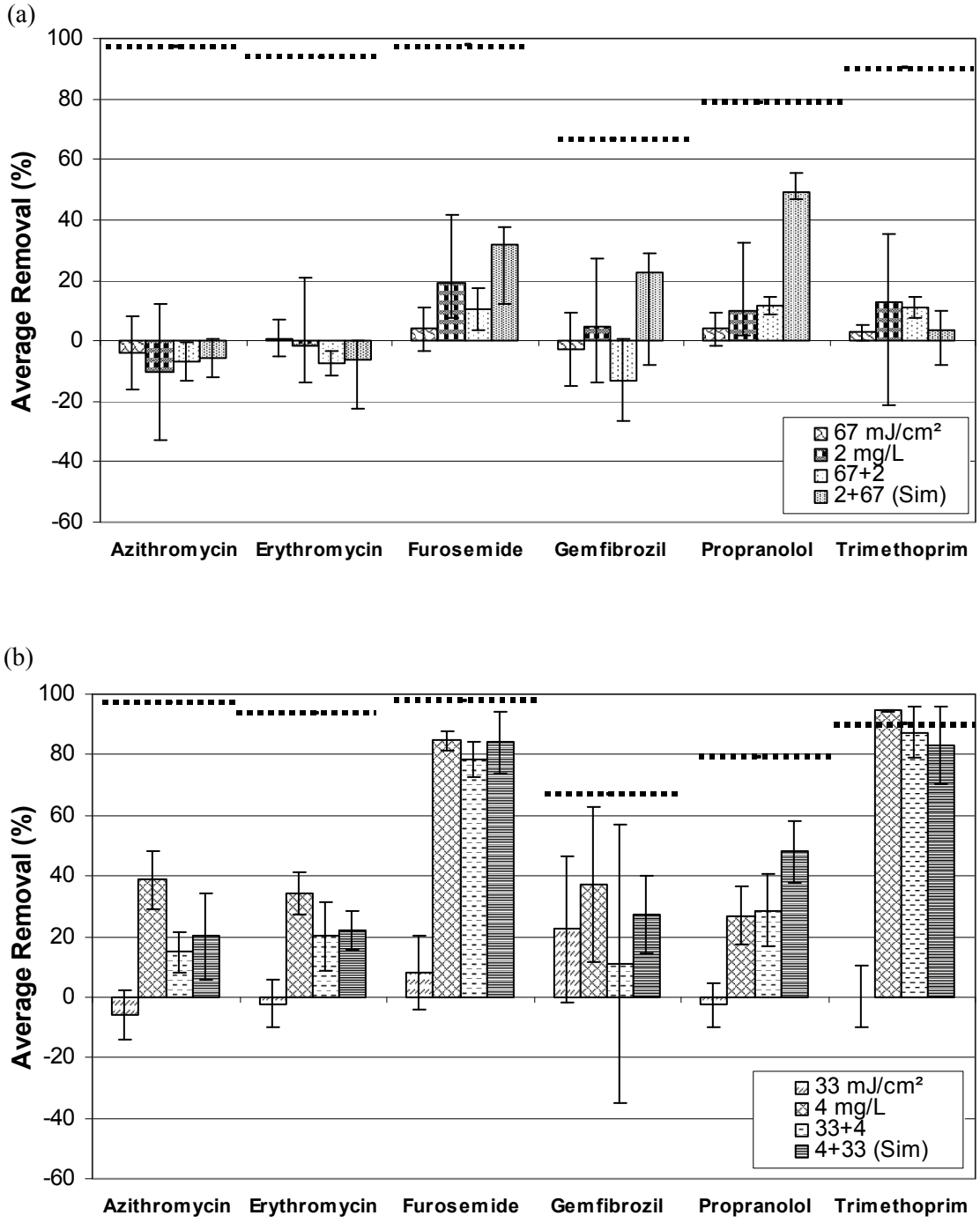


Figure 5.11. Pilot experiments: Removal of compounds that were insignificantly affected by UV and strongly affected by free chlorine. (a) UV at a dose of 67 mJ/cm^2 and/or free chlorine at a dose of 2 mg Cl_2/L, (b) UV at a dose of 33 mJ/cm^2 and/or free chlorine at a dose of 4 mg Cl_2/L. Dotted lines represent average removal to reporting limits, i.e., the maximum removal that could be detected (Section 5.4.1).

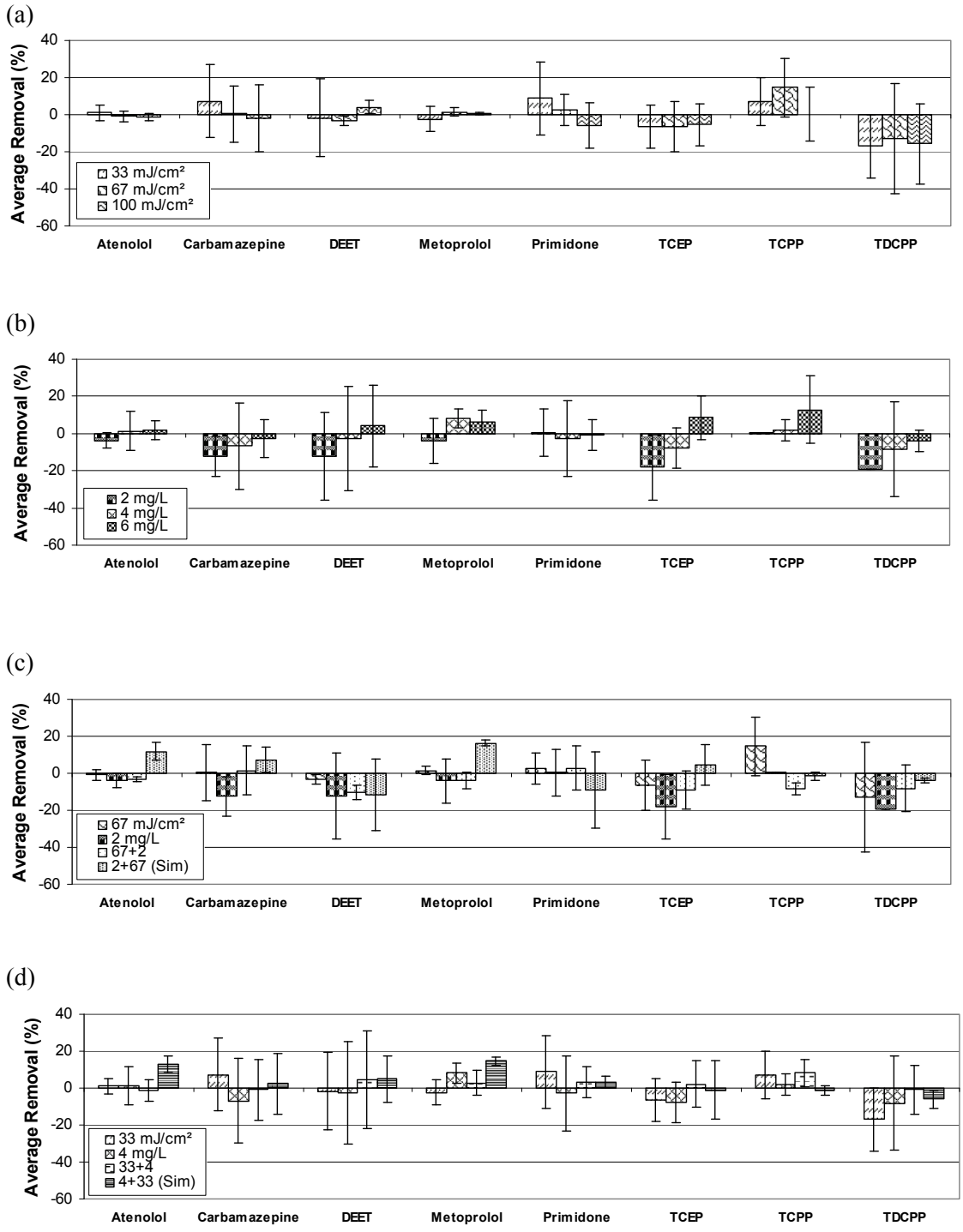


Figure 5.12. Pilot experiments: Removal of compounds that were insignificantly affected by UV and inconclusively or insignificantly affected by free chlorine. (a) UV, (b) Free chlorine, (c) UV and/or free chlorine at a dose of 2*67, (d) UV and/or free chlorine at a dose of 4*33. Average removals to reporting limits are beyond the scale of the y-axis and are not shown, but have the following values: 99% for atenolol, 97% for carbamazepine, 76% for DEET, 98% for metoprolol, 91% for primidone, 94% for TCEP, 97% for TCPP, and 90% for TDCPP.

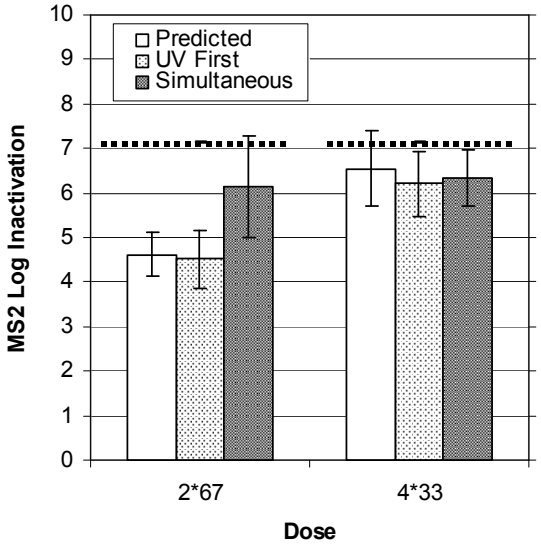


Figure 5.13. Pilot experiments: Effects of disinfectant application order and synergism on MS2 inactivation. Dotted lines represent average removal to reporting limits, i.e., the maximum removal that could be detected.

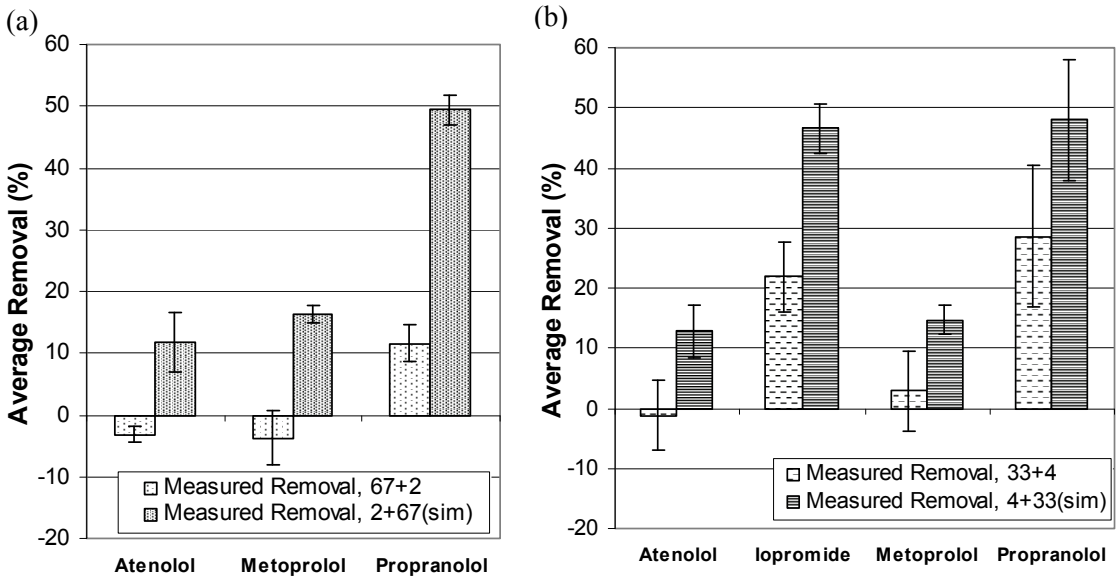


Figure 5.14. Pilot experiments: Effects of disinfectant application order on TrOCs. (a) Doses of 2*67, (b) Doses of 4*33. Average removals to reporting limits are beyond the scale of the y-axis and are not shown here; limits can be found in Figures 5.5 through 5.12.

5.5.2 Synergistic and Antagonistic Effects

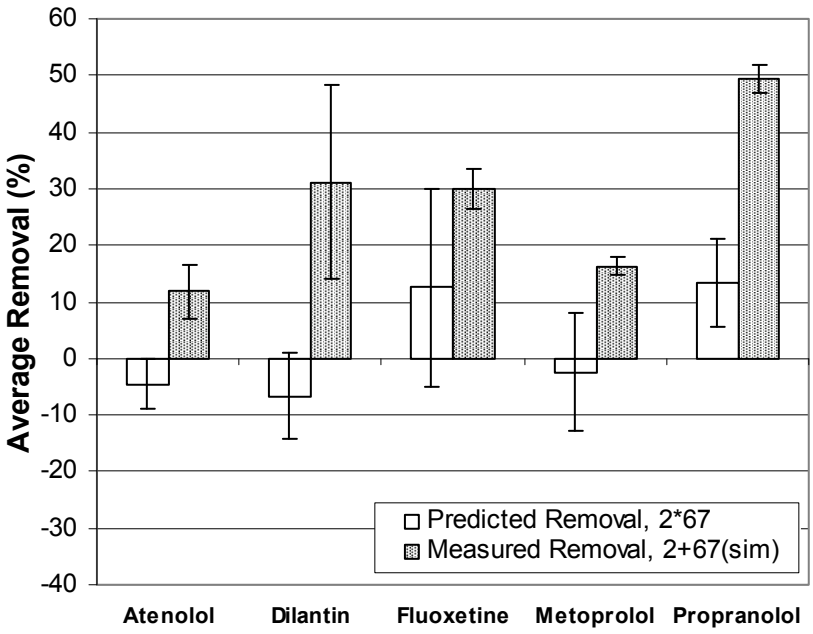
Welch's *t*-test with α of 0.05 was used to identify synergistic and antagonistic effects, by comparing measured MS2 inactivation and TrOC removals with combined UV/chlorine to predicted inactivation or removals. Predicted inactivation or removals were determined using the methods described in Section 3.7.1.

Combined UV/chlorine doses were considered potentially synergistic if inactivation/removals with the combined doses were significantly greater than predicted inactivation/removals. MS2 disinfection results (Figure 5.13) were consistent with laboratory results: Synergistic effects were observed at doses of 2+67(sim). For TrOCs, synergistic effects were not observed with UV-first doses, but were observed with simultaneous dosing for five compounds: atenolol, dilantin, metoprolol, and propranolol at doses of both 2+67(sim) and 4+33(sim), and fluoxetine at a dose of 2+67(sim). Figure 5.15 compares measured and predicted removals for these compounds and doses.

Combined UV/chlorine doses were considered potentially antagonistic if inactivation/removals with the combined doses were significantly less than predicted inactivation/removals. For MS2 (Figure 5.13), no significant antagonistic effects were observed. Figure 5.16 compares TrOC removals with combined UV/chlorine doses to predicted removals for the seven compounds that showed antagonistic effects: iopromide, nonylphenol, and octylphenol at a dose of 67+2; azithromycin at a dose of 33+4; erythromycin[-H_2O] and gemfibrozil at a dose of 4+33(sim); and sulfamethoxazole at doses of 67+2, 2+67(sim) and 33+4. Unlike synergistic effects, the observed antagonistic effects were not consistent across disinfection schemes. More data are required to confirm these antagonistic effects.

Two other compounds yielded removals that were significantly lower than the predicted removals: carbamazepine at a dose of 2+67(sim) and TCEP at doses of 2+67(sim), 67+2, and 33+4. These results suggest antagonistic effects; however, removals at these combined doses were not significantly different than zero, nor were removals at the individual doses (2 mg Cl_2/L, 4 mg Cl_2/L, 33 mJ/cm^2, or 67 mJ/cm^2). The fact that removals were insignificant at all doses indicates that any antagonistic effects from combining the two disinfectants would have little practical impact.

(a)



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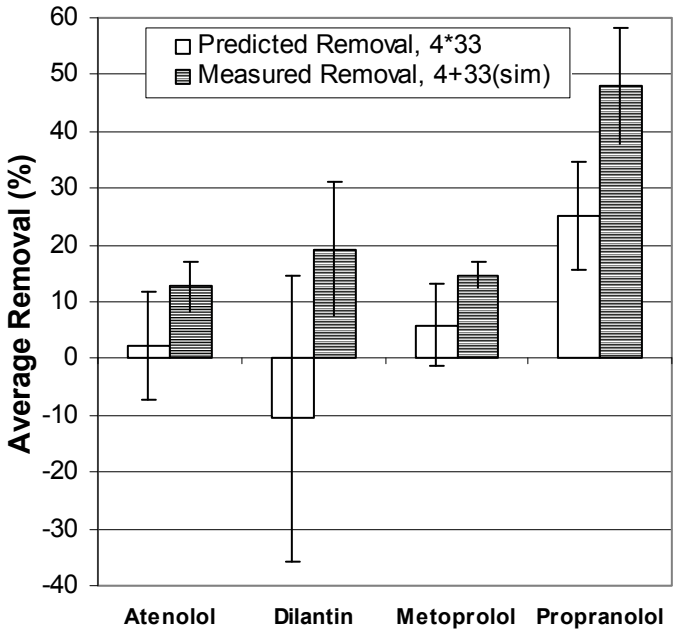

Figure 5.15. Pilot experiments: Synergistic effects on TrOCs. (a) Dose of 2+67(sim), (b) Dose of 4+33(sim). Average removals to reporting limits are beyond the scale of the y-axis and are not shown here; limits can be found in Figures 5.5 through 5.12.

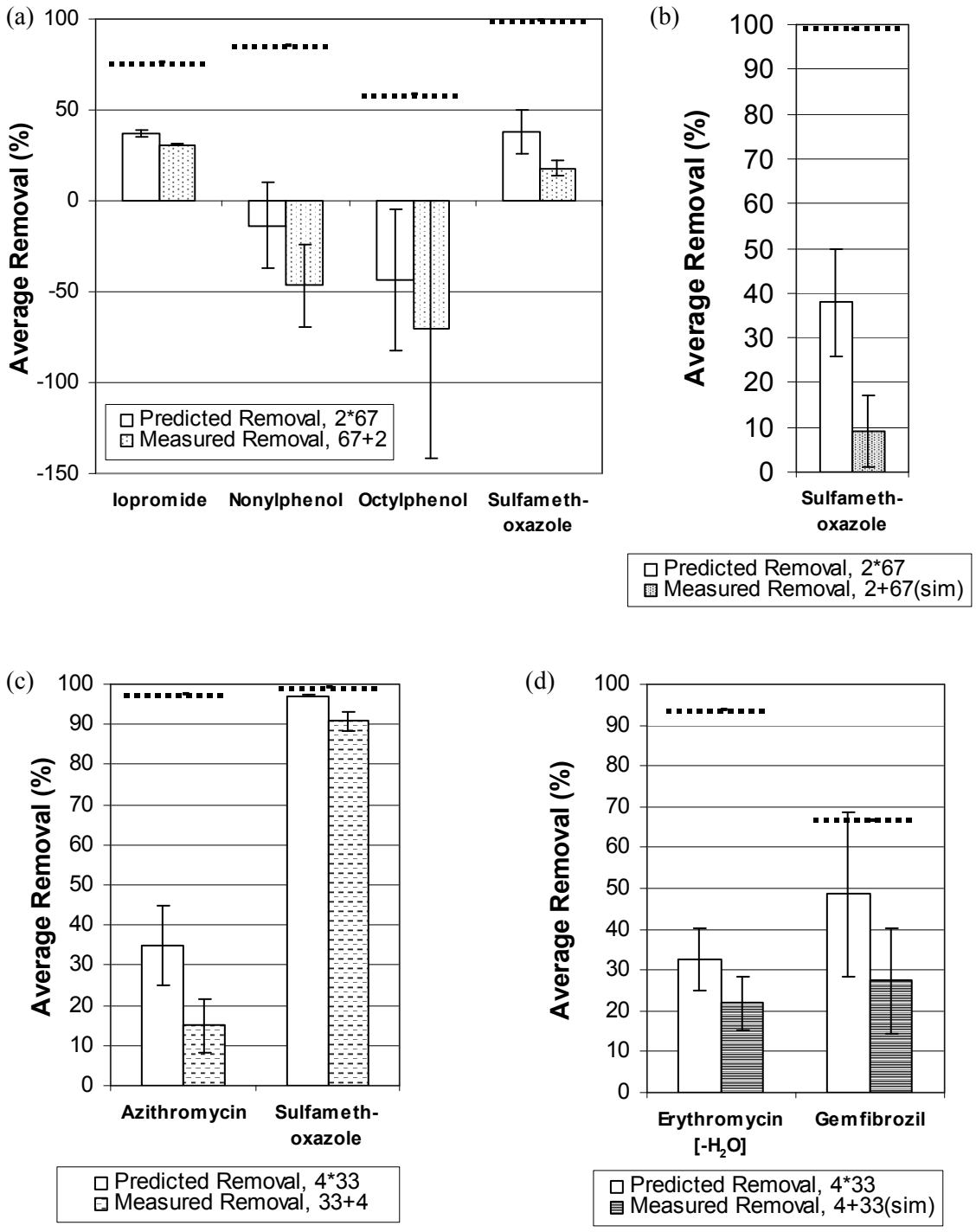

Figure 5.16. Pilot experiments: Antagonistic effects on TrOCs. (a) Dose of 67+2, (b) Dose of 2+67(sim), (c) Dose of 33+4, (d) Dose of 4+33(sim). Dotted lines represent average removal to reporting limits, i.e., the maximum removal that could be detected (Section 5.4.1).

5.5.3 Analysis of Disinfectant Application Order and Synergistic and Antagonistic Effects

5.5.3.1 Disinfectant Application Order and Synergistic Effects

Table 5.9 summarizes the effects of disinfectant application order and synergism in bench- and pilot-scale experiments with UV and free chlorine. The effects of disinfectant application order and synergism were consistent with each other and were also consistent between the bench- and pilot-scale experiments. At doses of 2*67 in the bench- and pilot-scale experiments, the simultaneous and chlorine-first doses provided more MS2 disinfection than predicted (synergism) and also provided more disinfection than the UV-first dose. Similarly, at doses of 2*67 and 4*33 in the pilot experiments, the simultaneous dose provided more removal than predicted and more removal than the UV-first dose for atenolol, metoprolol, and propranolol in all cases, and also for dilantin, fluoxetine, and iopromide under some disinfection schemes. Atenolol, metoprolol, and propranolol are all beta blocking pharmaceuticals used to treat cardiovascular disease and all share similar chemical structures (Figure 5.17).

The effects of disinfectant application order and synergism on MS2 disinfection were significant at doses of 2*67 but not doses of 4*33, and in filtered effluent but not secondary effluent. This result suggests that these effects are stronger at doses of 2*67 than at doses of 4*33 and are also stronger in filtered effluent than in secondary effluent.

Three possible explanations are presented here for the observed effects of disinfectant application order and synergism. First, UV could photolyze free and combined chlorine to form chlorine or hydroxyl radicals that could increase disinfection and react with TrOCs (Cassan et al., 2006; Watts and Linden, 2007); hydroxyl radicals produced from UV radiation and hydrogen peroxide have been shown to increase disinfection of MS2 (Mamane et al., 2007). In this case, dosing chlorine before or simultaneously with UV would allow formation of these radical species, although UV-first dosing would not. The effect may be more pronounced at a dose of 2+67(sim) than at 4+33(sim) because the higher UV dose could create more radicals, even with a lower chlorine dose. The effect may also be more pronounced in filtered effluent, which should be "cleaner" and contain lower levels of constituents that would consume radicals.

The second hypothesis is that chlorine weakens MS2 and makes it more susceptible to disinfection by UV radiation, or that chlorine reacts with TrOCs to form intermediates that are then susceptible to UV radiation; this weakening effect has been observed with other combinations of disinfectants (Leong et al., 2008). Under this hypothesis, the effects of disinfectant application order should be stronger in filtered effluent than in secondary effluent, because filtered effluent had lower levels of chlorine demand. This hypothesis appears to be inconsistent with the observation that the effects of disinfectant application order and synergism were stronger at doses of 2*67 than 4*33, because higher doses of chlorine would be expected to have stronger effects; however, it is possible that after the chlorine dose of 4 mg Cl_2/L, the subsequent UV dose of 33 mJ/cm^2 was insufficient to cause additional inactivation, or that the chlorine dose of 2 mg Cl_2/L caused the maximum damage to the MS2 and increasing the dose to 4 mg Cl_2/L had no further effect.

Table 5.9. Summary: Effects of Disinfectant Application Order, Synergism, and Antagonism in Bench and Pilot-Scale Experiments With Filtered Effluent

		Effects of Disinfectant Application Order		Synergistic Effects		Antagonistic Effects	
		2*67	4*33	2*67	4*33	2*67	4*33
Bench-Scale	MS2	Less inactivation at 67+2 than at 2+67(sim), 2+67(seq)	None observed	At doses of 2+67(sim), 2+67(seq)	None observed	None observed	At doses of 33+4[†]
Pilot-Scale	MS2	Less inactivation at 67+2 than at 2+67(sim)	None observed	At doses of 2+67(sim)	None observed	None observed	None observed
	TrOCs	Less removal at 67+2 than at 2+67(sim) for atenolol, metoprolol, propranolol	Less removal at 33+4 than at 4+33(sim) for atenolol, iopromide, metoprolol, propranolol	At doses of 2+67(sim) for atenolol, dilantin, fluoxetine, metoprolol, propranolol	At doses of 4+33(sim) for atenolol, dilantin, metoprolol, propranolol	At doses of 67+2 for iopromide, nonylphenol, octylphenol, and sulfamethoxazole. At doses of 2+67(sim) for sulfamethoxazole.	At doses of 33+4 for azithromycin and sulfamethoxazole. At doses of 4+33(sim) for erythromycin[-H_2O] and gemfibrozil

[†]Antagonistic effects were also observed at doses of 33+4 in secondary effluent. No other statistically significant effects were observed in secondary effluent.

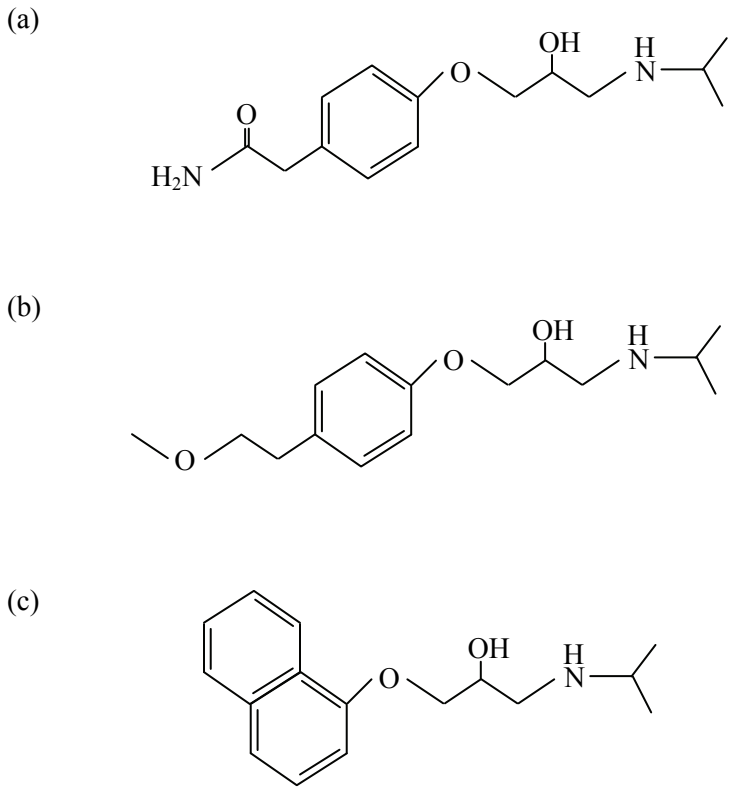

Figure 5.17. Chemical structure of beta blockers. (a) Atenolol, (b) Metoprolol, (c) Propranolol.

The third hypothesis is that free chlorine and chloramines alter the effluent UVT and increase the effectiveness of a given UV dose when chlorine is applied before or simultaneously with UV (Section 4.2). The collimated beam exposure times in the bench-scale experiments and the flow rates used in the pilot-scale experiments did not account for changes in UVT caused by the addition of free chlorine or chloramines. Consequently, the UV dose applied to the effluent was 1 to 8% higher for a given UV intensity when chlorine was applied before or simultaneously with UV (depending on the starting UVT and dose calculation method), and 1 to 14% lower when chloramines were applied before or simultaneously with UV. However, this hypothesis is not supported by the experimental results, because the effects of disinfectant application order were stronger at chlorine doses of 2*67 than 4*33, whereas the UVT changes were greater at the chlorine dose of 4 mg Cl_2/L than 2 mg Cl_2/L (Figure 4.1a). In addition, the small increase in UV dose to the microorganisms might account for the small increase in MS2 disinfection efficacy when doses of 4 mg Cl_2/L were applied simultaneously or before UV, but cannot explain the difference of almost 2-log inactivation at doses of 2 mg Cl_2/L, when the chlorine-induced UVT changes are very small. Finally, chloramines decreased UVT, which should decrease inactivation, but there were no significant differences in disinfection of MS2 and total coliforms between the UV-first and chloramine-first doses.

5.5.3.2 Antagonistic Effects

Antagonistic effects on MS2 inactivation and TrOC removal were less consistent than the effects of disinfectant application order and synergism. For MS2 disinfection, antagonistic effects were observed at doses of 33+4 at the bench scale in both filtered and secondary effluents, but were not observed at the pilot scale. Both effects of disinfectant application order and synergism were observed for MS2 inactivation and three TrOCs, whereas only iopromide showed both antagonistic effects and effects of disinfectant application order; however, the two effects occurred at different doses for iopromide. Similarly, four TrOCs showed effects of disinfectant application order and/or synergism at doses of 2*67 and 4*33, whereas only sulfamethoxazole showed antagonistic effects under multiple doses. Because the observed antagonistic effects were not consistent, more data are required to confirm these antagonistic effects.

5.5.3.3 Practical Implications

The results of this study suggest that dosing chlorine before or simultaneously with UV may improve MS2 disinfection and/or removal of some TrOCs, although more research is warranted to determine the nature of the effects of disinfectant application order and synergism, and to confirm antagonistic effects.

However, from a practical perspective, the effects of disinfectant order and synergism may play a minor role in determining disinfectant application order at specific plants, because synergistic effects were observed only in some cases: for only 6 of the 43 analyzed TrOCs, and for MS2 disinfection only at doses of 2*67 in filtered effluent. In addition, doses of 4*33 generally provided higher levels of disinfection and greater removal of TrOCs than doses of 2*67. Consequently, doses of 4*33 (where effects were not observed for MS2 at the pilot scale) may be more likely to be implemented at full-scale, and facilities may determine disinfectant application order based on logistical constraints (e.g., equipment configurations that are convenient to implement), rather than any differences in performance that are due to disinfectant application order.

5.6 SUMMARY

Findings from the pilot-scale experiments include the following.

For disinfection:

- Results with MS2, total coliforms, and adenovirus generally met the disinfection benchmarks described in Section 3.4 and were consistent with the results in filtered effluent in the bench-scale tests.

- As in the bench-scale tests, at doses of 2*67, more MS2 were inactivated when UV and chlorine were simultaneously dosed than when UV was dosed first.

For DBPs:

- TTHM levels increased with increasing chlorine doses, but remained below the USEPA drinking water standard of 80 μg/L under all disinfection schemes.

- Total cyanide concentrations were generally below 2 μg/L for all disinfection schemes.

- NDMA levels did not increase significantly after chlorine-only doses. Concentrations decreased significantly with UV-only and combined UV/chlorine doses.

For hormones, pharmaceuticals, personal care products, and other chemicals:

- UV treatment provided moderate removal of five compounds (diclofenac, iopromide, sulfamthoxzole, triclocarban, and triclosan), but increased concentrations of octylphenol and nonylphenol.

- Chlorine significantly removed the following compounds at a dose of 6 mg Cl_2/L: azithromycin, diclofenac, erythromycin[-H_2O], estrone, furosemide, gemfibrozil, octylphenol, propranolol, sulfamethoxazole, triclosan, and trimethoprim.

- The concentrations of most compounds were not affected by disinfectant application order or synergism between UV and chlorine. However, the concentrations of the three analyzed beta blockers (atenolol, metoprolol, and propranolol) were affected by both disinfectant application order and synergism at doses of 2*67. More research is warranted to understand the cause of synergistic and disinfectant application order effects.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

The research described in this report examined disinfection processes that combined UV with either free chlorine or chloramines for application to recycled water. UV was tested at doses of 33, 67, or 100 mJ/cm^2, in combination with applied free chlorine at doses of 2, 4, or 6 mg Cl_2/L, or chloramines at CT values of 150, 300, or 450 mg-min/L. Data from these experiments were used to evaluate the following:

- Effects of ultraviolet (UV) radiation on free chlorine or chloramines, and vice versa:
    - Decay of chlorine residuals in the presence or absence of UV radiation
    - Changes in UV transmittance (UVT) caused by free chlorine or chloramines
- UV, ammonia-chlorine process, and chlorine-ammonia process (individually or in combination with each other) for disinfection of MS2, poliovirus, and total coliforms
- UV and free chlorine, individually or in combination with each other:
    - Disinfection of MS2, poliovirus, adenovirus, and total coliforms
    - Disinfection byproduct formation
    - Removal of trace organic constituents (TrOCs)
    - Effects of disinfectant application order and synergism

6.1 CHANGES IN CHLORINE RESIDUALS AND UVT

Free chlorine residuals decayed rapidly in DFB, filtered effluent, and secondary effluent samples that were seeded with MS2. Total chlorine residuals decayed more slowly than free chlorine residuals, and total chlorine residuals formed by chloramines decayed more slowly than residuals formed by free chlorine. These results suggest that compounds measured as total chlorine residual were different for free chlorine and chloramine disinfection.

In free chlorine experiments, UV at doses of 2+67 or 2+67(sim) caused approximately 10 to 15% loss of total chlorine residuals in filtered and secondary effluents; at doses of 4+33 or 4+33(sim), losses were smaller in filtered effluent and were statistically insignificant in secondary effluent. The loss of the chlorine residuals indicates that the compounds composing the total chlorine residual are sensitive to UV radiation. In chloramine experiments, UV did not significantly alter total chlorine residual concentrations.

Free chlorine doses of 4 or 6 mg Cl_2/L increased UVT by approximately 2 percentage points, possibly because of the reaction of free chlorine with compounds that absorb UV radiation. The UVT increase translated to an increase of less than 2% in UV radiation exposure dose, based on the collimated beam dose calculations in the UVDGM (USEPA, 2006); however, the operating equation (Eqn. D2) for the pilot system predicted a larger increase of 7 to 8% in

the delivered UV dose. Chloramines at CT values between 150 and 450 mg-min/L decreased UVT by an average of 3.7 percentage points, possibly because of absorption of the UV radiation by chloramines. This decrease in UVT translated to a decrease of approximately 3% in UV radiation exposure dose, based on the dose calculations in the UVDGM (USEPA, 2006), and a decrease of approximately 14% in the delivered UV dose, based on the operating equation (Eqn. D2) for the pilot system. Despite the predicted decreases in UV dose, no significant differences in MS2 disinfection were observed in the bench-scale experiments between the UV-first and chloramine-first doses (Fig 4.13).

6.2 UV/CHLORAMINE EXPERIMENTS

UV was tested in combination with the ammonia-chlorine and chlorine-ammonia processes. In the ammonia-chlorine process, 1.3 mg N/L of ammonia was first mixed into the effluent, followed by 6.5 mg Cl_2/L of free chlorine. In the chlorine-ammonia process, 6.5 mg Cl_2/L of free chlorine was first added to the effluent, followed by 20 s of mixing, then 1.3 mg N/L of ammonia. The chlorine-ammonia process provided free chlorine disinfection for the first 20 s (until ammonia was added), and chloramine disinfection after ammonia addition.

6.2.1 Ammonia-Chlorine Process

At the tested doses, combined UV/ammonia-chlorine provided more than 5-log inactivation of poliovirus, and often yielded levels below detection. Total coliforms were generally inactivated to less than 2 CFU/100 mL. Chloramines alone provided no MS2 inactivation. Consequently, the “mostly chlorine” dose of 300*33 yielded only 2- to 3-log inactivation of MS2, and the “mostly UV” dose of 150*67 yielded only 3- to 4-log inactivation of MS2.

These results suggest that adding UV to an ammonia-chlorine process would improve virus disinfection. Combined UV/chloramines achieved 5-log poliovirus inactivation, which is required by the CA Title 22 regulations for disinfected tertiary recycled water. However, demonstrating this level of poliovirus disinfection at the pilot-scale is impractical because of safety concerns. MS2 is commonly used as a surrogate, but 5-log inactivation of this organism was not achieved at the doses applied in this study.

6.2.2 Chlorine-Ammonia Process

The chlorine-ammonia process yielded more disinfection of MS2 and poliovirus than the ammonia-chlorine process, presumably because of the 20 s of free chlorine contact time; disinfection of total coliforms was similar for the two chloramination methods. Disinfection using UV combined with the chlorine-ammonia process was generally similar to or worse than disinfection using UV/free chlorine, even though the chlorine-ammonia process used higher applied doses of free chlorine. The efficacy of the chlorine-ammonia process might be improved by optimizing the applied chlorine and ammonia doses, the ratio of chlorine to ammonia, the free chlorine contact time before ammonia addition, and the total contact time; further research is needed to determine optimum operating conditions.

In practice, the chlorine-ammonia process can only be used in fully nitrified effluents, where free chlorine could also be used. The chlorine-ammonia process provides the benefit of a disinfectant residual, but disinfection with free chlorine would use less chlorine and no ammonia, be less expensive, and be less complex than the chlorine-ammonia process. Because free chlorine was more promising than with either the ammonia-chlorine or chlorine-ammonia process, most of this project focused on the UV/free chlorine disinfection schemes.

6.3 UV/FREE CHLORINE EXPERIMENTS

Combined UV/free chlorine was investigated at the bench-scale in three waters (fully nitrified secondary effluent, fully nitrified filtered effluent, and DFB) with three disinfectant application orders (UV-first, simultaneous dosing of UV and free chlorine, and chlorine-first). Poliovirus, adenovirus, MS2, and total coliforms were tested. At the pilot scale, UV/free chlorine was tested in fully nitrified filtered effluent with two disinfectant application orders (UV-first and simultaneous dosing). MS2 and total coliforms were monitored for disinfection efficacy, and the effects of UV and/or chlorine on disinfection byproducts and TrOCs were also analyzed.

6.3.1 Disinfection Efficacy

Combined UV/free chlorine generally disinfected total coliforms to median levels below 2 CFU/100 mL and provided greater than 5-log inactivation of poliovirus, adenovirus, and MS2. Exceptions are noted in Sections 4.4 and 5.2.

Results indicated higher levels of free chlorine disinfection in filtered effluent than in secondary effluent. Doses of 4*33 generally provided more disinfection than doses of 2*67 in filtered effluent, probably because the full dose of free chlorine provided more disinfection than the full dose of UV for most organisms. Welch's *t*-tests with α of 0.05 indicated that disinfectant application order and synergistic effects were both statistically significant for MS2 inactivation at doses of 2*67. In bench- and pilot-scale tests at these doses, chlorine-first and simultaneous dosing provided significantly more MS2 inactivation than the UV-first dose or the predicted additive inactivation.

6.3.2 Disinfection Byproducts

In the pilot tests with filtered effluent, THMs were not detected in the influent or after UV treatment, but increased with increasing free chlorine doses. TTHM levels remained below the USEPA drinking water standard of 80 μg/L for all disinfection schemes. Total cyanide levels were generally less than 2 μg/L for all disinfection schemes. UV radiation decreased NDMA levels, with approximately 40% removal at a dose of 100 mJ/cm^2, whereas free chlorine did not significantly change NDMA levels.

6.3.3 Trace Organic Constituents

Of the 43 TrOCs analyzed during the pilot tests, 24 were consistently detected in the fully nitrified filtered effluent used as the system influent. Results with the individual disinfectants were generally consistent with literature, and results with combined UV/free chlorine doses were generally consistent with those predicted from the individual doses. Eleven compounds were strongly (>50%) removed by the full free chlorine dose of 6 mg Cl_2/L. UV radiation provided moderate (20–50%) removal of five compounds, but significantly increased concentrations of octylphenol and nonylphenol, possibly because of the breakdown of precursor compounds.

For most of the TrOCs, disinfectant application order had little effect, and synergistic or antagonistic effects were generally not observed. However, atenolol, metoprolol, and propranolol showed effects of both disinfectant application order and synergism. Simultaneous doses of 2+67(sim) or 4+33(sim) yielded significantly higher removals than UV-first dosing or predicted removals. Iopromide also showed effects of disinfectant

application order, with significantly higher removals at doses of 4+33(sim) than at doses of 33+4. Dilantin showed synergistic effects at doses of both 2+67(sim) and 4+33(sim), whereas fluoxetine showed synergistic effects at 4+33(sim). Antagonistic effects were also observed for some compounds, but the effects were inconsistent; more data are needed to confirm the antagonistic effects.

6.3.4 Operating Conditions and Synergism

The data from this project showed that operating conditions affect disinfection and removal of TrOCs. Bench-scale experiments indicated that free chlorine contact times beyond 10 min did not significantly improve MS2 disinfection in secondary effluent. In addition, the relative dose affected disinfection and TrOC removal: for organisms and TrOCs that were more susceptible to chlorine than to UV, increasing the relative chlorine dose from 2*67 to 4*33 increased disinfection or removal.

The data from this project also suggest that chlorine and UV interact when chlorine is dosed before UV. UV radiation decreased total chlorine residuals. In addition, at doses of 2*67, adding chlorine before or simultaneously with UV significantly increased MS2 inactivation in both the bench- and pilot-scale experiments. Finally, removals of several TrOCs were higher with simultaneous dosing of UV and free chlorine than with UV-first dosing and/or than predicted removals.

These results are consistent with UV-induced formation of radical species from free chlorine, as observed by Watts and Linden (2007). These radicals can then disinfect MS2 and react with the TrOCs to improve the observed levels of inactivation and removal. Alternatively, chlorine may weaken MS2 and make it more susceptible to UV disinfection. Chlorine may also react with the TrOCs to form intermediates that are then susceptible to photolysis by UV radiation. More research is needed to determine the cause of the synergistic effects.

6.4 CONCLUDING REMARKS

The results from this project indicate that UV combined with chloramines can achieve median total coliform levels below 2 CFU/100 mL and 5-log poliovirus inactivation; the UV/chlorine-ammonia process also generally provided 5-log MS2 inactivation, but the UV/ammonia-chlorine process provided <4-log MS2 inactivation. Free chlorine was a more effective disinfectant than chloramines. Combined UV/free chlorine provided 5-log inactivation of poliovirus and MS2, and median total coliform levels below 2 CFU/100 mL in most of the bench- and pilot-scale experiments.

6.4.1 Benefits of Combining UV and Free Chlorine

Overall, the results confirm the benefits of using multiple disinfectants. Combined UV/free chlorine generally provided equivalent or more disinfection of MS2, poliovirus, and adenovirus than UV alone at the full dose of 100 mJ/cm^2, and equivalent or more disinfection of total coliforms than free chlorine alone at the full dose of 6 mg Cl_2/L. In addition, concentrations of DBPs such as THMs and NDMA were lower with combined UV/free chlorine than with free chlorine alone at the full dose of 6 mg Cl_2/L. Finally, UV and free chlorine targeted different TrOCs, and in some cases, acted synergistically to increase removals of these compounds. A summary of the benefits is provided in Table 6.1.

Table 6.1. Summary of Benefits of Combining UV and Chlorine

Effluent	Single Disinfectant	Change	Benefits
Fully nitrified	Chloramines	Add UV	Improved disinfection of viruses (MS2, poliovirus) and protozoa* Decreased concentrations of DBPs such as NDMA* Removal of a slightly wider range of TrOCs*
	Chloramines	Change to free chlorine and UV	Improved disinfection of viruses (MS2, poliovirus, adenovirus*) and protozoa* Decreased concentrations of DBPs such as NDMA* Removal of a wider range of TrOCs*
	Free chlorine	Add UV	Improve disinfection of total coliforms and protozoa* Decreased concentrations of DBPs Removal of a slightly wider range of TrOCs Possible synergistic effects to increase disinfection and/or removal of TrOCs
	UV	Add free chlorine	Improved disinfection of adenovirus Removal of a wider range of TrOCs Possible synergistic effects to increase disinfection and/or removal of TrOCs Possible use for disinfection of peak flows and/or stormwater* Backup disinfection system in case of problems with UV (e.g., power outage)*
Non-nitrified	Chloramines	Add UV	Improved disinfection of viruses and protozoa* Decreased concentrations of DBPs such as NDMA* Removal of a slightly wider range of TrOCs*
	UV	Add chloramines	Residual for distribution of recycled water Possible use for disinfection of peak flows and/or stormwater* Backup disinfection system in case of problems with UV (e.g., power outage)*

*Based on literature.

6.4.2 Implications for UV Design

The results of this study may have implications for UV design. For example, the NWRI/AWWA Guidelines recommend a redundant bank of UV lamps or a redundant train (Melin, 2003). These redundant banks may not be necessary if a chlorine disinfection system is available to supplement a UV system and provide redundancy. Combined UV/chlorine might also be used to reduce the size requirement (and corresponding costs) for a new UV system, to increase the flow rating on an existing UV system, or to disinfect wet weather flows more effectively. For example, if a facility's flow increases or water quality (e.g., UVT) decreases, chlorine could be used to meet regulatory disinfection requirements in lieu of adding more UV equipment or using a lower flow rating.

6.4.3 Regulatory Implications

This project clearly demonstrated advantages in combining UV with free chlorine and provides a starting point for regulatory approval of combined UV/chlorine disinfection schemes. More work is still needed to establish an appropriate process control strategy for implementation of the free chlorine disinfection process. Although traditional control strategies use a CT value, results of the laboratory experiments indicated that effective disinfection could be achieved with essentially no measurable free chlorine residual, that is, a CT value of zero. Consequently, results in this report were presented in terms of applied dose. However, applied dose does not account for changes in water quality and therefore would be insufficient as the only control parameter; instead, the process may be controllable by establishing minimum values for multiple parameters such as applied dose, modal contact time, and free chlorine residual at that contact time. Site-specific testing is recommended to ensure that a proposed system combining UV and chlorine meets all relevant disinfection and effluent requirements.

6.4.4 Recommendations for Future Research

Recommendations for future research fall into two categories: research to improve practical implementation of combined UV/chlorine processes, and more fundamental research.

To improve practical implementation:

- An appropriate and practical process control strategy is needed for the free chlorine disinfection process (Section 6.4.3).

- More data are needed to confirm that bench- and pilot-scale experiments yield comparable results. If bench- and pilot-scale results are similar, then site-specific testing could be conducted with only bench-scale experiments, which would reduce the costs and time required for testing.

- This study investigated doses required to comply with CA Title 22 regulations for disinfected tertiary recycled water. For less stringent effluent limits, lower doses may be applicable and should be investigated.

- Results of this study indicated that free chlorine disinfection is more effective in filtered effluent than in secondary effluent. More highly treated effluents, such as membrane bioreactor or reverse osmosis effluents could also be tested, because the dose requirements for these effluents may be even lower than those presented in this study.

- This study investigated disinfection of MS2, poliovirus, adenovirus, and total coliforms. Data are also needed on the effects of combined UV/chlorine on other microorganisms of interest, such as *Cryptosporidium* and *Giardia*.

- This work tested LP UV in combination with chlorine; data are also needed to establish the performance of MP UV combined with chlorine.

Fundamental research:

- Determine the fate of TrOCs. For this study, removal was defined as a decrease in concentration; this decrease could be caused by partial transformation to an intermediate or daughter product, and it is important to ascertain the health and ecological effects of these reaction products.

- Under some conditions tested in this study, effects of disinfectant application order, synergism, and antagonism were observed when UV and chlorine were combined. More research is needed to confirm these effects, and to understand the underlying mechanisms.

- Further research is also needed to identify the specific water quality parameters that affect disinfection performance (e.g., between secondary and filtered effluents).

- In this study, different organisms responded differently to UV, free chlorine, or chloramines. For example, chloramines achieved 5-log poliovirus inactivation with a CT value of approximately 450 mg-min/L, but provided virtually no disinfection of MS2. With the wide variability in microorganism responses to each disinfectant, more research is needed to determine which organisms would best serve as indicator organisms during testing of new disinfection methods.

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APPENDIX A

PARTICLE SIZE DISTRIBUTION DATA FOR THE FILTERED AND SECONDARY EFFLUENTS

FIGURES

TABLES

An eight-channel Hach 2200 PCX particle counter was used to monitor particle size distributions (PSDs) in filtered and secondary effluents. Data points were taken every 5 min, and two Hoboware U12-008 four-channel, all-weather, analog data loggers were used to record the data. Table A1 shows the particle sizes monitored, and the upper and lower detection limits for each size range. The particle counter was gravity-fed filtered effluents from the filter effluent wet well and secondary effluents from the secondary effluent channel. As with all PSD measurements, sampling technique may affect results. As the water traveled through pipes to reach the particle counter, particles may have broken up because of turbulence or may have settled out in pipes or fittings.

Table A1. Theoretical Detection Limits for Particle Counter

Particle Size (μm)	Filtered Effluent		Secondary Effluent	
	Lower Limit (Particle Counts/mL)	Upper Limit (Particle Counts/mL)	Lower Limit (Particle Counts/mL)	Upper Limit (Particle Counts/mL)
>2	0.5	2000	0.7	3000
>5	0.5	2000	0.3	1000
>10	0.2	1000	0.14	600
>20	0.02	100	0.03	100
>50	0.0005	2	0.003	10
>100	0.0002	1	0.0014	6
>200	0.0002	1	0.0014	6
>500	0.00005	0.2	0.0014	6

PSD data for filtered effluent were measured over a seven-day period in November 2007 and a four-day period in December 2007. PSD data for the secondary effluent were measured from April 4–17, 2008. Although water quality samples were not taken specifically for this project during these periods, data for secondary and final effluent were obtained from 24-h composite samples taken for routine process monitoring. Turbidity values were 1.16 ± 0.19 NTU during the measurements of secondary effluent, and 1.00 ± 0.25 NTU in the final effluent during the measurements of filtered effluent. A *t*-test indicates no statistically significant difference between the turbidities in the secondary and final effluents. Suspended solids concentrations were generally below the reporting limit of 5 mg/L in secondary effluent and 2.5 mg/L in final effluent.

Table A2 gives the average particle concentrations in each size range, and Figures A1 and A2 present the trended data. Most particle concentrations followed a diurnal cycle, with a peak at midday and a trough near midnight. This pattern may reflect greater flow throughput at midday, which results in shorter residence times in the treatment process. For both filtered and secondary effluents, concentrations decreased with increasing particle size. No particles greater than 20 μm were detected in filtered effluent.

As expected, secondary effluent had greater particle concentrations than filtered effluent. These results suggest that secondary effluent should be more difficult to disinfect with chlorine and/or UV because the particles may shield microorganisms from the disinfectant or may react with the chlorine and reduce the effective dose.

Table A2. Average Particle Concentrations and Standard Deviation Values in Secondary and Filtered Effluents

Particle Size Range (μm)	Secondary Effluent (Particle Counts/mL)	Filtered Effluent (Particle Counts/mL)
2-5	708 ± 246	310 ± 95
5-10	209 ± 92	37 ± 10
10-20	68 ± 26	32 ± 20
20-50	13 ± 14	< 0.625
50-100	0.3 ± 0.4	< 0.013
100-200	0.1 ± 0.1	< 0.0063
200-500	0.2 ± 0.2	< 0.0063
>500	0.7 ± 0.8	< 0.0013

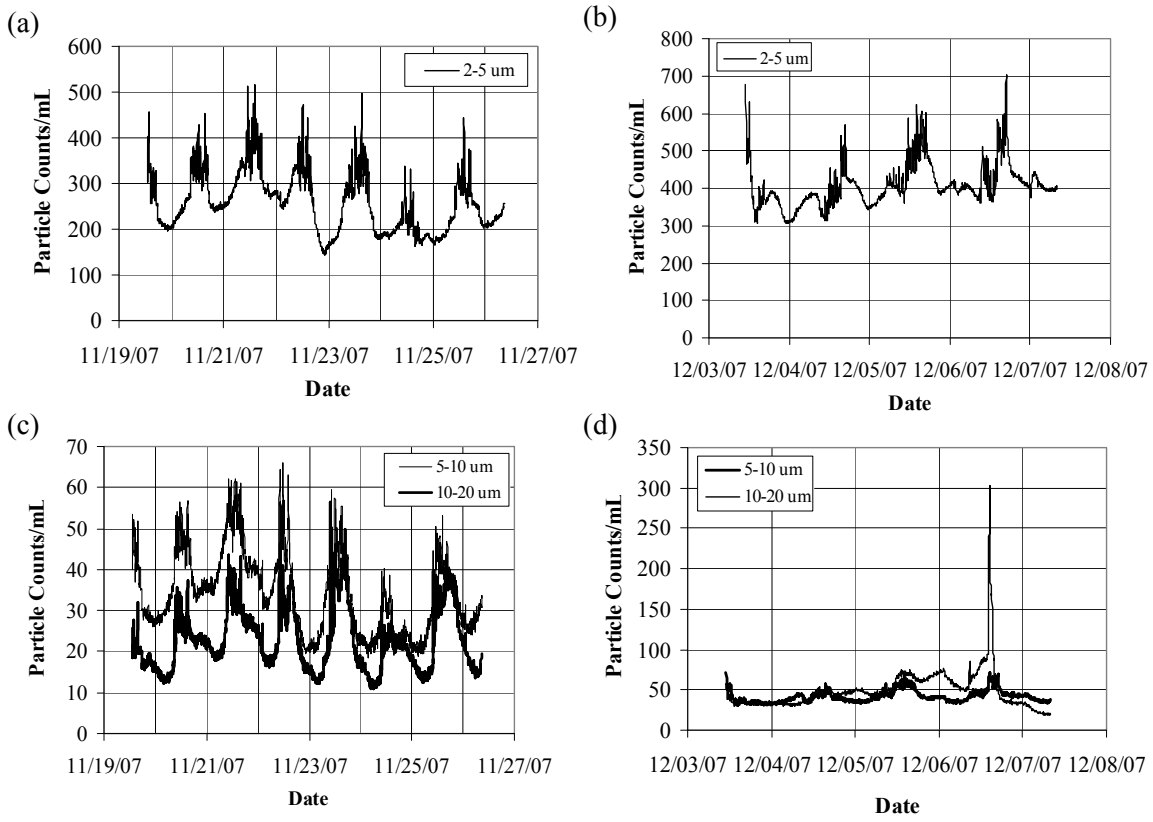

Figure A1. Particle size distributions for filtered effluent: 2–5 micron particles on (a) November 19–26, 2007 and (b) December 3–7, 2007; 5–10 and 10–20 micron particles on (c) November 19–26, 2007 and (d) December 3-7, 2007. No particles greater than 20 μm were detected in filtered effluent.

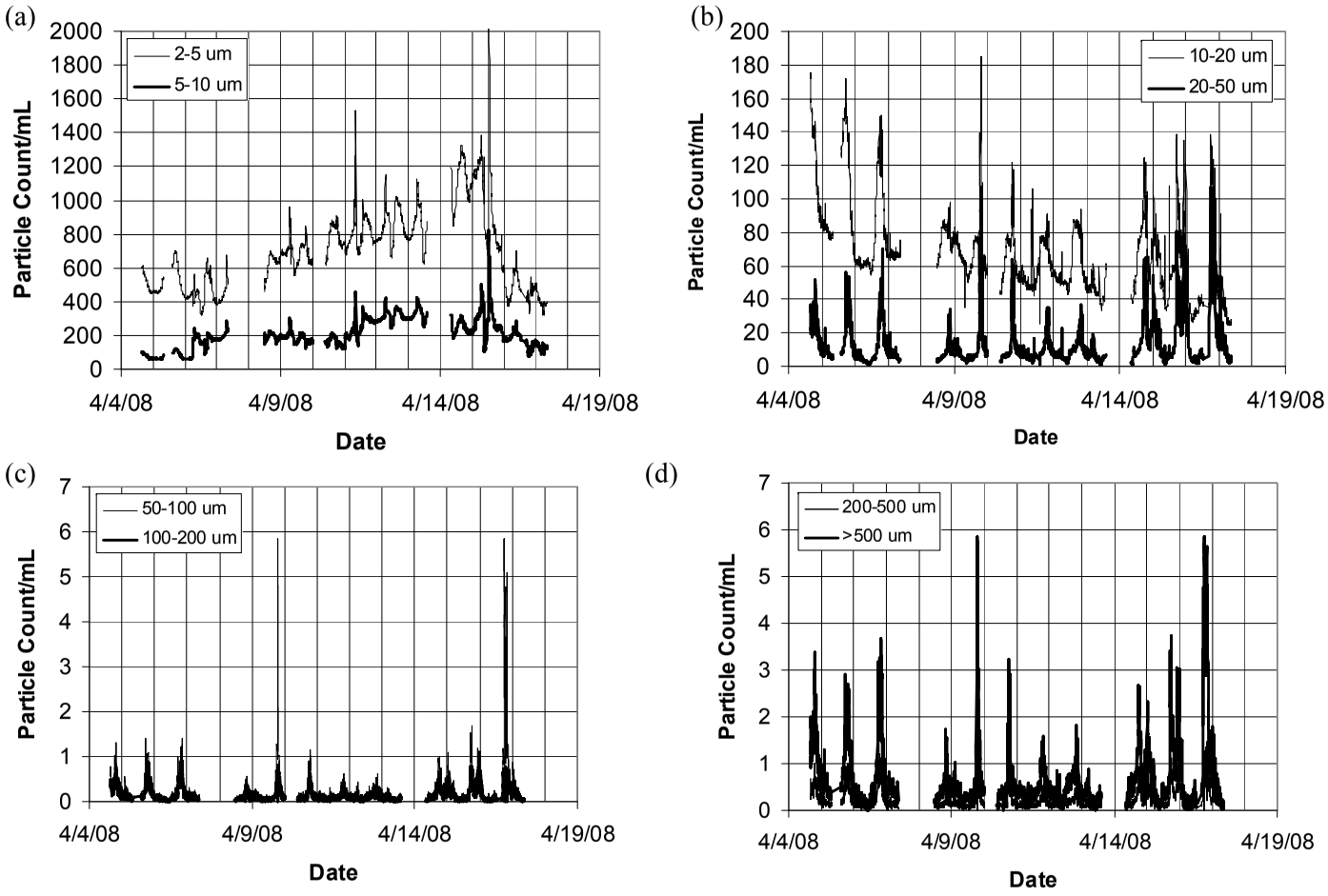

Figure A2. Particle size distributions for secondary effluent. (a) 2–5 and 5–10 micron particles, (b) 10–20 and 20–50 micron particles, (c) 50–100 and 100–200 micron particles, and (d) 200–500 and greater than 500 micron particles.

APPENDIX B

ANALYTICAL METHODS FOR TRACE ORGANIC CONSTITUENTS

TABLES

B.1 INTRODUCTION

This appendix describes the methods used to analyze TrOCs. Samples were sent to two different laboratories: the Advanced Water Technology Center (Aqwatec, Golden, CO) or the Districts' San Jose Creek Water Quality Laboratory (SJCWQL, Whittier, CA).

- Samples sent to Aqwatec were analyzed according to Reddersen and Heberer (2003), who used solid-phase extraction (SPE) and gas chromatography with mass spectrometry (GC/MS).

- At SJCWQL, estrogenic compounds and alkylphenols were analyzed according to Nelson and Do (2008). This method uses SPE and liquid chromatography with tandem mass spectrometry (LC/MS/MS), and was used to analyze estrone, 17-β estradiol, 17-α ethynylestradiol, progesterone, octylphenol, and nonyphenol.

- The method used by SJCWQL for the other TrOCs (referred to here as "PPCPs") also uses SPE with LC/MS/MS, and is described in more detail below.

B.2 PPCP ANALYSIS AT SJCWQL

The PPCP analysis at SJCWQL used a Shimadzu HPLC system equipped with two LC 10AD-vp metering pumps, a DGU-14A degassing unit, and a SIL-HTc autosampler unit. The mass spectrometer was an Applied Biosystems API 5000 tandem mass spectrometer with an electrospray ionization (ESI) probe, which was operated in both positive and negative ESI modes. Two HPLC columns were used: a Dionex Polar Advantage II™ C18 HPLC column (150 x 2.1mm, 3 μm particle size) was used for positive ESI mode, and an Agilent Zorbax C18 HPLC column (150 x 4.0 mm, 5 μm particle size) was used for negative ESI mode.

The first phase of the sample preparation was SPE, which used Waters Oasis® HLB™ cartridges (200 mg resin/6 cm^3) with a Caliper Life Sciences Autotrace™ programmable SPE workstation. The SPE system was first cleaned by flushing with a sequence of rinses: 15 mL each of methanol, dichloromethane, and methanol, followed by a final 40 mL flush with reagent water and 3 min of air-drying. The cartridges were then conditioned with a progression of rinses: 3 mL of dichloromethane, 5 mL of methanol, and finally 7 mL of reagent water.

Prior to extraction, a mixture of isotopically labeled analog compounds was added to the effluent samples to facilitate isotope dilution quantitation. Samples (200 mL) were passed through the SPE cartridges, which were then washed with 4 mL of a 5% methanol solution (in reagent water) to remove polar interferences, dried with compressed air for 50 min, and eluted with 5 mL of methanol, followed by 5 mL of a mixture containing 30% dichloromethane and 70% methanol. The eluent volume was reduced to less than 1 mL by a stream of dry air in an Organomation Associates N-Evap™ 111 nitrogen evaporator, and the final volume was brought up to 1 mL using methanol.

Two separate analyses were conducted on the same sample: one using positive ESI mode and one using negative ESI mode. Positive ESI mode used 2.0 µL of sample on the Dionex Polar Advantage II™ C18 HPLC column; compounds were separated using gradient program with two solvents at a combined flow rate of 0.35 mL/min. Solvent A was 0.1% formic acid in a 1 mg/L solution of ammonium formate, and solvent B was 0.1% formic acid in a 1:1 solution of methanol and acetonitrile. Negative ESI mode used 3.0 µL of sample on an Agilent Zorbax C18 HPLC column; compounds were separated using gradient program with two solvents at a combined flow rate of 0.40 mL/min. Solvent A was 40 mg/L of ammonium acetate, and solvent B was methanol. Table B1 provides the gradient profile used for each mode.

For the MS, positive ESI used an ionization energy of 5500V and a temperature of 400ºC, whereas negative ESI used an ionization energy of –4500V and a temperature of 300ºC. The probe height was 5 mm. Other conditions on the instrument were as follows: gas 1 at 40 psi, gas 2 at 55 psi, curtain gas at 25, and collision gas at a setting of 6. Nitrogen was used as the curtain, heater, and collision gas. Multiple reaction monitoring (MRM) transitions were used to identify each of the compounds as shown in Table B2. Chromatographically resolved analytes were quantified by peak area to internal standard area ratios for each specific parent/daughter mass transition as measured by tandem mass spectrometry and calculated by Analyst® software.

Table B1. LC Gradient Profiles for TrOC Analysis

Positive ESI Mode		Negative ESI Mode	
Time (min)	% of Solvent B in the Mobile Phase	Time (min)	% of Solvent B in the Mobile Phase
0.0	3	0.0	3
10.0	95	1.0	25
16.0	95	6.0	99
17.0	3	11.0	99
25.0	End	13.0	3
		20.0	End

Note. In the LC analysis, the mobile phase consisted of solvent A and solvent B. In positive ESI mode, solvent A was 0.1% formic acid in a 1 mg/L solution of ammonium formate, and solvent B was 0.1% formic acid in a 1:1 solution of methanol and acetonitrile. In negative ESI mode, solvent A was 40 mg/L of ammonium acetate, and solvent B was methanol.

Table B2. MRM Transitions for TrOC Analysis

Compound	ESI Mode	Quantitation Transition
Acetaminophen	Positive	152.4→110.1
Atenolol	Positive	267.3 → 145.3
Atorvastatin	Positive	559.3→440.2
o-Hydroxyatorvastatin	Positive	575.1 → 440.2
p-Hydroxyatorvastatin	Positive	575.1 → 440.2
Azithromycin	Positive	749.5→591.5
Bisphenol A	Negative	227.1→132.8
Caffeine	Positive	195.2 → 138.2
Carbamazepine	Positive	237.1→194.1
DEET	Positive	192.0 → 119.0
Diclofenac	Negative	294.0→249.8
Dilantin	Positive	253.0 → 182.0
Erythromycin [-H_2O]	Positive	716.1→558.4
Fluoxetine	Positive	310.2→44.0
Furosemide	Negative	329.0→205.0
Gemfibrozil	Negative	249.2→120.8
Ibuprofen	Negative	205.1→160.9
Iopromide	Negative	790.0→126.8
Ketoprofen	Negative	252.9 → 209.3
Metoprolol	Positive	268.4 →133.1
Naproxen	Negative	229.0→120.0
Primidone	Positive	219.2→162.0
Propranolol	Positive	260.0 → 115.9
Simvastatin OH	Negative	435.2 → 319.3
Sulfamethoxazole	Positive	253.9→156.0
TCEP	Positive	284.9 → 222.8
Triclocarban	Negative	313.0 → 159.8
Triclosan	Negative	287.0→ 35.1
Trimethoprim	Positive	291.0→261.0

APPENDIX C

SET-UP AND WATER QUALITY DATA FOR BENCH- AND PILOT-SCALE EXPERIMENTS

FIGURES

TABLES

Table C1. Water Quality Data for Bench-Scale Experiments: Before Seeding Microorganisms

Disinfectant	Effluent/Water	Date	pH	Chlorine Demand (mg/L)	Turbidity (NTU)	UVT (%)	Ammonia (mg/L)	TKN (mg/L)	Nitrate (mg/L)	Nitrite (mg/L)	Total COD (mg/L)	Total Coliform (CFU/100 mL)
Free Chlorine	Filtered Effluent	9/28/2007	7.39	3.0	0.6	77.6	<0.10	0.94	3.31	<0.03	18	6200
		12/4/2007	7.29	3.0	0.6	76.2	<0.10	1.03	2.63	0.03	14	—
		12/5/2007	7.51	2.8	0.7	77.8	<0.10	1.09	3.78	<0.03	17	—
		12/11/2007	7.4	3.3	0.6	75.8	<0.10	1.03	3.39	0.08	15	—
		12/12/2007	7.04	2.9	1.0	76.4	<0.10	1.06	3.12	0.07	16	—
		12/18/2007	7.48	3.22	0.6	76.2	<0.10	0.97	2.15	0.05	17	—
		12/20/2007	7.22	3.11	0.5	77.8	<0.10	1.06	2.67	0.06	<10	—
	Secondary Effluent	6/27/2007	7.34	4.25	1.6	75.6	0.22	1.50	2.48	0.08	15	—
		9/12/2007	7.36	3.6	0.7	76.6	0.12	1.26	2.30	0.04	17	25333
		9/27/2007	7.56	3.6	0.6	76.2	0.12	1.12	1.9	<0.03	17	9400
		11/27/2007	7.50	3.4	0.8	76.9	0.12	1.26	2.03	0.04	10	—
Ammonia-Chlorine	Filtered Effluent	1/29/2008	6.99	3.3	1.0	76.7	<0.10	1.08	2.51	0.05	<10	—
		1/30/2008	6.95	3.3	0.4	76.6	<0.10	1.21	2.86	0.06	13	—
Chlorine-Ammonia	Filtered Effluent	2/5/2008	7.02	3.4	0.4	76.2	<0.10	1.53	2.94	0.05	10	—
		2/6/2008	7.14	3.5	1.8	75.9	<0.10	0.95	3.92	0.07	15	—

Note. Dashes indicate that data were not taken. DFB was not analyzed before seeding.

Table C2. Water Quality Data for Bench-Scale Experiments: After Seeding Microorganisms

Disinfectant	Effluent/Water	Date	pH	Turbidity (NTU)	UVT (%)	Ammonia (mg/L)	TKN (mg/L)	Nitrate (mg/L)	Nitrite (mg/L)	Total COD (mg/L)	Total Coliform (CFU/100 mL)
Free Chlorine	DFB	8/22/2007	7.08	0.1	99.6	<0.10	0.37	<0.20	0.03	22	—
	Filtered Effluent	9/28/2007	—	—	78.5	—	—	—	—	—	—
		12/4/2007	7.37	0.8	75.7	<0.10	1.21	2.59	<0.03	27	12000
		12/5/2007	7.65	0.8	79.1	<0.10	1.50	3.78	<0.03	21	9400
		12/11/2007	7.47	0.7	75.0	0.13	1.25	3.38	0.07	19	13000
		12/12/2007	7.30	1.2	77.0	<0.10	1.11	3.20	0.06	22	9000
		12/18/2007	7.51	0.6	78.3	<0.10	1.06	2.12	0.05	20	—
		12/20/2007	7.42	0.6	77.8	<0.10	1.10	2.69	0.06	12	—
	Secondary Effluent	9/12/2007	—	—	75.2	—	—	—	—	—	23000
		9/27/2007	—	—	76.2	—	—	—	—	—	—
		11/27/2007	7.54	0.7	75.5	0.18	1.59	2.02	0.04	17	19000
Ammonia-Chlorine	Filtered Effluent	1/29/2008	7.25	1.1	76.6	<0.10	1.32	2.50	0.06	23	13000
		1/30/2008	7.22	0.5	75.9	<0.10	1.14	2.85	0.06	20	15000
Chlorine-Ammonia	Filtered Effluent	2/5/2008	7.19	0.4	76.0	<0.10	1.26	2.91	0.05	17	14000
		2/6/2008	7.32	2.0	75.9	0.10	1.21	3.93	0.07	25	22000

Note. Dashes indicate that data were not taken. TKN = total Kjeldahl nitrogen.

Table C3. Number of Samples Analyzed in Bench-Scale Experiments With UV and/or Free Chlorine

Disinfection Scheme	Chlorine Contact Time (min)	MS2			Poliovirus			Adenovirus	Total Coliform		Chlorine Residual		
		DFB	FE	SE	DFB	FE	SE	FE	FE	SE	DFB	FE	SE
33 mJ/cm^2	NA	1	5	4	1	5	3	2	5	3	0	0	0
67 mJ/cm^2	NA	1	5	4	1	5	3	2	5	3	0	0	0
100 mJ/cm^2	NA	1	5	4	1	5	2	2	5	3	0	0	0
UV First (2*67 or 4*33)	10	1	0	2	1	0	1	0	0	1	1	0	2
	20	1	5	4	1	5	3	2	5	3	1	7	4
	30	1	0	2	1	0	1	0	0	1	1	0	2
Sim NaOCl (2*67 or 4*33)	10	1	0	2	1	0	1	0	0	0	1	0	2
	20	1	4	3	1	4	2	2	4	1	1	6	3
	30	1	0	2	1	0	1	0	0	0	1	0	2
Chlorine-first (2*67 or 4*33)	10	1	0	2	1	0	1	0	0	1	1	0	2
	20	1	5	4	1	5	3	2	5	2	1	7	4
	30	1	0	2	1	0	1	0	0	1	1	0	2
2 mg Cl_2/L	1	0	1	1	0	1	1	0	1	1	0	1	1
	5	1	0	2	1	0	1	0	0	1	1	0	2
	20	0	4	1	0	4	1	2	4	1	0	6	1
4 mg Cl_2/L	1	0	1	1	0	1	1	0	1	1	0	1	1
	5	1	0	2	1	0	1	0	0	1	1	0	2
	20	0	4	1	0	4	1	2	4	1	0	6	1
6 mg Cl_2/L	1	0	1	1	0	1	1	0	1	1	0	1	1
	10	1	0	2	1	0	1	0	0	1	1	0	2
	20	1	5	4	1	5	3	2	5	3	1	7	4
	30	1	0	2	1	0	1	0	0	1	1	0	2

Note. DFB = Demand-free buffer, FE = filtered effluent, SE = secondary effluent. Adenovirus was only seeded into FE. Indigenous total coliforms were not present in DFB and were not measured.

Table C4. Water Quality Data for Pilot-Scale Experiments in Filtered Effluent: Initial Samples Each Day

Date	pH	Turbidity (NTU)	UVT (%)	Ammonia (mg/L)	TKN (mg/L)	Nitrate (mg/L)	Nitrite (mg/L)	Soluble COD (mg/L)	Total COD (mg/L)	Total Coliform (CFU/100 mL)
11/13/2008	6.97	0.7	—	0.10	1.17	4.02	0.07	29	34	—
11/18/2008	6.81	0.5	77.3	<0.10	0.86	1.79	0.05	15	17	8100
11/19/2008	7.67	<0.5	76.0	<0.10	0.78	3.61	0.05	10	13	7700
12/2/2008	6.88	0.6	76.6	<0.10	1.07	3.57	0.05	12	20	13300
12/3/2008	6.94	0.5	76.7	<0.10	0.66	5.12	0.04	13	16	12300
12/9/2008	6.9	0.6	75.3	<0.10	1.26	2.97	0.04	15	20	12100
1/13/2009	7.01	0.5	78.5	<0.10	1.01	3.66	0.06	<10	<10	6200
1/14/2009	7.06	0.6	74.6	<0.10	1.07	3.39	0.04	17	22	10200
1/21/2009	6.99	0.56	75.9	<0.10	1.00	3.16	0.06	20	23	10700
1/27/2009	7.03	0.5	76.7	<0.10	1.10	3.11	0.06	18	25	9300
1/29/2009	7.05	0.5	77.1	<0.10	0.85	4.24	0.05	17	21	7600

Note. Dashes indicate that data were not taken.

Table C5. Water Quality Data for Pilot-Scale Experiments in Filtered Effluent: Final Samples Each Day

Date	pH	Turbidity (NTU)	UVT (%)	Ammonia (mg/L)	TKN (mg/L)	Nitrate (mg/L)	Nitrite (mg/L)	Soluble COD (mg/L)	Total COD (mg/L)	Total Coliform (CFU/100 mL)
11/13/2008	7.17	0.5	—	0.13	1.04	3.56	0.06	26	30	—
11/18/2008	7.06	0.4	78.0	<0.10	1.06	2.19	0.04	13	16	—
11/19/2008	7.66	<0.4	78.5	<0.10	0.91	3.27	0.05	10	13	20800
12/2/2008	7.09	0.5	78.0	<0.10	1.11	3.34	0.05	14	15	12000
12/3/2008	7.16	0.5	77.6	<0.10	0.95	4.07	0.04	15	19	11100
12/9/2008	7.20	0.6	77.4	<0.10	1.04	2.71	<0.03	14	17	11500
1/13/2009	7.22	0.4	80.0	<0.10	0.94	3.61	0.05	<10	<10	3600
1/14/2009	7.32	0.5	76.9	<0.10	1.11	4.32	0.05	15	21	5700
1/21/2009	7.25	0.43	77.8	<0.10	0.94	1.93	0.05	17	21	4900
1/27/2009	7.23	0.5	78.2	<0.10	1.05	3.36	0.05	16	21	3700
1/29/2009	7.24	0.5	77.4	<0.10	0.86	4.68	0.04	15	18	4200

Note. Dashes indicate that data were not taken.

Table C6. Sampling Times in Pilot-Scale Experiments With UV Max G Reactors and Open Channel Chlorine Contactors

Date	Initial Influent	Final Influent	33 mJ/cm^2	67 mJ/cm^2	100 mJ/cm^2	2 mg/L	4 mg/L	6 mg/L	67+2	2+67 (sim)	33+4	4+33 (sim)
11/18/2008	8:25	11:40	9:30	8:35	8:20	11:35	—	10:45	9:18	—	10:04	—
11/19/2008	8:15	11:44	9:30	8:25	8:07	—	10:50	11:33	9:10	—	10:10	—
12/2/2008	9:15	12:53	11:09	9:05	13:10	—	—	—	9:55	10:40	11:55	12:40
12/3/2008	8:25	12:07	10:25	8:40	8:18	—	—	—	9:22	10:07	11:15	12:00
12/9/2008	8:20	12:10	10:25	8:30	8:15	—	—	—	9:15	10:10	11:10	12:00
1/13/2009	9:20	13:25	11:35	9:30	9:10	10:30	11:20	12:45	10:15	11:05	12:30	13:15
1/14/2009	7:15	10:53	10:04	8:10	7:22	7:55	8:37	9:29	—	8:45	—	10:45
1/21/2009	7:25	11:10	9:38	7:36	7:20	8:35	9:30	10:20	8:25	9:21	10:11	11:00
1/27/2009	10:10	12:30	10:03	—	—	10:45	11:35	12:23	—	—	10:55	11:45
1/29/2009	9:45	12:58	13:05	10:43	9:55	10:10	10:50	11:45	13:46	11:22	—	—

Note. Dashes indicate that data were not taken. All sampling times are given on a 24-hour clock (e.g., 13:30, not 1:30 p.m.).

Table C7. Effluent Flow Rates (gpm) to UV Max G Reactors in Pilot-Scale Experiments

Date	33 mJ/cm^2	67 mJ/cm^2	100 mJ/cm^2	67+2	2+67 (sim)	33+4	4+33 (sim)
11/18/2008	11.5	11.6	11.6	11.6	—	11.5	—
11/19/2008	11.4	11.4	11.3	11.4	—	11.2	—
12/2/2008	10.8	10.8	10.8	10.9	10.9	10.8	10.8
12/3/2008	11.8	11.8	11.7	11.8	11.8	11.8	11.8
12/9/2008	11.2	11.5	11.4	11.5	11.3	11.2	11.2
1/13/2009	13.1	13.0	13.1	12.8	13.1	13.1	12.7
1/14/2009	13.1	12.7	12.9	—	13.0	—	13.0
1/21/2009	13.7	13.7	13.8	13.7	13.8	13.8	13.6
1/27/2009	13.1	—	—	—	—	13.0	13.0
1/29/2009	13.1	13.1	13.1	13.1	13.1	—	—

Note. Dashes indicate that data were not taken.

Table C8. UVT Values (%) in Pilot-Scale Experiments

Date	Initial Influent	Final Influent	33 mJ/cm^2	67 mJ/cm^2	100 mJ/cm^2	2 mg/L	4 mg/L	6 mg/L	67+2	2+67 (sim)	33+4	4+33 (sim)
11/18/2008	77.3	78.0	77.6	77.8	78.2	79.1	—	81.5	79.4	—	80.4	—
11/19/2008	76.0	78.5	78.5	78.9	76.9	—	80.2	81.7	80.0	—	80.9	—
12/2/2008	76.6	78.0	78.5	77.1	78.5	—	—	—	78.0	78.5	80.2	80.2
12/3/2008	76.7	77.6	76.7	77.6	77.4	—	—	—	78.0	77.8	79.3	78.7
12/9/2008	75.3	77.4	77.4	76.7	76.6	—	—	—	78.2	77.3	78.9	79.4
1/13/2009	78.5	80.0	79.4	78.0	78.5	79.4	81.5	82.0	79.4	80.4	81.7	82.6
1/14/2009	74.6	76.9	77.3	76.4	74.0	77.1	78.3	79.1	—	77.3	—	79.4
1/21/2009	75.9	77.8	77.1	77.1	77.1	76.9	78.9	79.8	77.1	78.3	78.7	79.6
1/27/2009	76.7	78.2	76.8	—	—	78.2	79.4	80.3	—	—	79.2	80.0
1/29/2009	77.1	77.4	77.8	78.0	78.2	78.0	80.7	79.4	78.9	78.7	—	—

Note. Dashes indicate that data were not taken.

Table C9. Predicted and Delivered UV Doses (mJ/cm^2) During Pilot-Scale Experiments

Date	33 mJ/cm^2 only		33+4	4+33 (sim)	67 mJ/cm^2 only		67+2	2+67 (sim)	100 mJ/cm^2 only	
	Predicted Dose	Delivered Dose	Predicted Dose	Predicted Dose	Predicted Dose	Delivered Dose	Predicted Dose	Predicted Dose	Predicted Dose	Delivered Dose
11/18/2008	38	33	37	—	75	86	74	—	115	128
11/19/2008	39	32	38	—	80	89	74	—	110	129
12/2/2008	41	34	38	38	77	76	77	77	122	125
12/3/2008	35	27	36	36	74	70	72	72	110	102
12/9/2008	38	48	35	36	72	98	72	72	108	136
1/13/2009	36	30	36	37	69	69	74	72	106	103
1/14/2009	34	37	—	32	66	66	—	63	88	98
1/21/2009	32	25	32	32	64	58	63	63	96	90
1/27/2009	33	45	34	34	—	—	—	—	—	—
1/29/2009	34	23	—	—	69	61	67	67	104	98
Average	36	33	36	35	72	75	72	70	107	112

Table C10. Effluent Flow Rates (gpm) to Chlorine Contact Channels in Pilot-Scale Experiments

	Contact Channel #1			Contact Channel #2			
Date	2 mg Cl_2/L	4 mg Cl_2/L	6 mg Cl_2/L	67+2	2+67 (sim)	33+4	4+33 (sim)
11/13/2008	—	8.1	8.1	—	—	—	—
11/18/2008	8.1	—	8.1	8.0	—	8.1	—
11/19/2008	—	8.2	8.2	8.0	—	8.1	—
12/2/2008	—	—	—	8.0	10.9	8.2	10.8
12/3/2008	—	—	—	8.0	11.8	8.0	11.8
12/9/2008	—	—	—	8.0	11.3	8.2	11.2
1/13/2009	8.0	8.0	8.0	8.4	13.1	8.1	12.7
1/14/2009	8.1	8.1	8.0	—	13.0	—	13.0
1/21/2009	8.0	8.0	8.0	8.0	13.8	8.1	13.6
1/27/2009	8.0	8.0	8.0	—	—	8.1	13.0
1/29/2009	8.0	8.0	8.0	7.9	13.1	—	—

Note. Dashes indicate that data were not taken.

Table C11. Flow Rates (mL/min) for Chlorine Stock Solutions Used During Pilot-Scale Experiments

Date	2 mg/L	4 mg/L	6 mg/L	67+2	2+67 (sim)	33+4	4+33 (sim)
11/18/2008	—	152	228	—	—		—
11/18/2008	53	—	117	60	—	92	—
11/19/2008	—	87	126	58	—	78	—
12/2/2008	—	—	—	71	104	85	201
12/3/2008	—	—	—	64	97	70	198
12/9/2008	—	—	—	67	102	77	213
1/13/2009	63	105	82	57	105	123	217
1/14/2009	53	133	101	—	95	—	190
1/21/2009	57	130	96	54	95	129	207
1/27/2009	52	131	93	—	—	118	220
1/29/2009	50	137	113	70	95	—	—

Note. Dashes indicate that data were not taken.

Table C12. Concentrations of Chlorine Stock Solutions (mg Cl_2/L) in Pilot-Scale Experiments

Date	2 mg Cl_2/L	4 mg Cl_2/L	6 mg Cl_2/L	67+2	2+67 (sim)	33+4	4+33 (sim)
11/13/2008	—	760	760	—	—	—	—
11/18/2008	1040	—	1500	1020	—	1500	—
11/19/2008	—	1540	1540	1000	—	1540	—
12/2/2008	—	—	—	800	840	1580	860
12/3/2008	—	—	—	1020	1000	1480	1040
12/9/2008	—	—	—	800	800	1500	820
1/13/2009	1020	1020	2040	1040	1080	1040	1060
1/14/2009	1000	1000	1920	—	1080	—	1080
1/21/2009	980	980	2040	1000	960	1000	1020
1/27/2009	1000	1000	2000	—	—	1000	1000
1/29/2009	1020	1020	1960	1020	1000	—	—

Note. Dashes indicate that data were not taken.

Table C.13. Calculated Chlorine Doses (mg Cl_2/L) During Pilot-Scale Experiments

	Chlorine-Only Doses			Combined UV/Chlorine Doses			
Date	2 mg Cl_2/L	4 mg Cl_2/L	6 mg Cl_2/L	67+2	2+67(sim)	33+4	4+33(sim)
11/13/2008	—	3.8	5.7	—	—	—	—
11/18/2008	1.8		5.8	2.0	—	4.5	—
11/19/2008	—	4.3	6.3	1.9	—	3.9	—
12/2/2008	—	—	—	1.9	2.1	4.3	4.2
12/3/2008	—	—	—	2.2	2.2	3.4	4.6
12/9/2008	—	—	—	1.8	1.9	3.7	4.1
1/13/2009	2.1	3.5	5.5	1.9	2.3	4.2	4.8
1/14/2009	1.7	4.3	6.4	—	2.1	—	4.2
1/21/2009	1.8	4.2	6.5	1.8	1.8	4.2	4.1
1/27/2009	1.7	4.3	6.2	—		3.9	4.5
1/29/2009	1.7	4.6	7.3	2.4	1.9	—	—
Average	1.8	4.2	6.2	2.0	2.0	4.0	4.4

Table C14. Collimated Beam Data

Date	Dose (mJ/cm^2)	MS2 Level (PFU/mL)	MS2 Log Inactivation
11/18/2008	0	13995873	
	21	570000	1.4
	50	69000	2.3
	79	4000	3.5
	110	450	4.5
	140	68	5.3
12/2/2008	0	17988709	
	25	370000	1.7
	49	21000	2.9
	74	1000	4.3
	100	130	5.1
	125	34	5.7
12/9/2008	0	11994993	
	25	530000	1.4
	50	55000	2.3
	75	5100	3.4
	101	1700	3.8
	125	270	4.6
1/13/2009	0	3000000	
	25	120000	1.4
	50	7100	2.6
	75	500	3.8
	99	31	5.0
	123	6	5.7
1/21/2009	0	3000000	
	25	140000	1.3
	51	5400	2.7
	75	1000	3.5
	99	56	4.7
	124	18	5.2
1/27/2009	0	1200000	
	24	74000	1.2
	50	4800	2.4
	75	560	3.3
	101	61	4.3
	125	8.3	5.2

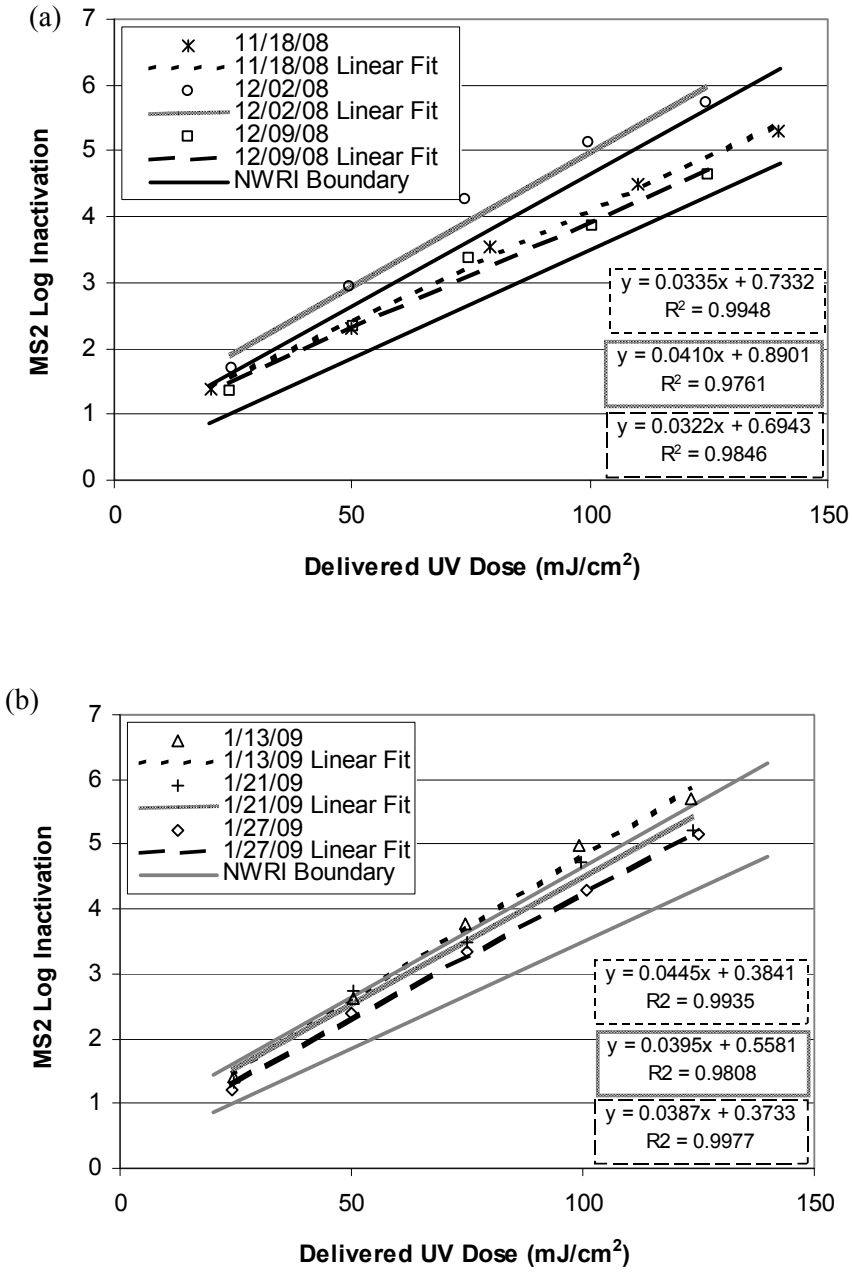

Figure C1. Collimated beam curves for pilot experiments (a) 2008, (b) 2009.

APPENDIX D

CHARACTERIZATION OF THE PILOT-SCALE SYSTEM

FIGURES

TABLES

This appendix describes the analysis of the dose testing data for the UV reactors and hydraulic tracer testing for the chlorine contactors.

D.1 EVALUATING AND PREDICTING UV DOSE

The UV pilot system consisted of three Trojan UV Max G reactors in series (designated "A," "B," and "C"). Each reactor contained one LSI brand LPHO lamp. Preliminary experiments tested UVT values ranging from approximately 70% (the lowest value observed during earlier UVT monitoring) to the typical background UVT value of approximately 78%. Dose testing aimed for a range around a dose of 33 mJ/cm^2 with a single reactor. Trojan estimated that in drinking water, a dose of 33 mJ/cm^2 would require a flow of 18 gpm at a UVT of 78% and 13 gpm at a UVT of 70%.

The first preliminary experiment tested whether the three reactors behaved similarly. Problems with calibration of the flow meter prevented accurate assessment of the flow rates, so flow rates for this experiment are approximate. Filtered effluent at the background UVT of 78% was tested at estimated flow rates of 12 and 21 gpm, and effluent at approximately 70% UVT was tested at estimated flow rates of 8 and 16 gpm; instant coffee dissolved in hot water was added to reduce the UVT of the effluent. Table D1 provides the results. Under all four conditions tested, the reactors behaved similarly.

Table D1. Comparison of the Three Trojan UV Max G Reactors

UVT	Estimated Flow	MS2 Log Inactivation			
(%)	(gpm)	Lamp A	Lamp B	Lamp C	Average
78	21	1.0	1.1	1.1	1.1
78	12	1.7	1.9	2.0	1.9
68	16	1.3	1.3	1.2	1.3
70	8	1.9	1.9	1.8	1.9

The next preliminary experiments were "validation tests" that were conducted to establish the relationship between UV dose, flow rate, UVT, and number of lamps. Samples were taken over two days, at flow rates between 5 and 20 gpm, at UVT values between 68 and 78%, and with one, two, or three lamps in series. In total, 16 samples were analyzed. Data from the experiments are given in Table D2.

Table D2. Validation Tests for Trojan UV Max G Reactors: MS2 Inactivation and UV Dose Under Varying Flow Rates, UVT Values, and Number of Reactors

Flow (gpm)	UVT (%)	# of Reactors	MS2 Log Inactivation	Delivered Dose (mJ/cm^2)	Predicted Dose (mJ/cm^2)	Percent Error (%)
5	69	3	6.1	127	138	-8
5	69	1	3.0	51	46	12
10	68	3	3.9	73	83	-12
10	68	1	2.2	31	28	10
10	70	3	4.5	87	89	-2
10	70	2	3.5	62	59	5
10	76	3	5.6	115	107	8
10	76	1	2.2	32	36	-10
15	70	3	4.1	77	68	13
15	70	1	1.8	20	23	-12
15	77	3	3.5	64	84	-24
15	77	1	2.3	33	28	17
15	78	3	4.6	91	86	6
15	78	2	3.3	57	57	0
20	77	3	4.3	83	69	20
20	77	1	1.8	20	23	-11

A sample was also taken during the second day of experiments for collimated beam analysis, which is shown in Figure D1. The delivered UV doses in Table D2 were calculated using this collimated beam analysis (i.e., the equation shown in Figure D1) and the MS2 inactivation values in Table D2. A multiple linear regression was then performed to obtain the operating equation, shown in Equation D1. This operating equation was used to determine the flow rate needed to obtain a desired dose during the pilot experiments or to predict the UV dose under given operating conditions (flow rate in gpm, UVT in %, number of lamps). Figure D2 compares the delivered UV dose to the predicted dose from the operating equation; the black line on the figure represents a perfect fit to the predicted dose.

Initial Operating Equation:

$$\text{Log(Dose/Reactor)} = -1.937 + 2.213 \times \log(\text{UVT}) - 0.675 \times \log(\text{Flow}) \qquad \text{(Eqn. D1)}$$

Differences between the predicted and delivered UV doses (i.e., the error values given in Table D2) were calculated as

$$\text{Error} = (\text{Delivered dose} - \text{Predicted dose})/(\text{Predicted dose})$$

The largest errors in delivered dose were -24% and +20% from the predicted dose, and the average absolute error was 11%. As shown in Figures D3 through D5, there was no obvious bias that was due to flow, UVT, or number of lamps operated, that is, the operating equation did not over- or under-predict the delivered dose under specific conditions.

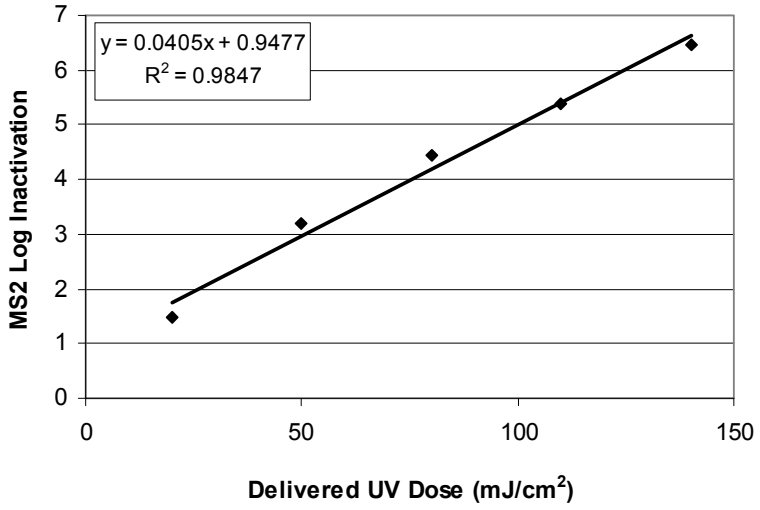

Figure D1. Collimated beam dose-response curve for dose characterization experiments.

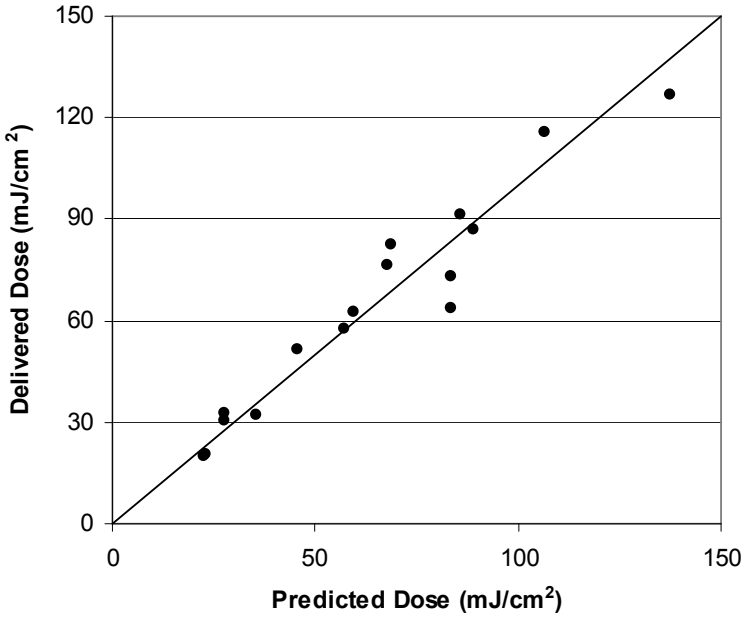

Figure D2. Fit of measured data to predicted dose from the original operating equation (line represents perfect fit to the predicted dose).

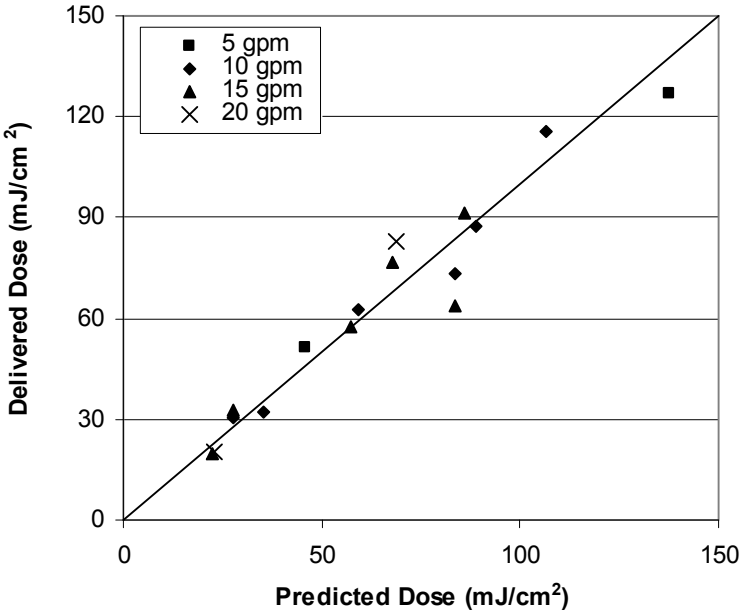

Figure D3. No dose bias with flow rate (line represents perfect fit to the predicted dose).

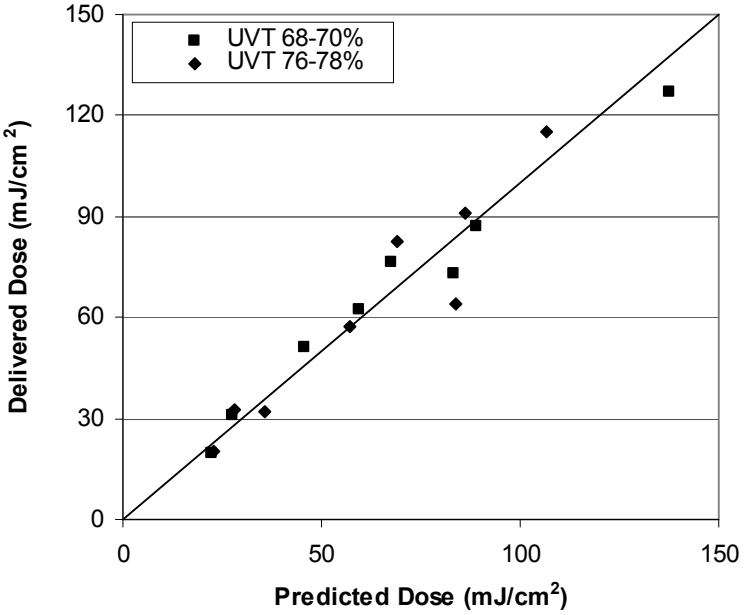

Figure D4. No dose bias with UVT (line represents perfect fit to the predicted dose).

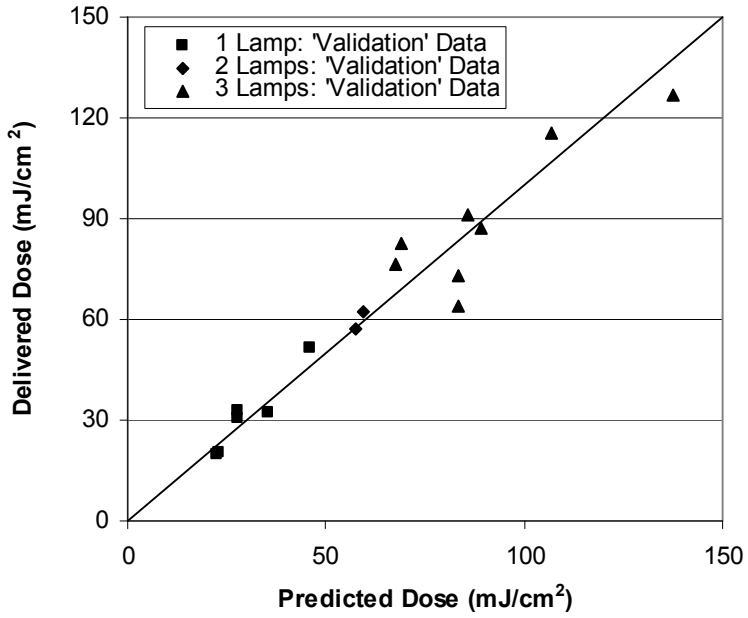

Figure D5. No dose bias with number of lamps (line represents perfect fit to the predicted dose).

The lack of bias with number of lamps was supported by data taken during the UV-only disinfection schemes in the pilot experiments (Figure D6): For the same predicted dose, data taken with two lamps during the pilot experiments overlaps with data taken with three lamps during the "validation" test. A lack of bias suggests that dose was approximately additive in this system under the conditions tested, that is, two lamps provided roughly twice the dose of a single lamp, whereas three lamps provided three times the dose of a single lamp. Although data from the pilot experiments may appear to show some bias (two lamps appear to provide slightly more than twice the dose of a single lamp, whereas three lamps appear to provide slightly more than three times the dose of a single lamp), this apparent bias is more likely to be an indication that the original operating equation was not optimal, most likely because of the relatively limited data (only 16 points taken over two days).

A new multiple linear regression was performed on all UV data to obtain a revised operating equation, shown in Equation D2. Equation D2 was used to calculate the predicted UV doses for the pilot experiments under the operating conditions (flow rate, UVT, number of lamps). Figure D7 compares the delivered UV dose to the predicted dose from the revised operating equation. Using the revised operating equation, the largest errors in delivered dose were –31% and +42% relative to the predicted dose, with an average error of ±15%.

Revised Operating Equation with All Pilot UV Data:

$$\text{Log(Dose/Reactor)} = -3.017 + 2.849 \times \log(\text{UVT}) - 0.760 \times \log(\text{Flow}) \qquad \text{(Eqn. D2)}$$

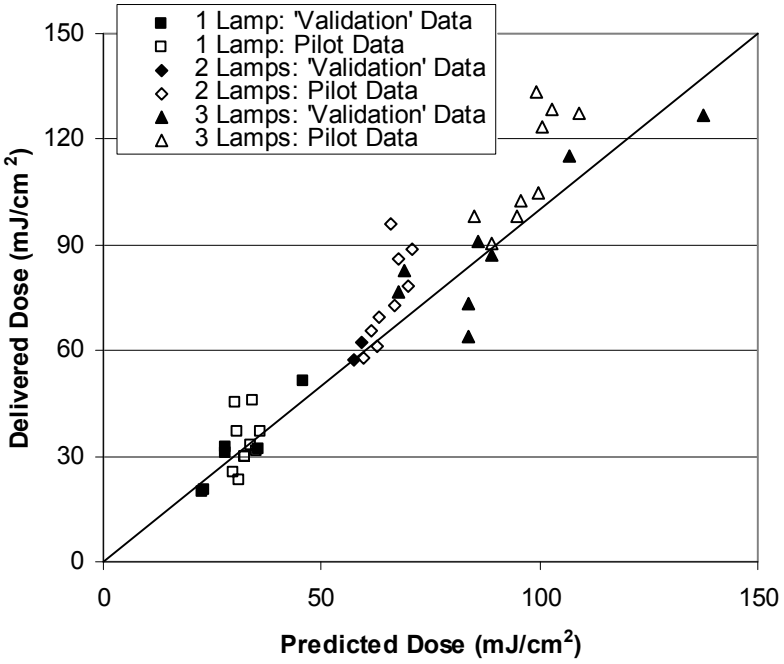

Figure D6. Comparison of validation data and data from pilot experiments using the original validation equation (Eqn. D1) (line represents perfect fit to the predicted dose).

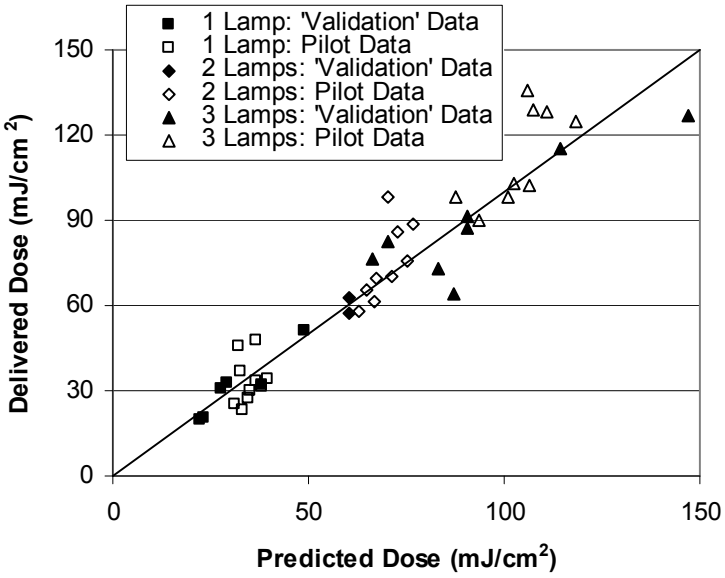

Figure D7. Fit of measured data to predicted dose from the revised operating equation (Eqn. D2) (line represents perfect fit to the predicted dose).

D.2 DETERMINING CONTACT TIMES FOR THE CHLORINE CONTACT CHANNELS

Hydraulic tracer testing of the chlorine contactors used pulse injections of Rhodamine WT dye, which was injected at one of the three chlorine dosing points on the pilot tests (see Figure 3.1 for system schematic). Dosing Point #1 was upstream of the UV reactors and chlorine contactor and was used for the simultaneous UV/free chlorine disinfection schemes. Dosing Point #2 was between the UV reactors and the chlorine contactor and was used for the UV-first disinfection schemes. Dosing Point #3 was upstream of the standalone chlorine contactor and was used for the chlorine-only disinfection schemes. Rhodamine WT levels were monitored using a Turner Designs Model 10-AU-005-CE UV fluorometer (Sunnyvale, CA).

The goal of the hydraulic tests was to establish a flow rate that would provide a modal chlorine contact time of 10 min. Practical constraints favored the shortest possible contact time, and previous laboratory experiments suggested small differences in disinfection among contact times of 10, 20, and 30 min.

Thirteen tracer tests were conducted on the chlorine contact channels. Samples were taken at two points: Point A was four feet upstream of the end of the channel and was used during three tests; Point B was two feet upstream of the end of the channel and was used during the other eight tests. The modal contact time was the time with the maximum fluorescence count.

Table D3 summarizes results of the tracer tests. At Point A, some modal contact times were less than 10 min (i.e., unacceptably short) for flow rates of 8.2 gpm. At 7.9 to 8.2 gpm at Point B, the modal contact time was 10 to 12 min. Based on these results, a flow rate of approximately 8 gpm was deemed acceptable for Point B in the open channels.

Table D3. Contact Times (min) in the Chlorine Contact Channels

	Sampling Point A[a]	Sampling Point B[a]		
	CDP#2[b]	CDP#1[b]	CDP#2[b]	CDP#3[b]
	8.4	10.8	10.6	11.2[c]
	8.6	11.0	9.8	12.1[d]
	9.4		10.8	11.8[d]
				11.4[d]
				11.2[d]
Average ± Standard Deviation	8.5 ± 0.1	10.9 ± 0.1	10.4 ± 0.5	11.5 ± 0.4

[a]Point A was four feet from the end of the open channel; Point B was two feet from the end.

[b]CDP = chlorine dosing point. See Figure 3.1 for locations.

[c] Flow rate was 7.9 gpm in this test. Flow rate was 8.2 gpm in all other tests, except those noted with footnote d.

[d]Flow rate was 8.0 gpm in these tests. Flow rate was 8.2 gpm in all other tests, except those noted with footnote c.

APPENDIX E

DATA FROM BENCH-SCALE EXPERIMENTS

TABLES

Table E1. UVT Values (%) During Bench-Scale Free Chlorine Experiments

	Date	Pre-seeding	Post-seeding	2 mg Cl_2/L	4 mg Cl_2/L	6 mg Cl_2/L
DFB	8/22/07	—	99.6	—	—	—
Filtered Effluent	9/28/07	77.6	78.5	—	—	—
	12/4/07	76.2	75.7	73.1	74.1	74.3
	12/5/07	77.8	79.1	78.9	82.0	82.4
	12/11/07	75.8	75.0	75.0	78.2	78.0
	12/12/07	76.4	77.0	77.9	77.5	79.6
	12/18/07	76.2	78.3	79.6	81.5	82.0
	12/20/07	77.8	77.8	78.0	79.1	79.4
Secondary Effluent	6/27/07	75.3	75.9	—	—	—
	9/12/07	76.6	75.2	—	—	—
	9/27/07	76.2	76.2	—	—	—
	11/27/07	76.9	75.5	—	—	—

Note. Dashes indicate that measurements were not taken.

Table E2. UVT Values (%) During Bench-Scale Chloramine Experiments in Filtered Effluent

Date	Pre-seeding	Post-seeding	CT150	CT300	CT450
1/29/08	76.7	76.6	72.1	72.1	72.3
1/30/08	76.6	75.9	73.3	72.3	73.4
2/5/08	76.2	76.0	75.0	74.5	75.2
2/6/08	75.9	75.9	74.6	74.3	74.6

Table E3. Free Chlorine Residuals (mg Cl_2/L) During Free Chlorine Experiments With 2 mg Cl_2/L, Alone or in Combination With UV

		Chlorine Contact Time (min)											
		2 mg Cl_2/L			67 mJ/cm^2 + 2 mg Cl_2/L			2 mg Cl_2/L + 67 mJ/cm^2 (sim)			2 mg Cl_2/L + 67 mJ/cm^2 (seq)		
	Date	1	5	20	10	20	30	10	20	30	10	20	30
DFB	8/22/07	—	<0.05	—	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Filtered Effluent	9/28/07	<0.05	—	—	—	<0.05	—	—	—	—	—	<0.05	—
	12/4/07	—	—	<0.05	—	<0.05	—	—	<0.05	—	—	<0.05	—
	12/5/07	—	—	0.05	—	<0.05	—	—	<0.05	—	—	0.05	—
	12/11/07	—	—	0.07	—	<0.05	—	—	<0.05	—	—	0.09	—
	12/12/07	—	—	<0.05	—	<0.05	—	—	<0.05	—	—	<0.05	—
	12/18/07	—	—	<0.05	—	<0.05	—	—	<0.05	—	—	<0.05	—
	12/20/07	—	—	<0.05	—	<0.05	—	—	<0.05	—	—	<0.05	—
Secondary Effluent	6/27/07	—	0.26	—	0.06	0.07	0.04	0.04	0.06	<0.05	0.08	0.04	0.04
	9/12/07	—	0.05	—	0.05	0.05	<0.05	0.05	<0.05	<0.05	0.06	<0.05	<0.05
	9/27/07	0.06	—	—	—	<0.05	—	—	—	—	—	<0.05	—
	11/27/07	—	—	0.07	—	<0.05	—	—	<0.05	—	—	<0.05	—

Note. Dashes indicate that measurements were not taken.

Table E4. Free Chlorine Residuals (mg Cl_2/L) During Free Chlorine Experiments With 4 mg Cl_2/L, Alone or in Combination With UV

		Chlorine Contact Time (min)											
		4 mg Cl_2/L			33 +4			4 + 33 (sim)			4 + 33 (seq)		
	Date	1	5	20	10	20	30	10	20	30	10	20	30
DFB	8/22/07	—	1.67	—	0.65	0.28	0.09	1.54	1.41	1.38	1.62	1.47	1.31
Filtered Effluent	9/28/07	0.52	—	—	—	0.05	—	—	—	—	—	0.07	—
	12/4/07	—	—	0.06	—	0.07	—	—	0.06	—	—	0.10	—
	12/5/07	—	—	0.10	—	0.05	—	—	0.06	—	—	0.06	—
	12/11/07	—	—	0.05	—	0.06	—	—	0.05	—	—	<0.05	—
	12/12/07	—	—	0.07	—	0.08	—	—	0.07	—	—	0.07	—
	12/18/07	—	—	0.30	—	0.27	—	—	0.28	—	—	0.17	—
	12/20/07	—	—	0.33	—	0.31	—	—	0.20	—	—	0.17	—
Secondary Effluent	6/27/07	—	0.16	—	0.09	0.06	0.06	0.23	0.59	0.07	0.1	0.53	0.04
	9/12/07	—	0.11	—	0.06	0.06	0.06	0.07	0.12	0.06	0.05	0.07	0.13
	9/27/07	0.36	—	—	—	0.07	—	—	—	—	—	0.1	—
	11/27/07	—	—	0.05	—	0.06	—	—	0.07	—	—	0.07	—

Note. Dashes indicate that measurements were not taken.

Table E5. Free Chlorine Residuals (mg Cl_2/L) During Free Chlorine Experiments With 6 mg Cl_2/L

		6 mg Cl_2/L Chlorine Contact Time (min)			
	Date	1	10	20	30
DFB	8/22/07	—	3.5	3.5	3.5
Filtered Effluent	9/28/07	1.63	—	0.37	—
	12/4/07	—	—	0.82	—
	12/5/07	—	—	0.94	—
	12/11/07	—	—	0.79	—
	12/12/07	—	—	1.25	—
	12/18/07	—	—	1.14	—
	12/20/07	—	—	1.6	—
Secondary Effluent	6/27/07	—	0.72	0.46	0.37
	9/12/07	—	0.66	0.37	0.23
	9/27/07	1.21	—	0.12	—
	11/27/07	—	—	0.06	—

Note. Dashes indicate that measurements were not taken.

Table E6. Total Chlorine Residuals (mg Cl_2/L) During Bench-Scale Experiments With Free Chlorine Alone

			Chlorine Contact Time (min)															
			2 mg Cl_2/L			4 mg Cl_2/L						6 mg Cl_2/L						
	Organisms Seeded into Effluent?	Date	1	5	20	1	3	5	10	20	30	1	3	5	10	20	30
DFB	No	8/22/07	—	—	—	3.6	3.5	3.4	3.2	—	2.9	—	—	—	—	—	—
	Yes	8/22/07	—	1.47	—	—	—	3.0	—	—	—	—	—	—	4.6	4.4	4.4
Filtered Effluent	Yes	9/28/07	1.10	—	—	1.95	—	—	—	—	—	3.4	—	—	—	1.61	—
	Yes	12/4/07	—	—	0.73	—	—	—	—	1.15	—	—	—	—	—	2.1	—
	Yes	12/5/07	—	—	0.66	—	—	—	—	1.14	—	—	—	—	—	2.2	—
	Yes	12/11/07	—	—	0.80	—	—	—	—	1.08	—	—	—	—	—	2.1	—
	Yes	12/12/07	—	—	0.73	—	—	—	—	1.17	—	—	—	—	—	2.5	—
	Yes	12/18/07	—	—	0.43	—	—	—	—	1.01	—	—	—	—	—	1.8	—
	Yes	12/20/07	—	—	0.41	—	—	—	—	0.98	—	—	—	—	—	2.5	—
Secondary Effluent	No	6/27/07	—	—	—	1.90	1.63	1.55	1.49	—	1.40	3.0	2.2	1.65	1.21	—	0.84
	Yes	6/27/07	—	0.87	—	—	—	1.57	—	—	—	—	—	—	1.49	1.20	0.99
	No	9/12/07	—	—	—	2.0	1.51	1.35	1.03	—	0.74	3.7	3.0	2.8	2.3	—	1.62
	Yes	9/12/07	—	1.08	—	—	—	1.71	—	—	—	—	—	—	1.69	1.46	1.24
	Yes	9/27/07	1.26	—	—	2.2	—	—	—	—	—	3.4	—	—	—	1.45	—
	Yes	11/27/07	—	—	1.07	—	—	—	—	1.73	—	—	—	—	—	1.68	—

Note. Dashes indicate that measurements were not taken.

Table E7. Total Chlorine Residuals (mg Cl_2/L) After a Contact Time of 20 Min at Free Chlorine Doses of 2 or 4 mg Cl_2/L, Alone or in Combination with UV

	Date	2 mg Cl_2/L	67+2	2 + 67 (sim)	2 + 67 (seq)	4 mg Cl_2/L	33 +4	4 + 33 (sim)	4 + 33 (seq)
Filtered Effluent	12/4/07	0.73	0.76	0.65	0.64	1.15	1.16	1.08	1.03
	12/5/07	0.66	0.71	0.62	0.59	1.14	1.11	1.09	1.01
	12/11/07	0.80	0.69	0.60	0.66	1.08	1.05	1.03	1.01
	12/12/07	0.73	0.61	0.61	0.63	1.17	1.04	1.11	1.05
	12/18/07	0.43	0.48	0.38	0.37	1.01	0.96	0.95	0.79
	12/20/07	0.41	0.43	0.32	0.36	0.98	0.91	0.82	0.79
Secondary Effluent	11/27/07	1.07	1.12	0.97	0.95	1.73	1.76	1.71	1.61
	11/28/07	1.23	1.23	1.05	1.10	2.6	2.7	2.5	2.5

Table E8. Total Chlorine Residuals (mg Cl_2/L) During Chloramine Decay Experiments in Secondary Effluent

Free Chlorine Dose (mg Cl_2/L)	4			6			8			10		
Ammonia Dose (mg N/L)	0.8			1.2			1.6			2.0		
Chlorine Contact Time (min)	10	50	90	10	50	90	10	50	90	10	50	90
Test 1	2.8	2.7	2.5	5	4.5	4.4	6.6	6.5	6.3	>8	>8	>8
Test 2	3.2	3	2.8	5.1	4.7	4.5	6.9	6.5	6.3	>8	>8	7.9

Table E9. Total Chlorine Residuals and CT Values During Chloramine Experiments in Filtered Effluent

	Total Chlorine Residual (mg Cl_2/L)				CT Value (mg-min/L)			
	Ammonia-Chlorine		Chlorine-Ammonia		Ammonia-Chlorine		Chlorine-Ammonia	
Dose	1/29/08	1/30/08	2/5/08	2/6/08	1/29/08	1/30/08	2/5/08	2/6/08
67+150	6.5	4.9	4.1	4.1	195	147	123	123
150+67(sim)	6.1	4.7	3.8	3.7	183	141	114	111
150+67(seq)	5.9	—	3.8	3.9	177	—	114	117
33+300	6.5	5.2	4.0	4.0	390	312	240	240
300+33(sim)	6.2	4.9	3.8	3.9	372	294	228	234
300+33(seq)	6.5	5.2	3.9	3.8	390	312	234	228
CT150	6.3	5.2	4.1	4.1	189	156	123	123
CT300	6.5	5.3	4.1	3.9	390	318	246	234
CT450	6.4	4.8	3.8	3.7	576	432	342	333

Note. Dashes indicate that measurements were not taken.

Table E10. *P*-Values for Percent Change in Total Chlorine Residuals Due to UV Radiation

Disinfectant application order	Free Chlorine Secondary Effluent (2 Data Points)		Free Chlorine Filtered Effluent (6 Data Points)		Chloramines Secondary Effluent (2 Data Points)	
	67 mJ/cm^2 UV 2 mg Cl_2/L NaOCl	33 mJ/cm^2 UV 4 mg Cl_2/L NaOCl	67 mJ/cm^2 UV 2 mg Cl_2/L NaOCl	33 mJ/cm^2 UV 4 mg Cl_2/L NaOCl	67 mJ/cm^2 UV CT150 mg-min/L	33 mJ/cm^2 UV CT300 mg-min/L
UV before chlorine	0.42	0.12	0.95	0.03	0.80	0.42
Simultaneous dosing	0.05	0.20	0.00	0.01	0.19	0.05
Chlorine before UV	0.00	0.07	0.00	0.00	NM	0.42

Note. Null hypothesis was that the percent change values equaled zero. NM = not meaningful; only one sample was measured.

Table E11. Inactivation of MS2 After 20 Min of Contact Time With Free Chlorine and UV

	DFB	Filtered Effluent					Secondary Effluent			
Dose	**8/22/07**	**9/28/07**	**12/4/07**	**12/5/07**	**12/11/07**	**12/12/07**	**6/27/07**	**9/12/07**	**9/27/07**	**11/27/07**
33 mJ/cm^2	1.79	2.16	2.09	2.17	2.0	2.0	1.92	2.21	2.24	2.18
67 mJ/cm^2	3.26	3.76	3.27	3.48	3.4	3.4	3.33	4.12	3.65	3.59
100 mJ/cm^2	4.57	4.82	4.79	4.62	4.6	4.8	4.54	5.76	—	4.69
67+2	4.08	5.54	4.59	4.62	4.39	5.00	3.85	5.28	4.15	3.92
2+67(sim)	6.67	—	5.45	6.40	5.95	5.93	4.19	5.10	—	4.30
2+67(seq)	7.52[a]	5.86[b]	7.03	6.76	6.87	6.88	4.44[a]	5.52[a]	5.34[b]	4.35
33+4	>6.91	6.43	7.09	7.58	7.54	6.65	4.60	5.95	5.35	4.22
4+33(sim)	>7.20	—	7.36	7.68	7.62	6.11	4.03	6.15	—	4.63
4+33(seq)	>7.20[a]	7.58[b]	6.88	7.02	8.32	6.61	4.14[a]	6.40[a]	5.40[b]	5.33
2 mg Cl_2/L	—	—	1.16	1.10	1.41	2.03	—	—	—	0.02
4 mg Cl_2/L	—	—	6.56	6.96	7.15	6.39	—	—	—	3.77
6 mg Cl_2/L	>7.20	7.10	6.81	7.24	6.86	6.84	4.53	6.70	5.25	4.73

Note. Dashes indicate that measurements were not taken.

[a]UV was dosed after 5 min of chlorine contact time; total contact time was 20 min.

[b]UV was dosed after 1 min of chlorine contact time; total contact time was 20 min.

Table E12. Inactivation of MS2 After 1, 5, 10, or 30 Min of Contact Time With Free Chlorine and UV

Dose	Contact Time (min)	DFB 8/22/07	Filtered Effluent 9/28/07	Secondary Effluent 6/27/07	9/12/07	9/27/07
67+2	10	3.97	—	3.89	5.32	—
	30	4.13	—	3.94	5.40	—
2+67(sim)	10	6.67	—	4.28	5.66	—
	30	6.92	—	4.19	5.08	—
2+67(seq)	10	7.52	—	4.48	5.50	—
	30	7.22	—	4.51	5.61	—
33+4	10	>6.91	—	4.60	5.62	—
	30	>6.91	—	4.67	5.80	—
4+33(sim)	10	>7.20	—	3.97	6.52	—
	30	>7.20	—	3.94	6.50	—
4+33(seq)	10	>7.20	—	3.87	6.10	—
	30	>7.20	—	3.93	7.00	—
2 mg Cl_2/L	1	—	1.00	—	—	0.85
	5	2.03	—	0.76	1.12	—
4 mg Cl_2/L	1	—	4.6	—	—	4.07
	5	>7.20	—	4.33	5.26	—
6 mg Cl_2/L	1	—	5.32	—	—	4.23
	10	6.43	—	4.19	6.70	—
	30	>7.20	—	4.67	7.00	—

Note. Dashes indicate that measurements were not taken. For doses of 2+67(seq) and 4+33(seq), UV was dosed after 5 min of chlorine contact time; total contact time was 10 or 30 min, as indicated.

Table E13. Inactivation of Poliovirus After 20 Min of Contact Time With Free Chlorine and UV

	DFB	Filtered Effluent					Secondary Effluent		
Dose	**8/22/07**	**9/28/07**	**12/4/07**	**12/5/07**	**12/11/07**	**12/12/07**	**9/12/07**	**9/27/07**	**11/27/07**
33 mJ/cm^2	4.71	4.68	5.15	4.52	4.64	4.51	4.79	5.06	5.00
67 mJ/cm^2	5.56	4.68	>5.63	5.01	5.34	4.71	>6.15	6.10	6.63
100 mJ/cm^2	5.16	5.02	>5.63	5.19	5.94	4.86	>5.91	—	6.15
67+2	4.03	5.46	>5.63	5.36	4.86	5.14	>6.15	6.27	6.15
2+67(sim)	>6.17	—	5.63	5.97	5.64	5.08	>6.27	--	5.85
2+67(seq)	>6.17[a]	5.38[b]	>5.63	>5.97	5.64	5.48	5.97[a]	6.57[b]	6.63
33+4	>5.86	>6.16	>5.63	>5.97	>5.94	>6.26	5.85	6.57	6.03
4+33(sim)	>6.04	—	>5.63	>5.97	>5.94	>6.26	>6.22	—	5.73
4+33(seq)	>6.04[a]	>6.16[b]	>5.63	5.97	>5.94	>6.26	>6.22[a]	>6.57[b]	6.15
2 mg Cl_2/L	—	—	0.55	0.17	0.82	3.08	—	—	0.57
4 mg Cl_2/L	—	—	>5.63	>5.97	>5.94	>6.26	—	—	4.00
6 mg Cl_2/L	>6.04	>6.16	>5.63	>5.97	>5.94	>6.26	5.92	6.57	4.87

Note. Dashes indicate that measurements were not taken.

[a]UV was dosed after 5 min of chlorine contact time; total contact time was 20 min.

[b]UV was dosed after 1 min of chlorine contact time; total contact time was 20 min.

Table E14. Inactivation of Poliovirus After 1, 5, 10, or 30 Min of Contact Time With Free Chlorine and UV

Dose	Contact Time (min)	DFB 8/22/07	Filtered Effluent 9/28/07	Secondary Effluent 9/12/07	Secondary Effluent 9/27/07
67+2	10	>6.06	—	4.02	—
	30	>6.15	—	4.12	—
2+67(sim)	10	6.67	—	6.27	—
	30	6.92	—	6.27	—
2+67(seq)	10	7.52	—	6.27	—
	30	7.22	—	6.27	—
33+4	10	5.85	—	>5.86	—
	30	>6.15	—	>5.56	—
4+33(sim)	10	>7.20	—	6.22	—
	30	>7.20	—	6.22	—
4+33(seq)	10	>7.20	—	6.22	—
	30	>7.20	—	6.22	—
2 mg Cl_2/L	1	—	0.00	—	0.47
	5	3.12	—	0.64	—
4 mg Cl_2/L	1	—	5.46	—	4.06
	5	>6.04	—	4.18	—
6 mg Cl_2/L	1	—	6.16	—	4.71
	10	>6.04	—	5.75	—
	30	>6.04	—	5.75	—

Note. Dashes indicate that measurements were not taken. For doses of 2+67(seq) and 4+33(seq), UV was dosed after 5 min of chlorine contact time; total contact time was 10 or 30 min, as indicated.

Table E15. Inactivation of Adenovirus After 20 Min of Contact Time With Free Chlorine and UV in Filtered Effluent

	Experiment	
Dose	**12/18/07**	**12/20/07**
33 mJ/cm^2	0.76	0.91
67 mJ/cm^2	1.39	1.60
100 mJ/cm^2	2.21	2.34
67+2	5.96	5.31
2+67(sim)	5.74	4.75
2+67(seq)	4.87	4.45
33+4	6.44	6.51
4+33(sim)	>6.44	6.41
4+33(seq)	>6.44	>6.51
2 mg Cl_2/L	3.26	3.07
4 mg Cl_2/L	>6.44	>6.51
6 mg Cl_2/L	>6.44	>6.51

Table E16. Total Coliform Levels (CFU/100 mL) After 20 Min of Contact Time With Free Chlorine and UV

	Filtered Effluent					Secondary Effluent		
Dose	**9/28/07**	**12/4/07**	**12/5/07**	**12/11/07**	**12/12/07**	**9/12/07**	**9/27/07**	**11/27/07**
33 mJ/cm^2	<2	<2	<2	<2	<2	<10	2	<2
67 mJ/cm^2	<2	<2	<2	<2	<2	<10	<2	<2
100 mJ/cm^2	<2	<2	<2	<2	<2	<10	<2	<2
67+2	<2	<2	<2	<2	<2	<10	<2	<2
2+67(sim)	—	<2	<2	2	<2	—	—	<2
2+67(seq)	<2	<2	<2	<2	<2	<10	<2	<2
33+4	<2	<2	<2	<2	<2	<10	2	<2
4+33(sim)	—	<2	<2	<2	<2	—	—	<2
4+33(seq)	<2	<2	<2	<2	<2	<10	<2	<2
2 mg Cl_2/L	49	26	52	44	56	—	—	470
4 mg Cl_2/L	24	<2	<2	170	<2	—	—	14
6 mg Cl_2/L	2	<2	<2	<2	<2	40	2	6

Note. Dashes indicate that measurements were not taken. Total coliforms were also not sampled in DFB because no indigenous coliforms were present.

Table E17. Total Coliform Levels (CFU/100 mL) After 1, 5, 10, or 30 Min of Contact Time With Free Chlorine and UV

Dose	Contact Time (min)	Filtered Effluent 9/28/07	Secondary Effluent 9/12/07	Secondary Effluent 9/27/07
67+2	10	—	<10	—
	30	—	<10	—
2+67(seq)	10	—	<10	—
	30	—	<10	—
33+4	10	—	<10	—
	30	—	<10	—
4+33(seq)	10	—	<10	—
	30	—	<10	—
2 mg Cl_2/L	1	49	—	3800
	5	—	4200	—
4 mg Cl_2/L	1	24	—	260
	5	—	130	—
6 mg Cl_2/L	1	10	—	100
	10	—	40	—
	30	—	20	—

Note. Dashes indicate that measurements were not taken.

Table E18. Inactivation of MS2, Poliovirus, and Total Coliforms With UV and/or the Ammonia-Chlorine Process* in Filtered Effluent

Dose	MS2 Log Inactivation 1/29/08	MS2 Log Inactivation 1/30/08	Poliovirus Log Inactivation 1/29/08	Poliovirus Log Inactivation 1/30/08	Total Coliform Level (CFU/100 mL) 1/29/08	Total Coliform Level (CFU/100 mL) 1/30/08
33 mJ/cm^2	1.28	1.29	4.31	5.28	<2	<2
67 mJ/cm^2	3.07	2.84	4.40	>5.98	<2	<2
100 mJ/cm^2	4.28	3.71	4.71	>5.98	<2	<2
67+150	3.45	3.21	>5.92	>5.98	4	<2
150+67(sim)	3.46	3.41	>5.92	>5.98	2	<2
150+67(seq)	4.12	2.82	>5.92	>5.98	<2	<2
33+300	2.07	1.91	5.92	>5.98	<2	<2
300+33 (sim)	2.34	1.87	>5.92	>5.98	2	<2
300+33 (seq)	3.56	2.21	>5.92	>5.98	<2	<2
CT150	-0.39	0.00	3.37	3.05	<2	<2
CT300	-0.21	-0.05	4.07	4.05	<2	<2
CT450	-0.06	-0.07	5.01	4.80	<2	<2

*The ammonia-chlorine process is ammonia addition, followed by free chlorine addition.

Table E19. Inactivation of MS2, Poliovirus, and Total Coliforms With UV and/or the Chlorine-Ammonia Process* in Filtered Effluent

Dose	MS2 Log Inactivation		Poliovirus Log Inactivation		Total Coliform Level (CFU/100 mL)	
	2/05/08	2/05/08	2/05/08	2/05/08	2/05/08	2/05/08
33 mJ/cm^2	1.62	1.56	5.03	3.80	<2	<2
67 mJ/cm^2	3.25	3.08	>5.81	4.19	<2	4
100 mJ/cm^2	4.25	4.24	>5.81	4.41	<2	<2
67+150	6.35	5.53	>5.81	>5.89	<2	<2
150+67(sim)	6.73	6.33	>5.81	>5.89	<2	4
150+67(seq)	5.65	6.29	>5.81	>5.89	<2	<2
33+300	4.11	4.00	>5.81	>5.89	<2	<2
300+33 (sim)	5.43	4.53	>5.81	>5.89	<2	<2
300+33 (seq)	5.05	4.89	>5.81	>5.89	<2	<2
CT150	2.23	2.90	5.03	5.81	<2	4
CT300	2.78	2.94	5.03	5.11	<2	4
CT450	3.11	2.29	>5.81	5.59	<2	<2

* The chlorine-ammonia process was free chlorine addition, followed by 20 seconds of mixing, then ammonia addition.

Table E20. *P*-Values for Statistical Comparison of Average MS2 Inactivation With Combined UV/Free Chlorine in Secondary vs. Filtered Effluents

Dose(s)	*P*-Value
2 mg Cl_2/L	0.07
4 mg Cl_2/L	0.01
6 mg Cl_2/L	0.04
33 mJ/cm^2	0.64
67 mJ/cm^2	0.34
100 mJ/cm^2	0.23
67+2	0.26
2+67(sim)	0.04
2+67(seq)	0.01
33+4	<0.01
4+33(sim)	0.07
4+33(seq)	0.06

Note. Null hypothesis was that the average inactivation values were the same in secondary and filtered effluents.

Table E21. *P*-Values for Statistical Comparison of Different Chlorine Contact Times for MS2 Inactivation in Secondary Effluent

Dose	10 vs 20 Minutes	10 vs 30 Minutes	20 vs 30 Minutes
67+2	NM	0.96	0.93
2+67(sim)	0.74	0.73	0.99
2+67(seq)	0.99	0.93	0.93
33+4	0.86	0.88	0.97
4+33(sim)	0.93	0.99	0.94
4+33(seq)	0.87	0.83	0.93
6 mg Cl_2/L	0.83	0.69	0.83

Note. Null hypothesis was that the average inactivation values were the same for both chlorine contact times. A *p*-value could not be calculated for the 67+2 dose at contact times of 10 and 20 min, because the difference in inactivation values between 10 and 20 min was the same for both samples, that is, the standard deviation in the difference was zero.

Table E22. *P*-Values for Statistical Comparison of Average MS2 Inactivation in Filtered Effluent With Combined UV/Free Chlorine Under Different Disinfectant Application Orders

Disinfectant Application Orders Compared	2*67	4*33
UV-first vs. Simultaneous Dosing	0.01	0.77
UV-first vs. Chlorine-first	<0.01	0.63
Simultaneous Dosing vs. Chlorine-first	0.28	0.77

Note. Null hypothesis was that the average inactivation values were the same for the two disinfectant application orders.

Table E23. *P*-Values for Statistical Comparison of Average MS2 Inactivation at Doses of 2*67 vs. 4*33

Doses Compared	Effluent	UV-first	Simultaneous Dosing	Chlorine-first
2*67 vs 4*33	Secondary	0.22	0.65	0.56
2*67 vs 4*33	Filtered	<0.01	0.03	0.29

Note. Null hypothesis was that the average inactivation values were the same for the two relative doses.

Table E24. *P*-Values for Statistical Comparison of Average MS2 Inactivation Values vs. Predicted Values

Dose	Effluent	UV-first	Simultaneous Dosing	Chlorine First
2*67	Secondary	0.93	0.56	0.15
2*67	Filtered	0.97	0.01	<0.01
4*33	Secondary	0.03	0.21	0.15
4*33	Filtered	0.02	0.19	0.12

Note. Null hypothesis was that the average inactivation values were the same as predicted values.

APPENDIX F

DATA FROM PILOT-SCALE UV/FREE CHLORINE EXPERIMENTS

TABLES

Table F1. Free and Total Chlorine Residuals in Pilot-Scale Experiments With UV Max G Reactors and Open Channel Chlorine Contactors

	Free Chlorine Residuals (mg Cl_2/L)							Total Chlorine Residuals (mg Cl_2/L)						
Date	2 mg Cl_2/L	4 mg Cl_2/L	6 mg Cl_2/L	67+2	2+67 (sim)	33+4	4+33 (sim)	2 mg Cl_2/L	4 mg Cl_2/L	6 mg Cl_2/L	67+2	2+67 (sim)	33+4	4+33 (sim)
11/13/2008	—	0.46	0.95	—	—	—	—	—	1.02	1.49	—	—	—	—
11/18/2008	0.08	—	1.45	0.14	—	0.38	—	0.46	—	1.82	0.53	—	0.75	—
11/19/2008	—	0.21	1.26	0.14	—	0.28	—	—	0.79	1.83	0.64	—	0.80	—
12/2/2008	—	—	—	0.14	0.30	0.32	0.20	—	—	—	0.71	0.53	0.80	0.77
12/3/2008	—	—	—	0.17	0.14	0.12	0.32	—	—	—	0.64	0.52	0.80	0.75
12/9/2008	—	—	—	0.42	0.13	0.14	0.14	—	—	—	0.54	0.43	0.80	0.77
1/13/2009	0.31	0.83	0.67	0.19	0.21	0.27	0.33	0.72	1.27	1.07	0.71	0.59	0.70	0.78
1/14/2009	0.34	0.56	1.46	—	0.28	—	0.29	0.53	1.10	2.01	—	0.50	—	0.82
1/21/2009	0.31	0.48	1.31	0.42	0.38	0.35	0.42	0.79	0.93	1.87	0.59	0.58	0.88	0.68
1/27/2009	0.37	0.29	0.63	—	—	0.25	0.22	0.61	0.73	1.17	—	—	0.75	0.77
1/29/2009	0.26	0.12	1.19	0.17	0.13	—	—	0.61	0.72	1.68	0.50	0.39	—	—
Average	0.28	0.42	1.11	0.22	0.20	0.25	0.27	0.62	0.92	1.64	0.68	0.51	0.80	0.81
Std. Dev.	0.10	0.24	0.33	0.12	0.11	0.09	0.09	0.12	0.22	0.37	0.18	0.07	0.07	0.13

Note. Dashes indicate that data were not taken.

Table F2. MS2 Log Inactivation in Pilot-Scale Experiments With UV Max G Reactors and Open Channel Chlorine Contactors

Date	33 mJ/cm^2	67 mJ/cm^2	100 mJ/cm^2	2 mg Cl_2/L	4 mg Cl_2/L	6 mg Cl_2/L	67+2	2+67 (sim)	33+4	4+33 (sim)
11/13/2008	—	—	—	—	6.7	6.8	—	—	—	—
11/18/2008	1.8	3.6	5.0	1.2	—	> 7.0	5.3	—	> 7.0	—
11/19/2008	1.8	3.7	4.9	—	6.5	6.8	4.8	—	6.0	—
12/2/2008	2.3	4.0	6.0	—	—	—	5.0	7.1	7.4	6.9
12/3/2008	2.0	3.8	5.1	—	—	—	4.5	6.8	5.9	5.7
12/9/2008	2.2	3.9	5.1	—	—	—	4.4	5.6	5.8	6.2
1/13/2009	1.7	3.5	5.0	1.3	> 7.1	7.1	4.8	7.1	5.4	7.1
1/14/2009	2.0	3.3	4.7	1.3	4.6	6.0	—	6.4	—	6.1
1/21/2009	1.9	3.1	4.4	1.7	> 6.9	6.9	3.8	6.3	6.6	6.9
1/27/2009	2.1	—	—	0.8	3.3	5.7	—	—	5.4	5.5
1/29/2009	1.3	2.7	4.2	0.9	3.2	4.2	3.4	3.8	—	—
Average	1.9	3.5	4.9	1.2	5.4	6.3	4.5	6.1	6.2	6.3
Std. Dev.	0.3	0.4	0.6	0.3	1.7	1.0	0.7	1.2	0.7	0.6

Note. Dashes indicate that data were not taken.

Table F3. Total Coliform Levels (CFU/100 mL) in Pilot-Scale Experiments With UV Max G Reactors and Open Channel Chlorine Contactors

Date	Initial Influent	Final Influent	33 mJ/cm^2	67 mJ/cm^2	100 mJ/cm^2	2 mg/L	4 mg/L	6 mg/L	67+2	2+67 (sim)	33+4	4+33 (sim)
11/18/2008	8,100	—	2	<1	<1	—	—	4	15	—	<1	—
11/19/2008	7,700	20,800	75	5	5	—	<1	4	8	—	<1	—
12/2/2008	13,300	12,000	9	6	<1	—	—	—	8	<1	<1	<1
12/3/2008	12,300	11,100	4	4	2	—	—	—	8	16	3	4
12/9/2008	12,100	11,500	4	<1	<1	—	—	—	24	2	8	<1
1/13/2009	6,200	3,600	<1	<1	<1	9	2	<1	<1	<1	<1	<1
1/14/2009	10,200	5,700	<1	<1	<1	68	<1	<1	—	4	—	<1
1/21/2009	10,700	4,900	<1	<1	4	4	2	<1	<1	<1	<1	<1
1/27/2009	9,300	3,700	<1	—	—	39	2	<1	—	—	<1	<1
1/29/2009	7,600	4,200	1	1	<1	37	<1	<1	<1	<1	—	—
Median	9,750	5,700	1.5	< 1	< 1	37	1.5	< 1	8	< 1	< 1	< 1

Note. Dashes indicate that data were not taken.

Table F4. Chloroform Levels (µg/L) in Pilot-Scale Experiments With UV Max G Reactors and Open Channel Chlorine Contactors

Date	Initial Influent	33 mJ/cm^2	67 mJ/cm^2	100 mJ/cm^2	2 mg/L	4 mg/L	6 mg/L	67+2	2+67 (sim)	33+4	4+33 (sim)
11/18/2008	ND	—	—	ND	8	—	34	10	—	27	—
12/3/2008	ND	ND	ND	ND	—	—	—	7	6	22	17
12/9/2008	ND	ND	ND	ND	—	—	—	6	3	17	14
1/13/2009	ND	ND	ND	ND	8	25	23	7	6	22	21
1/21/2009	ND	ND	ND	ND	12	26	30	7	6	22	23
1/27/2009	ND	ND	—	—	7	22	27	—	—	19	20
1/29/2009	ND	ND	ND	ND	7	24	29	5	4	—	—

Note. Dashes indicate that data were not taken. ND indicates that the concentration was below the reporting limit of 2 µg/L.

Table F5. Bromodichloromethane Levels (μg/L) in Pilot-Scale Experiments With UV Max G Reactors and Open Channel Chlorine Contactors

Date	Initial Influent	33 mJ/cm^2	67 mJ/cm^2	100 mJ/cm^2	2 mg/L	4 mg/L	6 mg/L	67+2	2+67 (sim)	33+4	4+33 (sim)
11/18/2008	ND	—	—	ND	ND	—	10	ND	—	9	—
12/3/2008	ND	ND	ND	ND	—	—	—	ND	ND	8	4
12/9/2008	ND	ND	ND	ND	—	—	—	ND	ND	5	2
1/13/2009	ND	ND	ND	ND	ND	9	8	ND	ND	8	8
1/21/2009	ND	ND	ND	ND	2	8	8	ND	ND	6	7
1/27/2009	ND	ND	—	—	ND	7	8	—	—	6	6
1/29/2009	ND	ND	ND	ND	ND	8	8	ND	ND	—	—

Note. Dashes indicate that data were not taken. ND indicates that the concentration was below the reporting limit of 2 μg/L.

Table F6. Dibromochloromethane Levels (μg/L) in Pilot-Scale Experiments With UV Max G Reactors and Open Channel Chlorine Contactors

Date	Initial Influent	33 mJ/cm^2	67 mJ/cm^2	100 mJ/cm^2	2 mg/L	4 mg/L	6 mg/L	67+2	2+67 (sim)	33+4	4+33 (sim)
11/18/2008	ND	—	—	ND	ND	—	3	ND	—	3	—
12/3/2008	ND	ND	ND	ND	—	—	—	ND	ND	2	ND
12/9/2008	ND	ND	ND	ND	—	—	—	ND	ND	ND	ND
1/13/2009	ND	ND	ND	ND	ND	2	2	ND	ND	ND	2
1/21/2009	ND	ND	ND	ND	ND	ND	2	ND	ND	ND	ND
1/27/2009	ND	ND	—	—	ND	ND	2	—	—	ND	ND
1/29/2009	ND	ND	ND	ND	ND	ND	2	ND	ND	—	—

Note. Dashes indicate that data were not taken. ND indicates that the concentration was below the reporting limit of 2 μg/L.

Table F7. Bromoform Levels (μg/L) in Pilot-Scale Experiments With UV Max G Reactors and Open Channel Chlorine Contactors

Date	Initial Influent	33 mJ/cm^2	67 mJ/cm^2	100 mJ/cm^2	2 mg/L	4 mg/L	6 mg/L	67+2	2+67 (sim)	33+4	4+33 (sim)
11/18/2008	ND	—	—	ND	ND	—	ND	ND	—	ND	—
12/3/2008	ND	ND	ND	ND	—	—	—	ND	ND	ND	ND
12/9/2008	ND	ND	ND	ND	—	—	—	ND	ND	ND	ND
1/13/2009	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
1/21/2009	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
1/27/2009	ND	ND	—	—	ND	ND	ND	—	—	ND	ND
1/29/2009	ND	ND	ND	ND	ND	ND	ND	ND	ND	—	—

Note. Dashes indicate that data were not taken. ND indicates that the concentration was below the reporting limit of 2 μg/L.

Table F8. Total Trihalomethane Levels (μg/L) in Pilot-Scale Experiments With UV Max G Reactors and Open Channel Chlorine Contactors

Date	Initial Influent	Final Influent	33 mJ/cm^2	67 mJ/cm^2	100 mJ/cm^2	2 mg/L	4 mg/L	6 mg/L	67+2	2+67 (sim)	33+4	4+33 (sim)
11/18/2008	ND	—	—	—	ND	14	—	49	16	—	41	—
12/3/2008	ND	—	ND	ND	ND	—	—	—	13	12	34	25
12/9/2008	ND	—	ND	ND	ND	—	—	—	12	9	26	20
1/13/2009	ND	—	ND	ND	ND	14	38	35	13	12	34	33
1/21/2009	ND	—	ND	ND	ND	18	38	42	13	12	32	34
1/27/2009	ND	—	ND	—	—	13	33	39	—	—	29	30
1/29/2009	ND	—	ND	ND	ND	13	36	41	11	10	—	—
Average	8	—	8	8	8	14	34	41	13	11	33	28
Std. Dev.	0	—	0	0	0	2	5	5	2	1	5	6

Note. Dashes indicate that data were not taken. Total trihalomethane (TTHM) levels were the sum of the concentrations of each of the four individual trihalomethanes (THMs). Reporting limit of each individual THM species was 2 μg/L, so the TTHM reporting limit was 8 μg/L. Individual THM concentrations below reporting limits were conservatively assigned a value of 2 μg/L. ND indicates that the concentrations of all individual THM species were below 2 μg/L.

Table F9. Total Cyanide Levels (µg/L) in Pilot-Scale Experiments With UV Max G Reactors and Open Channel Chlorine Contactors

Date	Initial Influent	Final Influent	33 mJ/cm^2	67 mJ/cm^2	100 mJ/cm^2	2 mg/L	4 mg/L	6 mg/L	67+2	2+67 (sim)	33+4	4+33 (sim)
11/18/2008	E2.1	—	—	—	E2.3	E2.1	—	E1.4	E2.3	—	E2.0	—
12/3/2008	ND	—	ND	ND	ND	—	—	—	E1.2	E1.1	E2.9	E1.1
12/9/2008	ND	—	ND	ND	ND	—	—	—	E1.3	E1.1	E2.9	E1.2
1/13/2009	ND	—	E1.6	E1.2	E1.3	E1.6	E2.6	E3.5	E1.2	E1.7	E2.9	E3.2
1/21/2009	ND	—	ND	ND	E1.5	ND	ND	ND	ND	ND	ND	ND
1/27/2009	ND	—	ND	—	—	ND	E1.0	E1.7	—	—	ND	ND
1/29/2009	ND	—	ND	ND	ND	ND	ND	ND	ND	ND	—	—
Average	1.2	—	1.1	1.0	1.4	1.3	1.4	1.7	1.3	1.2	2.1	1.5
Std. Dev.	0.4	—	0.2	0.1	0.5	0.5	0.8	0.9	0.5	0.3	0.9	1.0

Note. Dashes indicate that data were not taken. Method detection limit was 1.0 µg/L and reporting limit was 5.0 µg/L. Concentrations between 1.0 and 5.0 µg/L are estimates, as indicated by the "E" preceding the concentration value; concentrations below 1.0 µg/L are labeled as "ND." For calculations of average values, ND samples were conservatively assigned the method detection limit of 1.0 µg/L.

Table F10. Cyanogen Chloride Levels (µg/L) in Pilot-Scale Experiments With UV Max G Reactors and Open Channel Chlorine Contactors

Date	Initial Influent	Final Influent	33 mJ/cm^2	67 mJ/cm^2	100 mJ/cm^2	2 mg/L	4 mg/L	6 mg/L	67+2	2+67 (sim)	33+4	4+33 (sim)
11/18/2008	ND	—	—	—	ND	E2.0	—	E4.2	E2.3	—	7.0	—
12/3/2008	ND	—	ND	ND	ND	—	—	—	E1.1	E1.9	E2.9	E1.4
12/9/2008	ND	—	ND	ND	ND	—	—	—	ND	E1.6	E2.7	E1.4
1/13/2009	ND	—	E1.1	ND	ND	E2.9	7.0	7.0	E2.7	E2.4	7.0	7.0
1/21/2009	ND	—	E1.2	ND	ND	E2.9	6.0	6.0	E2.5	E2.2	6.0	5.0
1/27/2009	ND	—	ND	—	—	ND	E2.6	5.0	—	—	E2.3	E2.0
1/29/2009	ND	—	ND	ND	E1.4	ND	5.0	5.0	E1.1	E1.4	—	—
Average	1.0	—	1.1	1.0	1.0	2.0	5.2	5.0	1.8	1.9	4.7	3.4
Std. Dev.	0.0	—	0.1	0.0	0.0	1.0	1.9	1.1	0.8	0.4	2.2	2.5

Note. Dashes indicate that data were not taken. Method detection limit was 1.0 µg/L and reporting limit was 5.0 µg/L. Concentrations between 1.0 and 5.0 µg/L are estimates, as indicated by the "E" preceding the concentration value; concentrations below 1.0 µg/L are labeled as "ND." For calculations of average values, ND samples were conservatively assigned the method detection limit of 1.0 µg/L.

Table F11. NDMA Levels (ng/L) in Pilot-Scale Experiments With UV Max G Reactors and Open Channel Chlorine Contactors

Date	Initial Influent	Final Influent	33 mJ/cm^2	67 mJ/cm^2	100 mJ/cm^2	2 mg/L	4 mg/L	6 mg/L	67+2	2+67 (sim)	33+4	4+33 (sim)
11/18/2008	130	—	—	—	72	120	—	99	77	—	90	—
12/3/2008	140	270	200	120	88	—	—	—	130	150	220	220
12/9/2008	220	210	220	150	130	—	—	—	160	170	210	180
1/13/2009	270	160	180	200	160	280	240	180	190	190	160	130
1/21/2009	180	190	180	130	110	190	210	210	130	150	190	180
1/27/2009	100	68	88	—	—	100	90	75	—	—	87	75
1/29/2009	130	75	—	—	—	130	110	140	—	92	—	—
Average	167	162	174	150	112	173	165	176	137	165	160	157
Std. Dev.	60	79	51	36	35	81	71	73	42	19	59	56

Note. Dashes indicate that data were not taken.

Table F12. Acetaminophen Levels (ng/L) in Pilot-Scale Experiments With UV Max G Reactors and Open Channel Chlorine Contactors

Date	Lab	Initial Influent	Final Influent	33 mJ/cm^2	67 mJ/cm^2	100 mJ/cm^2	2 mg/L	4 mg/L	6 mg/L	67+2	2+67 (sim)	33+4	4+33 (sim)
12/2/2008	SJCWQL	< 10	< 10	< 10	< 10	< 10	—	—	—	< 10	< 10	< 10	< 10
12/9/2008	SJCWQL	< 10	< 10	< 10	< 10	< 10	—	—	—	< 10	< 10	< 10	< 10
1/21/2009	SJCWQL	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10
1/27/2009	SJCWQL	< 10	< 10	< 10	—	—	< 10	< 10	< 10	—	—	< 10	< 10
1/29/2009	SJCWQL	< 10	< 10	—	—	< 10	< 10	< 10	< 10	—	—	—	—

Note. Dashes indicate that data were not taken.

Table F13. Atenolol Levels (ng/L) in Pilot-Scale Experiments With UV Max G Reactors and Open Channel Chlorine Contactors

Date	Lab	Initial Influent	Final Influent	33 mJ/cm^2	67 mJ/cm^2	100 mJ/cm^2	2 mg/L	4 mg/L	6 mg/L	67+2	2+67 (sim)	33+4	4+33 (sim)
12/2/2008	SJCWQL	1750	1260	1390	1730	1240	—	—	—	1690	1290	1314	1050
12/9/2008	SJCWQL	1990	1500	1730	2050	2030	—	—	—	1940	1590	1610	1330
1/21/2009	SJCWQL	2100	1640	1830	2060	2170	2070	2010	1800	2060	1700	1910	1530
1/27/2009	SJCWQL	1820	1370	1860	—	—	1820	1530	1364	—	—	1720	1330
1/29/2009	SJCWQL	1990	1508	—	—	1990	1910	1610	1570	—	—	—	—

Note. Dashes indicate that data were not taken.

Table F14. Atorvastatin Levels (ng/L) in Pilot-Scale Experiments With UV Max G Reactors and Open Channel Chlorine Contactors

Date	Lab	Initial Influent	Final Influent	33 mJ/cm^2	67 mJ/cm^2	100 mJ/cm^2	2 mg/L	4 mg/L	6 mg/L	67+2	2+67 (sim)	33+4	4+33 (sim)
12/2/2008	SJCWQL	< 10	< 10	< 10	< 10	< 10	—	—	—	< 10	< 10	< 10	< 10
12/9/2008	SJCWQL	< 10	< 10	< 10	< 10	< 10	—	—	—	< 10	< 10	< 10	< 10
1/21/2009	SJCWQL	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10
1/27/2009	SJCWQL	< 10	< 10	< 10	—	—	< 10	< 10	< 10	—	—	< 10	< 10
1/29/2009	SJCWQL	< 10	< 10	—	—	< 10	< 10	< 10	< 10	—	—	—	—

Note. Dashes indicate that data were not taken.

Table F15. o-Hydroxy Atorvastatin Levels (ng/L) in Pilot-Scale Experiments With UV Max G Reactors and Open Channel Chlorine Contactors

Date	Lab	Initial Influent	Final Influent	33 mJ/cm^2	67 mJ/cm^2	100 mJ/cm^2	2 mg/L	4 mg/L	6 mg/L	67+2	2+67 (sim)	33+4	4+33 (sim)
12/2/2008	SJCWQL	< 10	< 10	< 10	< 10	< 10	—	—	—	< 10	< 10	< 10	< 10
12/9/2008	SJCWQL	24	19	19	19	19	—	—	—	< 10	< 10	< 10	< 10
1/21/2009	SJCWQL	22	< 10	< 10	15	28	< 10	< 10	< 10	< 10	< 10	< 10	< 10
1/27/2009	SJCWQL	10	< 10	12	—	—	< 10	< 10	< 10	—	—	< 10	< 10
1/29/2009	SJCWQL	12	< 10	—	—	11	< 10	< 10	< 10	—	—	—	—

Note. Dashes indicate that data were not taken.

Table F16. p-Hydroxy Atorvastatin Levels (ng/L) in Pilot-Scale Experiments With UV Max G Reactors and Open Channel Chlorine Contactors

Date	Lab	Initial Influent	Final Influent	33 mJ/cm^2	67 mJ/cm^2	100 mJ/cm^2	2 mg/L	4 mg/L	6 mg/L	67+2	2+67 (sim)	33+4	4+33 (sim)
12/2/2008	SJCWQL	< 10	< 10	< 10	< 10	< 10	—	—	—	< 10	< 10	< 10	< 10
12/9/2008	SJCWQL	< 10	11	< 10	< 10	< 10	—	—	—	< 10	13	< 10	< 10
1/21/2009	SJCWQL	11	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10
1/27/2009	SJCWQL	< 10	< 10	< 10	—	—	< 10	< 10	< 10	—	—	< 10	< 10
1/29/2009	SJCWQL	< 10	< 10	—	—	< 10	< 10	< 10	< 10	—	—	—	—

Note. Dashes indicate that data were not taken.

Table F17. Azithromycin Levels (ng/L) in Pilot-Scale Experiments With UV Max G Reactors and Open Channel Chlorine Contactors

Date	Lab	Initial Influent	Final Influent	33 mJ/cm^2	67 mJ/cm^2	100 mJ/cm^2	2 mg/L	4 mg/L	6 mg/L	67+2	2+67 (sim)	33+4	4+33 (sim)
12/2/2008	SJCWQL	238	203	208	271	206	—	—	—	258	222	162	167
12/9/2008	SJCWQL	392	284	364	350	380	—	—	—	401	364	266	270
1/21/2009	SJCWQL	606	485	567	644	610	546	334	92	571	606	446	296
1/27/2009	SJCWQL	486	407	554	—	—	636	309	128	—	—	426	366
1/29/2009	SJCWQL	543	412	—	—	517	521	257	72	—	—	—	—

Note. Dashes indicate that data were not taken.

Table F18. Bisphenol A Levels (ng/L) in Pilot-Scale Experiments With UV Max G Reactors and Open Channel Chlorine Contactors

Date	Lab	Initial Influent	Final Influent	33 mJ/cm^2	67 mJ/cm^2	100 mJ/cm^2	2 mg/L	4 mg/L	6 mg/L	67+2	2+67 (sim)	33+4	4+33 (sim)
11/19/2008	Aqwatec	< 25	—	< 25	< 25	< 25	—	< 25	< 25	< 25	—	< 25	—
12/2/2008	Aqwatec	< 25	—	< 25	< 25	< 25	—	—	—	< 25	< 25	< 25	< 25
12/2/2008	SJCWQL	< 25	< 25	< 25	< 25	< 25	—	—	—	< 25	< 25	< 25	< 25
12/9/2008	SJCWQL	< 10	< 10	< 10	< 10	< 10	—	—	—	< 10	< 10	< 10	< 10
1/13/2009	Aqwatec	< 25	—	< 25	< 25	< 25	< 25	< 25	< 25	< 25	< 25	< 25	< 25
1/21/2009	SJCWQL	< 25	< 25	< 25	< 25	< 25	< 25	< 25	< 25	< 25	< 25	< 25	< 25
1/27/2009	SJCWQL	< 25	< 25	< 25	—	—	< 25	< 25	< 25	—	—	< 25	< 25
1/29/2009	SJCWQL	< 25	< 25	—	—	< 25	< 25	< 25	< 25	—	—	—	—

Note. Dashes indicate that data were not taken.

Table F19. Caffeine Levels (ng/L) in Pilot-Scale Experiments With UV Max G Reactors and Open Channel Chlorine Contactors

Date	Lab	Initial Influent	Final Influent	33 mJ/cm^2	67 mJ/cm^2	100 mJ/cm^2	2 mg/L	4 mg/L	6 mg/L	67+2	2+67 (sim)	33+4	4+33 (sim)
12/2/2008	SJCWQL	< 10	< 10	< 10	< 10	< 10	—	—	—	< 10	< 10	< 10	< 10
12/9/2008	SJCWQL	13	13	16	17	20	—	—	—	20	19	< 10	< 10
1/21/2009	SJCWQL	< 10	< 10	12	13	15	< 10	< 10	< 10	< 10	< 10	< 10	< 10
1/27/2009	SJCWQL	< 10	< 10	< 10	—	—	< 10	< 10	< 10	—	—	< 10	< 10
1/29/2009	SJCWQL	< 10	< 10	—	—	< 10	< 10	< 10	< 10	—	—	—	—

Note. Dashes indicate that data were not taken.

Table F20. Carbamazepine Levels (ng/L) in Pilot-Scale Experiments With UV Max G Reactors and Open Channel Chlorine Contactors

Date	Lab	Initial Influent	Final Influent	33 mJ/cm^2	67 mJ/cm^2	100 mJ/cm^2	2 mg/L	4 mg/L	6 mg/L	67+2	2+67 (sim)	33+4	4+33 (sim)
11/19/2008	Aqwatec	325	—	174	258	303	—	299	321	333	—	334	—
12/2/2008	Aqwatec	325	—	262	294	254	—	—	—	235	306	278	261
12/2/2008	SJCWQL	257	291	273	263	295	—	—	—	277	258	270	266
12/9/2008	SJCWQL	301	280	292	291	291	—	—	—	296	281	280	278
1/13/2009	Aqwatec	247	—	277	308	342	302	360	295	269	200	335	316
1/21/2009	SJCWQL	325	340	344	339	330	335	294	318	339	321	309	298
1/27/2009	SJCWQL	281	286	280	—	—	341	290	276	—	—	273	279
1/29/2009	SJCWQL	269	263	—	—	279	281	283	278	—	—	—	—

Note. Dashes indicate that data were not taken.

Table F21. Clofibric Acid Levels (ng/L) in Pilot-Scale Experiments With UV Max G Reactors and Open Channel Chlorine Contactors

Date	Lab	Initial Influent	Final Influent	33 mJ/cm^2	67 mJ/cm^2	100 mJ/cm^2	2 mg/L	4 mg/L	6 mg/L	67+2	2+67 (sim)	33+4	4+33 (sim)
11/19/2008	Aqwatec	< 10	—	< 10	< 10	< 10	—	< 10	< 10	< 10	—	< 10	—
12/2/2008	Aqwatec	< 10	—	< 10	< 10	< 10	—	—	—	< 10	< 10	< 10	< 10
1/13/2009	Aqwatec	< 10	—	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10

Note. Dashes indicate that data were not taken.

Table F22. DEET Levels (ng/L) in Pilot-Scale Experiments With UV Max G Reactors and Open Channel Chlorine Contactors

Date	Lab	Initial Influent	Final Influent	33 mJ/cm^2	67 mJ/cm^2	100 mJ/cm^2	2 mg/L	4 mg/L	6 mg/L	67+2	2+67 (sim)	33+4	4+33 (sim)
12/2/2008	SJCWQL	60	23	32	62	21	—	—	—	57	41	21	21
12/9/2008	SJCWQL	67	23	41	66	65	—	—	—	62	55	34	25
1/21/2009	SJCWQL	65	31	57	67	65	74	62	45	64	60	51	36
1/27/2009	SJCWQL	82	28	88	—	—	61	41	30	—	—	61	40
1/29/2009	SJCWQL	38	14	—	—	35	39	27	17	—	—	—	—

Note. Dashes indicate that data were not taken.

Table F23. Dichlorprop Levels (ng/L) in Pilot-Scale Experiments With UV Max G Reactors and Open Channel Chlorine Contactors

Date	Lab	Initial Influent	Final Influent	33 mJ/cm^2	67 mJ/cm^2	100 mJ/cm^2	2 mg/L	4 mg/L	6 mg/L	67+2	2+67 (sim)	33+4	4+33 (sim)
11/19/2008	Aqwatec	< 10	—	< 10	< 10	< 10	—	< 10	< 10	< 10	—	< 10	—
12/2/2008	Aqwatec	< 10	—	< 10	< 10	< 10	—	—	—	< 10	< 10	< 10	< 10
1/13/2009	Aqwatec	< 10	—	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10

Note. Dashes indicate that data were not taken.

Table F24. Diclofenac Levels (ng/L) in Pilot-Scale Experiments With UV Max G Reactors and Open Channel Chlorine Contactors

Date	Lab	Initial Influent	Final Influent	33 mJ/cm^2	67 mJ/cm^2	100 mJ/cm^2	2 mg/L	4 mg/L	6 mg/L	67+2	2+67 (sim)	33+4	4+33 (sim)
11/19/2008	Aqwatec	23	—	31	25	13	—	<10	<10	19	—	<10	—
12/2/2008	Aqwatec	<10	—	<10	<10	<10	—	—	—	<10	<10		<10
12/2/2008	SJCWQL	122	94	150	105	54	—	—	—	73	72	25	20
12/9/2008	SJCWQL	87	88	47	23	16	—	—	—	17	22	11	31
1/13/2009	Aqwatec	133	—	104	93	63	106	52	<10	89	86	62	57
1/21/2009	SJCWQL	182	148	178	154	116	134	11	<10	122	81	53	<10
1/27/2009	SJCWQL	93	138	115	—	—	126	18	<10	—	—	39	22
1/29/2009	SJCWQL	97	109	—	—	81	124	10	<10	—	—	—	—

Note. Dashes indicate that data were not taken.

Table F25. Dilantin Levels (ng/L) in Pilot-Scale Experiments With UV Max G Reactors and Open Channel Chlorine Contactors

Date	Lab	Initial Influent	Final Influent	33 mJ/cm^2	67 mJ/cm^2	100 mJ/cm^2	2 mg/L	4 mg/L	6 mg/L	67+2	2+67 (sim)	33+4	4+33 (sim)
12/2/2008	SJCWQL	152	186	263	155	166	—	—	—	157	110	177	137
12/9/2008	SJCWQL	287	184	228	269	181	—	—	—	207	126	178	177
1/21/2009	SJCWQL	151	146	152	148	146	174	120	148	225	129	192	127
1/27/2009	SJCWQL	197	179	288	—	—	—	158	164	—	—	242	125
1/29/2009	SJCWQL	175	197	—	—	137	193	179	246	—	—	—	—

Note. Dashes indicate that data were not taken.

Table F26. Erythromycin[-H_2O] Levels (ng/L) in Pilot-Scale Experiments With UV Max G Reactors and Open Channel Chlorine Contactors

Date	Lab	Initial Influent	Final Influent	33 mJ/cm^2	67 mJ/cm^2	100 mJ/cm^2	2 mg/L	4 mg/L	6 mg/L	67+2	2+67 (sim)	33+4	4+33 (sim)
12/2/2008	SJCWQL	129	104	106	131	102	—	—	—	136	116	73	83
12/9/2008	SJCWQL	161	118	140	147	156	—	—	—	155	135	98	103
1/21/2009	SJCWQL	211	165	200	217	214	178	123	33	219	234	154	117
1/27/2009	SJCWQL	165	154	176	—	—	163	115	30	—	—	147	123
1/29/2009	SJCWQL	180	161	—	—	204	203	102	17	—	—	—	—

Note. Dashes indicate that data were not taken.

Table F27. Estrone Levels (ng/L) in Pilot-Scale Experiments With UV Max G Reactors and Open Channel Chlorine Contactors

Date	Lab	Initial Influent	Final Influent	33 mJ/cm^2	67 mJ/cm^2	100 mJ/cm^2	2 mg/L	4 mg/L	6 mg/L	67+2	2+67 (sim)	33+4	4+33 (sim)
11/18/2008	SJCWQL	11.7	8.2	9.4	8.2	8.3	5.3	—	< 2	4.2	—	2.1	—
12/2/2008	SJCWQL	7.2	7.8	5.6	4.8	5.0	—	—	—	5.6	4.3	< 2	< 2
12/9/2008	SJCWQL	10.6	7.1	6.8	8.8	9.1	—	—	—	7.6	6.2	< 2	< 2
1/13/2009	SJCWQL	6.9	7.6	4.1	4.4	6.3	3.8	< 2	< 2	3.2	2.9	< 2	< 2
1/21/2009	SJCWQL	9.7	6.5	3.3	6.9	7.7	4.3	2.3	< 2	6.2	6.3	< 2	< 2
1/27/2009	SJCWQL	6.6	5.0	6.4	—	—	5.2	< 2	< 2	—	—	< 2	< 2
1/29/2009	SJCWQL	4.5	7.3	—	10.6	3.7	—	—	—	2.8	3.2	—	—

Note. Dashes indicate that data were not taken.

Table F28. Fenofibrate Levels (ng/L) in Pilot-Scale Experiments With UV Max G Reactors and Open Channel Chlorine Contactors

Date	Lab	Initial Influent	Final Influent	33 mJ/cm^2	67 mJ/cm^2	100 mJ/cm^2	2 mg/L	4 mg/L	6 mg/L	67+2	2+67 (sim)	33+4	4+33 (sim)
11/19/2008	Aqwatec	< 50	—	< 50	< 50	< 50	—	< 50	< 50	< 50	—	< 50	—
12/2/2008	Aqwatec	< 50	—	< 50	< 50	< 50	—	—	—	< 50	< 50	< 50	< 50
1/13/2009	Aqwatec	< 50	—	< 50	< 50	< 50	< 50	< 50	< 50	< 50	< 50	< 50	< 50

Note. Dashes indicate that data were not taken.

Table F29. Fluoxetine Levels (ng/L) in Pilot-Scale Experiments With UV Max G Reactors and Open Channel Chlorine Contactors

Date	Lab	Initial Influent	Final Influent	33 mJ/cm^2	67 mJ/cm^2	100 mJ/cm^2	2 mg/L	4 mg/L	6 mg/L	67+2	2+67 (sim)	33+4	4+33 (sim)
12/2/2008	SJCWQL	28	27	22	20	19	—	—	—	22	18	18	22
12/9/2008	SJCWQL	30	25	30	23	23	—	—	—	24	20	21	21
1/21/2009	SJCWQL	36	33	30	39	35	35	43	31	37	25	31	30
1/27/2009	SJCWQL	34	34	35	—	—	35	29	26	—	—	32	28
1/29/2009	SJCWQL	40	39	—	—	37	41	34	36	—	—	—	—

Note. Dashes indicate that data were not taken.

Table F30. Furosemide Levels (ng/L) in Pilot-Scale Experiments With UV Max G Reactors and Open Channel Chlorine Contactors

Date	Lab	Initial Influent	Final Influent	33 mJ/cm^2	67 mJ/cm^2	100 mJ/cm^2	2 mg/L	4 mg/L	6 mg/L	67+2	2+67 (sim)	33+4	4+33 (sim)
12/2/2008	SJCWQL	485	189	259	426	167	—	—	—	354	181	37	20
12/9/2008	SJCWQL	702	310	467	696	647	—	—	—	553	449	114	101
1/21/2009	SJCWQL	754	426	598	728	687	445	108	60	640	404	114	46
1/27/2009	SJCWQL	540	268	470	—	—	386	53	31	—	—	100	45
1/29/2009	SJCWQL	579	260	—	—	495	494	61	27	—	—	—	—

Note. Dashes indicate that data were not taken.

Table F31. Gemfibrozil Levels (ng/L) in Pilot-Scale Experiments With UV Max G Reactors and Open Channel Chlorine Contactors

Date	Lab	Initial Influent	Final Influent	33 mJ/cm^2	67 mJ/cm^2	100 mJ/cm^2	2 mg/L	4 mg/L	6 mg/L	67+2	2+67 (sim)	33+4	4+33 (sim)
11/19/2008	Aqwatec	<25	—	<25	<25	<25	—	<25	<25	<25	—	<25	—
12/2/2008	Aqwatec	<25	—	<25	<25	<25	—	—	—	<25	<25		<25
12/2/2008	SJCWQL	62	28	30	57	30	—	—	—	53	32	<20	<20
12/9/2008	SJCWQL	204	38	103	207	212	—	—	—	187	131	69	38
1/13/2009	Aqwatec	63	—	<25	75	72	52	<25	<25	73	<25	<25	43
1/21/2009	SJCWQL	136	26	70	124	154	122	74	35	136	79	62	27
1/27/2009	SJCWQL	67	<20	61	—	—	44	20	<20	—	—	80	<20
1/29/2009	SJCWQL	180	56	—	—	197	161	84	36	—	—	—	—

Note. Dashes indicate that data were not taken.

Table F32. Ibuprofen Levels (ng/L) in Pilot-Scale Experiments With UV Max G Reactors and Open Channel Chlorine Contactors

Date	Lab	Initial Influent	Final Influent	33 mJ/cm^2	67 mJ/cm^2	100 mJ/cm^2	2 mg/L	4 mg/L	6 mg/L	67+2	2+67 (sim)	33+4	4+33 (sim)
11/19/2008	Aqwatec	< 10	—	< 10	< 10	< 10	—	< 10	< 10	< 10	—	< 10	—
12/2/2008	Aqwatec	< 10	—	< 10	< 10	< 10	—	—	—	< 10	< 10	< 10	< 10
12/2/2008	SJCWQL	< 10	< 10	< 10	< 10	< 10	—	—	—	< 10	< 10	< 10	< 10
12/9/2008	SJCWQL	< 10	< 10	< 10	< 10	< 10	—	—	—	< 10	< 10	< 10	< 10
1/13/2009	Aqwatec	< 10	—	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10
1/21/2009	SJCWQL	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10
1/27/2009	SJCWQL	< 10	< 10	< 10	—	—	< 10	< 10	< 10	—	—	< 10	< 10
1/29/2009	SJCWQL	< 10	< 10	—	—	< 10	< 10	< 10	< 10	—	—	—	—

Note. Dashes indicate that data were not taken.

Table F33. Iopromide Levels (ng/L) in Pilot-Scale Experiments With UV Max G Reactors and Open Channel Chlorine Contactors

Date	Lab	Initial Influent	Final Influent	33 mJ/cm^2	67 mJ/cm^2	100 mJ/cm^2	2 mg/L	4 mg/L	6 mg/L	67+2	2+67 (sim)	33+4	4+33 (sim)
12/2/2008	SJCWQL	561	443	377	385	221	—	—	—	372	321	340	219
12/9/2008	SJCWQL	302	263	247	198	155	—	—	—	203	204	217	146
1/21/2009	SJCWQL	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30
1/27/2009	SJCWQL	256	182	215	—	—	223	194	200	—	—	193	116
1/29/2009	SJCWQL	35	71	—	—	<30[a]	37	<30	<30	—	—	—	—

Note. Dashes indicate that data were not taken.

[a]This data point was ignored because the calculated influent value was very close to the reporting limit, so the calculated removal was low.

Table F34. Ketoprofen Levels (ng/L) in Pilot-Scale Experiments With UV Max G Reactors and Open Channel Chlorine Contactors

Date	Lab	Initial Influent	Final Influent	33 mJ/cm^2	67 mJ/cm^2	100 mJ/cm^2	2 mg/L	4 mg/L	6 mg/L	67+2	2+67 (sim)	33+4	4+33 (sim)
11/19/2008	Aqwatec	< 25	—	< 25	< 25	< 25	—	< 25	< 25	< 25	—	< 25	—
12/2/2008	Aqwatec	< 25	—	< 25	< 25	< 25	—	—	—	< 25	< 25	< 25	< 25
12/2/2008	SJCWQL	< 10	< 10	< 10	< 10	< 10	—	—	—	< 10	< 10	< 10	< 10
12/9/2008	SJCWQL	< 10	< 10	< 10	< 10	< 10	—	—	—	< 10	< 10	< 10	< 10
1/13/2009	Aqwatec	< 25	—	< 25	< 25	< 25	< 25	< 25	< 25	< 25	< 25	< 25	< 25
1/21/2009	SJCWQL	< 25	< 25	< 25	< 25	< 25	< 25	< 25	< 25	< 25	< 25	< 25	< 25
1/27/2009	SJCWQL	< 25	< 25	< 25	—	—	< 25	< 25	< 25	—	—	< 25	< 25
1/29/2009	SJCWQL	< 25	< 25	—	—	< 25	< 25	< 25	< 25	—	—	—	—

Note. Dashes indicate that data were not taken.

Table F35. Mecoprop Levels (ng/L) in Pilot-Scale Experiments With UV Max G Reactors and Open Channel Chlorine Contactors

Date	Lab	Initial Influent	Final Influent	33 mJ/cm^2	67 mJ/cm^2	100 mJ/cm^2	2 mg/L	4 mg/L	6 mg/L	67+2	2+67 (sim)	33+4	4+33 (sim)
11/19/2008	Aqwatec	< 10	—	< 10	< 10	< 10	—	< 10	< 10	< 10	—	< 10	—
12/2/2008	Aqwatec	< 10	—	< 10	< 10	< 10	—	—	—	< 10	< 10	< 10	< 10
1/13/2009	Aqwatec	< 10	—	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10

Note. Dashes indicate that data were not taken.

Table F36. Metoprolol Levels (ng/L) in Pilot-Scale Experiments With UV Max G Reactors and Open Channel Chlorine Contactors

Date	Lab	Initial Influent	Final Influent	33 mJ/cm^2	67 mJ/cm^2	100 mJ/cm^2	2 mg/L	4 mg/L	6 mg/L	67+2	2+67 (sim)	33+4	4+33 (sim)
12/2/2008	SJCWQL	686	536	566	678	534	—	—	—	657	515	534	478
12/9/2008	SJCWQL	783	598	695	745	774	—	—	—	760	584	589	510
1/21/2009	SJCWQL	716	576	685	714	706	688	612	598	737	547	607	481
1/27/2009	SJCWQL	596	439	634	—	—	649	470	428	—	—	576	425
1/29/2009	SJCWQL	682	548	—	—	674	618	548	518	—	—	—	—

Note. Dashes indicate that data were not taken.

Table F37. Naproxen Levels (ng/L) in Pilot-Scale Experiments With UV Max G Reactors and Open Channel Chlorine Contactors

Date	Lab	Initial Influent	Final Influent	33 mJ/cm^2	67 mJ/cm^2	100 mJ/cm^2	2 mg/L	4 mg/L	6 mg/L	67+2	2+67 (sim)	33+4	4+33 (sim)
11/19/2008	Aqwatec	< 10	—	< 10	< 10	< 10	—	< 10	< 10	< 10	—	< 10	—
12/2/2008	Aqwatec	< 10	—	< 10	< 10	< 10	—	—	—	< 10	< 10	< 10	< 10
12/2/2008	SJCWQL	12	< 10	< 10	< 10	< 10	—	—	—	< 10	< 10	< 10	< 10
12/9/2008	SJCWQL	22	< 10	13	19	20	—	—	—	18	14	< 10	< 10
1/13/2009	Aqwatec	< 10	—	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10
1/21/2009	SJCWQL	< 10	< 10	11	15	15	17	< 10	< 10	17	< 10	< 10	< 10
1/27/2009	SJCWQL	< 10	< 10	< 10	—	—	< 10	< 10	< 10	—	—	< 10	< 10
1/29/2009	SJCWQL	< 10	< 10	—	—	< 10	< 10	< 10	< 10	—	—	—	—

Note. Dashes indicate that data were not taken.

Table F38. Nonylphenol Levels (ng/L) in Pilot-Scale Experiments With UV Max G Reactors and Open Channel Chlorine Contactors

Date	Lab	Initial Influent	Final Influent	33 mJ/cm^2	67 mJ/cm^2	100 mJ/cm^2	2 mg/L	4 mg/L	6 mg/L	67+2	2+67 (sim)	33+4	4+33 (sim)
11/18/2008	SJCWQL	116	98	134	167	161	67	—	63	188	—	39	—
12/2/2008	SJCWQL	144	102	140	182	152	—	—	—	185	235	57	67
12/9/2008	SJCWQL	254	189	238	289	307	—	—	—	292	284	61	109
1/13/2009	SJCWQL	230	—	219	315	372	178	122	250	415	230	149	105
1/21/2009	SJCWQL	176	157	101	339	293	142	95	112	228	319	101	108
1/27/2009	SJCWQL	223	209	225	—	—	200	98	126	—	—	103	118
1/29/2009	SJCWQL	167	145	—	216	316	—	—	—	201	272	—	—

Note. Dashes indicate that data were not taken.

Table F39. Octylphenol Levels (ng/L) in Pilot-Scale Experiments With UV Max G Reactors and Open Channel Chlorine Contactors

Date	Lab	Initial Influent	Final Influent	33 mJ/cm^2	67 mJ/cm^2	100 mJ/cm^2	2 mg/L	4 mg/L	6 mg/L	67+2	2+67 (sim)	33+4	4+33 (sim)
11/18/2008	SJCWQL	12	12	15	21	24	7	—	< 5	20	—	< 5	—
12/2/2008	SJCWQL	10	6	9	23	10	—	—	—	19	22	< 5	5
12/9/2008	SJCWQL	22	10	20	37	42	—	—	—	33	29	< 5	8
1/13/2009	SJCWQL	19	—	15	29	40	15	5	< 5	26	22	< 5	< 5
1/21/2009	SJCWQL	18	11	10	35	43	14	< 5	< 5	30	32	6	< 5
1/27/2009	SJCWQL	12	8	18	—	—	11	< 5	< 5	—	—	< 5	< 5
1/29/2009	SJCWQL	11	7	—	14	22	—	—	—	11	17	—	—

Note. Dashes indicate that data were not taken.

Table F40. Phenacetine Levels (ng/L) in Pilot-Scale Experiments With UV Max G Reactors and Open Channel Chlorine Contactors

Date	Lab	Initial Influent	Final Influent	33 mJ/cm^2	67 mJ/cm^2	100 mJ/cm^2	2 mg/L	4 mg/L	6 mg/L	67+2	2+67 (sim)	33+4	4+33 (sim)
11/19/2008	Aqwatec	< 50	—	< 50	< 50	< 50	—	< 50	< 50	< 50	—	< 50	—
12/2/2008	Aqwatec	< 50	—	< 50	< 50	< 50	—	—	—	< 50	< 50	< 50	< 50
1/13/2009	Aqwatec	< 50	—	< 50	< 50	< 50	< 50	< 50	< 50	< 50	< 50	< 50	< 50

Note. Dashes indicate that data were not taken.

Table F41. Primidone Levels (ng/L) in Pilot-Scale Experiments With UV Max G Reactors and Open Channel Chlorine Contactors

Date	Lab	Initial Influent	Final Influent	33 mJ/cm^2	67 mJ/cm^2	100 mJ/cm^2	2 mg/L	4 mg/L	6 mg/L	67+2	2+67 (sim)	33+4	4+33 (sim)
11/19/2008	Aqwatec	249	—	128	230	240	—	200	234	222	—	222	—
12/2/2008	Aqwatec	201	—	220	214	216	—	—	—	183	288	197	199
12/2/2008	SJCWQL	194	164	169	175	181	—	—	—	185	190	165	161
12/9/2008	SJCWQL	188	155	142	162	158	—	—	—	154	167	151	154
1/13/2009	Aqwatec	169	—	164	175	181	163	178	186	169	154	167	161
1/21/2009	SJCWQL	187	163	187	194	213	187	190	184	215	191	192	163
1/27/2009	SJCWQL	214	187	201	—	—	174	172	182	—	—	185	179
1/29/2009	SJCWQL	168	182	—	—	205	193	227	166	—	—	—	—

Note. Dashes indicate that data were not taken.

Table F42. Propranolol Levels (ng/L) in Pilot-Scale Experiments With UV Max G Reactors and Open Channel Chlorine Contactors

Date	Lab	Initial Influent	Final Influent	33 mJ/cm^2	67 mJ/cm^2	100 mJ/cm^2	2 mg/L	4 mg/L	6 mg/L	67+2	2+67 (sim)	33+4	4+33 (sim)
12/2/2008	SJCWQL	47	48	51	46	42	—	—	—	40	23	27	21
12/9/2008	SJCWQL	51	53	52	46	48	—	—	—	45	25	43	32
1/21/2009	SJCWQL	52	53	49	52	53	45	34	22	48	28	36	23
1/27/2009	SJCWQL	36	42	39	—	—	32	33	<10	—	—	30	24
1/29/2009	SJCWQL	44	47	—	—	44	44	32	22	—	—	—	—

Note. Dashes indicate that data were not taken.

Table F43. Salicylic Acid Levels (ng/L) in Pilot-Scale Experiments With UV Max G Reactors and Open Channel Chlorine Contactors

Date	Lab	Initial Influent	Final Influent	33 mJ/cm^2	67 mJ/cm^2	100 mJ/cm^2	2 mg/L	4 mg/L	6 mg/L	67+2	2+67 (sim)	33+4	4+33 (sim)
11/19/2008	Aqwatec	18	—	30	< 10	31	—	35	45	32	—	29	—
12/2/2008	Aqwatec	< 10	—	< 10	< 10	< 10	—	—	—	< 10	< 10	< 10	< 10
1/13/2009	Aqwatec	< 10	—	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10

Note. Dashes indicate that data were not taken.

Table F44. Simvastatin OH Acid Levels (ng/L) in Pilot-Scale Experiments With UV Max G Reactors and Open Channel Chlorine Contactors

Date	Lab	Initial Influent	Final Influent	33 mJ/cm^2	67 mJ/cm^2	100 mJ/cm^2	2 mg/L	4 mg/L	6 mg/L	67+2	2+67 (sim)	33+4	4+33 (sim)
12/2/2008	SJCWQL	< 10	< 10	< 10	< 10	< 10	—	—	—	< 10	< 10	< 10	< 10
12/9/2008	SJCWQL	< 10	< 10	< 10	< 10	< 10	—	—	—	< 10	< 10	< 10	< 10
1/21/2009	SJCWQL	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10
1/27/2009	SJCWQL	< 10	< 10	< 10	—	—	< 10	< 10	< 10	—	—	< 10	< 10
1/29/2009	SJCWQL	< 10	< 10	—	—	< 10	< 10	< 10	< 10	—	—	—	—

Note. Dashes indicate that data were not taken.

Table F45. Sulfamethoxazole Levels (ng/L) in Pilot-Scale Experiments With UV Max G Reactors and Open Channel Chlorine Contactors

Date	Lab	Initial Influent	Final Influent	33 mJ/cm^2	67 mJ/cm^2	100 mJ/cm^2	2 mg/L	4 mg/L	6 mg/L	67+2	2+67 (sim)	33+4	4+33 (sim)
12/2/2008	SJCWQL	1320	1050	931	1090	509	—	—	—	982	1010	89	180
12/9/2008	SJCWQL	1630	1260	1290	1300	1200	—	—	—	1320	1440	167	530
1/21/2009	SJCWQL	1590	1190	1410	1290	1140	997	38	30	1230	1250	90	67
1/27/2009	SJCWQL	2300	1590	2170	—	—	1370	61	44	—	—	197	184
1/29/2009	SJCWQL	1570	1524	—	—	1270	1490	50	21	—	—	—	—

Note. Dashes indicate that data were not taken.

Table F46. TCEP Levels (ng/L) in Pilot-Scale Experiments With UV Max G Reactors and Open Channel Chlorine Contactors

Date	Lab	Initial Influent	Final Influent	33 mJ/cm^2	67 mJ/cm^2	100 mJ/cm^2	2 mg/L	4 mg/L	6 mg/L	67+2	2+67 (sim)	33+4	4+33 (sim)
11/19/2008	Aqwatec	228	—	242	246	242	—	214	232	229	—	186	—
12/2/2008	Aqwatec	479	—	612	597	569	—	—	—	449	402	438	430
12/2/2008	SJCWQL	482	485	435	480	435	—	—	—	576	417	450	453
12/9/2008	SJCWQL	502	469	529	503	537	—	—	—	559	520	576	619
1/13/2009	Aqwatec	840	—	892	997	915	858	986	805	916	893	823	838
1/21/2009	SJCWQL	348	457	400	312	317	450	400	346	449	375	403	403
1/27/2009	SJCWQL	319	429	346	—	—	494	441	328	—	—	381	405
1/29/2009	SJCWQL	318	308.6	—	—	367	348	360	320	—	—	—	—

Note. Dashes indicate that data were not taken.

Table F47. TCPP Levels (ng/L) in Pilot-Scale Experiments With UV Max G Reactors and Open Channel Chlorine Contactors

Date	Lab	Initial Influent	Final Influent	33 mJ/cm^2	67 mJ/cm^2	100 mJ/cm^2	2 mg/L	4 mg/L	6 mg/L	67+2	2+67 (sim)	33+4	4+33 (sim)
11/19/2008	Aqwatec	1170	—	1260	1140	1210	—	1100	1170	1290	—	1000	—
12/2/2008	Aqwatec	2710	—	2330	2470	2270	—	—	—	2840	2710	2430	2700
1/13/2009	Aqwatec	2910	—	2460	1960	3260	2900	2970	2160	3200	3000	2910	3005

Note. Dashes indicate that data were not taken.

Table F48. TDCPP Levels (ng/L) in Pilot-Scale Experiments With UV Max G Reactors and Open Channel Chlorine Contactors

Date	Lab	Initial Influent	Final Influent	33 mJ/cm^2	67 mJ/cm^2	100 mJ/cm^2	2 mg/L	4 mg/L	6 mg/L	67+2	2+67 (sim)	33+4	4+33 (sim)
11/19/2008	Aqwatec	362	—	375	284	355	—	327	361	341	—	311	—
12/2/2008	Aqwatec	539	—	734	715	754	—	—	—	606	556	602	553
1/13/2009	Aqwatec	806	—	895	1027	880	961	1018	871	954	844	846	882

Note. Dashes indicate that data were not taken.

Table F49. Triclocarban Levels (ng/L) in Pilot-Scale Experiments With UV Max G Reactors and Open Channel Chlorine Contactors

Date	Lab	Initial Influent	Final Influent	33 mJ/cm^2	67 mJ/cm^2	100 mJ/cm^2	2 mg/L	4 mg/L	6 mg/L	67+2	2+67 (sim)	33+4	4+33 (sim)
12/2/2008	SJCWQL	300	283	225	202	162	—	—	—	211	188	218	211
12/9/2008	SJCWQL	275	272	243	206	177	—	—	—	201	194	220	214
1/21/2009	SJCWQL	288	284	239	218	200	284	270	238	223	209	231	216
1/27/2009	SJCWQL	212	226	188	—	—	202	201	184	—	—	188	182
1/29/2009	SJCWQL	239	253	—	—	169	242	226	211	—	—	—	—

Note. Dashes indicate that data were not taken.

Table F50. Triclosan Levels (ng/L) in Pilot-Scale Experiments With UV Max G Reactors and Open Channel Chlorine Contactors

Date	Lab	Initial Influent	Final Influent	33 mJ/cm^2	67 mJ/cm^2	100 mJ/cm^2	2 mg/L	4 mg/L	6 mg/L	67+2	2+67 (sim)	33+4	4+33 (sim)
12/2/2008	SJCWQL	87	73	63	51	35	—	—	—	< 25	< 25	< 25	< 25
12/9/2008	SJCWQL	104	81	80	61	50	—	—	—	20	27	<10	<10
1/21/2009	SJCWQL	90	94	80	64	56	<25	34	36	<25	48	52	34
1/27/2009	SJCWQL	105	86	89	—	—	34	<25	<25	—	—	<25	<25
1/29/2009	SJCWQL	110	96	—	—	66	26	<25	<25	—	—	—	—

Note. Dashes indicate that data were not taken.

Table F51. Trimethoprim Levels (ng/L) in Pilot-Scale Experiments With UV Max G Reactors and Open Channel Chlorine Contactors

Date	Lab	Initial Influent	Final Influent	33 mJ/cm^2	67 mJ/cm^2	100 mJ/cm^2	2 mg/L	4 mg/L	6 mg/L	67+2	2+67 (sim)	33+4	4+33 (sim)
12/2/2008	SJCWQL	73	31	43	73	34	—	—	—	61	47	<10	<10
12/9/2008	SJCWQL	108	57	82	100	107	—	—	—	84	87	<10	15
1/21/2009	SJCWQL	215	147	190	206	218	107	<10	<10	171	183	<10	<10
1/27/2009	SJCWQL	256	154	265	—	—	283	<10	<10	—	—	14	<10
1/29/2009	SJCWQL	224	125	—	—	227	176	<10	<10	—	—	—	—

Note. Dashes indicate that data were not taken.

Table F52. *P*-Values for Removals With UV-only or Chlorine-only Doses

	33 mJ/cm^2	67 mJ/cm^2	100 mJ/cm^2	2 mg/L Cl_2	4 mg/L Cl_2	6 mg/L Cl_2
Atenolol	0.63	0.72	0.31	0.25	0.84	0.58
Azithromycin	0.24	0.64	0.44	0.50	0.02	<0.01
Carbamazepine	0.37	0.96	0.79	0.10	0.54	0.57
DEET	0.88	0.16	0.11	0.46	0.89	0.78
Diclofenac	0.65	0.15	<0.01	0.94	<0.01	<0.01
Dilantin	0.18	0.51	0.09	0.20	0.15	0.60
Erythromycin[-H_2O]	0.62	0.86	0.56	0.82	0.01	<0.01
Estrone	0.02	<0.01	0.02	0.02	<0.01	<0.01
Fluoxetine	0.48	0.34	0.09	0.21	0.93	0.12
Furosemide	0.27	0.44	<0.01	0.11	<0.01	<0.01
Gemfibrozil	0.11	0.68	<0.01	0.63	0.06	0.04
Iopromide	0.04	0.03	0.01	0.03	0.36	0.60
Metoprolol	0.53	0.39	0.08	0.62	0.12	0.22
Nonylphenol	0.96	0.01	<0.01	0.03	<0.01	0.12
Octylphenol	0.39	<0.01	<0.01	0.14	0.01	<0.01
Primidone	0.28	0.47	0.25	0.95	0.78	0.84
Propranolol	0.53	0.35	0.28	0.16	0.04	0.01
Sulfamethoxazole	0.22	<0.01	0.02	0.13	<0.01	<0.01
TCEP	0.20	0.28	0.26	0.13	0.19	0.19
TCPP	0.43	0.25	0.98	NA	0.71	0.50
TDCPP	0.23	0.53	0.34	NA	0.72	0.52
Triclocarban	0.01	<0.01	<0.01	0.39	0.02	<0.01
Triclosan	<0.01	0.01	<0.01	<0.01	<0.01	<0.01
Trimethoprim	0.98	0.21	0.20	0.58	<0.01	<0.01

Note. Null hypothesis was that the average removal values equaled zero. NA indicates that *P*-values could not be calculated for TCPP and TDCPP at a dose of 2 mg/L of free chlorine because only one effluent sample was taken.

Table F53. *P*-Values for Removals With Combined UV/Chlorine Doses

	67+2	2+67 (Sim)	33+4	4+33 (Sim)
Atenolol	0.05	0.05	0.73	0.01
Azithromycin	0.21	0.25	0.02	0.07
Carbamazepine	0.81	0.07	0.89	0.73
DEET	0.05	0.41	0.76	0.50
Diclofenac	0.02	0.01	<0.01	<0.01
Dilantin	0.70	0.09	0.42	0.05
Erythromycin[-H_2O]	0.08	0.58	0.04	<0.01
Estrone	<0.01	<0.01	<0.01	<0.01
Fluoxetine	0.31	<0.01	0.08	<0.01
Furosemide	0.13	0.10	<0.01	<0.01
Gemfibrozil	0.15	0.24	0.63	<0.01
Iopromide	<0.01	0.09	0.02	<0.01
Metoprolol	0.28	<0.01	0.45	<0.01
Nonylphenol	<0.01	0.04	<0.01	<0.01
Octylphenol	<0.01	0.02	<0.01	0.01
Primidone	0.59	0.38	0.35	0.05
Propranolol	0.02	<0.01	0.02	<0.01
Sulfamethoxazole	0.02	0.19	<0.01	<0.01
TCEP	0.08	0.38	0.69	0.87
TCPP	0.04	0.50	0.19	0.57
TDCPP	0.37	0.12	0.92	0.33
Triclocarban	<0.01	<0.01	<0.01	<0.01
Triclosan	<0.01	0.01	<0.01	<0.01
Trimethoprim	0.03	0.63	<0.01	<0.01

Note. Null hypothesis was that the average removal values equaled zero.

Table F54. *P*-Values for Statistical Comparison of Removals at Doses of 2*67

	2+67(sim) vs 67	2+67(sim) vs 2	2+67(sim) vs Predicted	67+2 vs 67	67+2 vs 2	67+2 vs Predicted
Atenolol	0.02	0.01	0.01	0.28	0.82	0.43
Azithromycin	0.82	0.76	0.32	0.73	0.81	0.38
Carbamazepine	0.35	0.03	<0.01	0.91	0.11	0.07
DEET	0.53	0.97	0.77	0.07	0.90	0.47
Diclofenac	0.19	0.02	0.07	0.42	0.05	0.26
Dilantin	0.09	0.04	0.05	0.66	0.90	0.91
Erythromycin[-H_2O]	0.55	0.73	0.66	0.14	0.50	0.19
Estrone	0.29	0.59	0.17	0.33	0.67	0.10
Fluoxetine	0.30	<0.01	0.02	0.84	0.26	0.89
Furosemide	0.12	0.41	0.51	0.34	0.33	0.07
Gemfibrozil	0.20	0.37	0.28	0.30	0.17	0.11
Iopromide	0.98	0.11	0.54	0.39	<0.01	<0.01
Metoprolol	<0.01	0.10	<0.01	0.17	0.98	0.77
Nonylphenol	0.54	0.01	0.08	0.75	<0.01	0.01
Octylphenol	0.61	0.01	0.11	0.64	<0.01	0.05
Primidone	0.28	0.42	0.26	0.98	0.77	0.96
Propranolol	<0.01	0.01	<0.01	0.12	0.74	0.60
Sulfamethoxazole	0.19	0.26	<0.01	0.95	0.60	<0.01
TCEP	0.16	0.07	<0.01	0.72	0.40	0.01
TCPP	0.22	NA	0.08	0.12	NA	0.12
TDCPP	0.66	NA	0.24	0.83	NA	0.83
Triclocarban	0.43	<0.01	0.62	0.71	<0.01	0.28
Triclosan	0.05	0.36	0.31	<0.01	0.55	0.68
Trimethoprim	0.90	0.69	0.35	0.03	0.93	0.67

Note. Null hypothesis was that the average removals were the same for the two disinfection schemes. NA indicates that *P*-values could not be calculated for comparisons involving TCPP and TDCPP at a dose of 2 mg/L of free chlorine, because only one effluent sample was taken at this dose.

Table F55. *P*-Values for Statistical Comparison of Removals at Doses of 4*33

	4+33(sim) vs 33	4+33(sim) vs 4	4+33(sim) vs Predicted	33+4 vs 33	33+4 vs 4	33+4 vs Predicted
Atenolol	0.01	0.19	0.01	0.56	0.74	0.41
Azithromycin	0.03	0.09	0.12	0.01	0.03	<0.01
Carbamazepine	0.64	0.47	0.86	0.41	0.64	0.81
DEET	0.61	0.70	0.42	0.73	0.75	0.60
Diclofenac	<0.01	0.86	0.81	<0.01	0.31	0.32
Dilantin	<0.01	0.40	0.01	0.44	0.14	0.99
Erythromycin[-H_2O]	<0.01	0.07	0.03	0.02	0.10	0.11
Estrone	<0.01	0.65	0.28	<0.01	0.23	0.89
Fluoxetine	0.19	0.39	0.18	0.23	0.36	0.26
Furosemide	<0.01	0.92	0.74	<0.01	0.13	0.08
Gemfibrozil	0.70	0.52	0.02	0.64	0.32	0.14
Iopromide	<0.01	0.33	0.12	0.43	0.99	0.07
Metoprolol	0.01	0.15	<0.01	0.31	0.30	0.47
Nonylphenol	<0.01	0.29	0.26	<0.01	0.60	0.56
Octylphenol	0.01	0.20	0.49	<0.01	0.50	0.64
Primidone	0.48	0.55	0.49	0.50	0.56	0.56
Propranolol	<0.01	0.04	0.01	0.01	0.85	0.61
Sulfamethoxazole	<0.01	0.15	0.15	<0.01	0.01	0.01
TCEP	0.52	0.45	0.10	0.22	0.19	0.01
TCPP	0.37	0.55	0.14	0.91	0.37	0.88
TDCPP	0.39	0.92	0.18	0.27	0.75	0.17
Triclocarban	0.09	<0.01	0.74	0.36	0.01	0.37
Triclosan	<0.01	0.57	0.18	<0.01	0.46	0.38
Trimethoprim	<0.01	0.17	0.34	<0.01	0.18	0.54

Note. Null hypothesis was that the average removals were the same for the two disinfection schemes.

Table F56. *P*-Values for Statistical Comparison of Removals for Simultaneous and UV-First Dosing

	2+67(sim) vs 67+2	4+33(sim) vs 33+4
Atenolol	0.03	0.01
Azithromycin	0.85	0.55
Carbamazepine	0.37	0.72
DEET	0.92	0.98
Diclofenac	0.53	0.35
Dilantin	0.19	0.07
Erythromycin[-H_2O]	0.90	0.80
Estrone	0.89	0.31
Fluoxetine	0.14	0.83
Furosemide	0.19	0.38
Gemfibrozil	0.10	0.48
Iopromide	0.75	0.01
Metoprolol	0.01	0.03
Nonylphenol	0.67	0.20
Octylphenol	0.42	0.38
Primidone	0.29	0.99
Propranolol	<0.01	0.05
Sulfamethoxazole	0.19	0.33
TCEP	0.06	0.71
TCPP	0.07	0.14
TDCPP	0.61	0.59
Triclocarban	0.24	0.29
Triclosan	0.26	0.64
Trimethoprim	0.40	0.60

Note. Null hypothesis was that the average removals were the same for the two disinfection schemes.

APPENDIX G

COMPARISON OF LABORATORY MEASUREMENTS OF TRACE ORGANIC CONSTITUENTS

FIGURES

In this study, TrOCs were measured by two laboratories: the Advanced Water Technology Center (Aqwatec, Golden, CO) or the Districts' San Jose Creek Water Quality Laboratory (SJCWQL, Whittier, CA). Samples analyzed by the SJCWQL were processed the same day or refrigerated overnight and processed the next day. Samples analyzed by Aqwatec were refrigerated overnight, packed in ice, shipped for next-day arrival, and on arrival, refrigerated until processed.

Of the 43 compounds analyzed during this project, 9 were analyzed by both laboratories (8 were measured only by Aqwatec, 26 were measured only by SJCWQL). On December 9, 2008, samples from the pilot experiment were sent to both laboratories for analysis. Four compounds (bisphenol A, ibuprofen, ketoprofen, and naproxen) were below reporting limits in all samples. Two compounds (diclofenac and gemfibrozil) were detected by SJCWQL but not by Aqwatec; this result may reflect sample degradation during shipping and handling, or may simply be due to variability in the measurement. The other three compounds (carbamazepine, primidone, and TCEP) were detected in all samples. Figure G1 compares the results from the two laboratories; measurements at the detection limit were assigned a value of the detection limit. Agreement was generally good between the two laboratories.

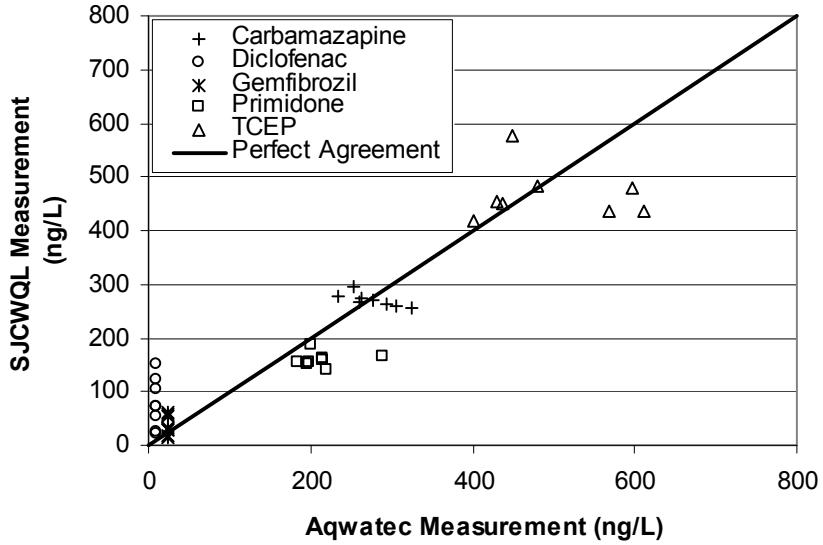

Figure G1. Comparison of TrOC measurements at SJCWQL and Aqwatec.

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WATEREUSE RESEARCH

1199 North Fairfax Street, Suite 410
Alexandria, VA 22314 USA
(703) 548-0880
Fax (703) 548-5085
E-mail: Foundation@WateReuse.org
www.WateReuse.org/Foundation