Formation and Fate of Chlorination Byproducts in Desalination Systems
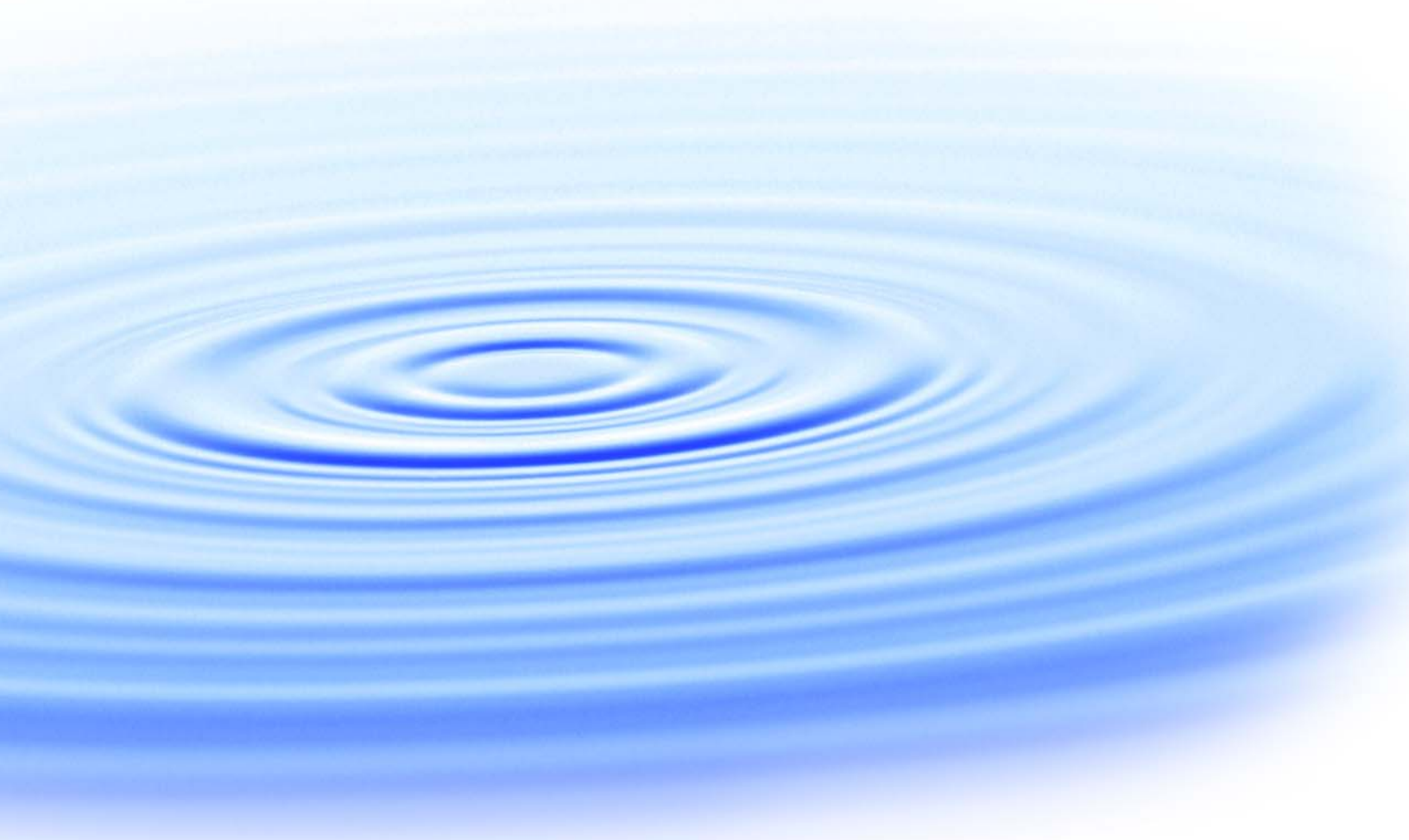
Formation and Fate of Chlorination Byproducts in Desalination Systems

About the WateReuse Foundation

The mission of the WateReuse 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 Southwest Florida Water Management District, 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.

Formation and Fate of Chlorination Byproducts in Desalination Systems

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ACRONYMS

BCAA   bromochloroacetic acid
BCAN   bromochloroacetonitrile
BDCAA   bromodichloroacetic acid
2-BP   2-bromophenol
C•t   chlorine dose contact time, in milligrams of Cl_2/L•minute
CDOM   chromophoric dissolved organic matter
DBP   disinfection byproduct
2,6-DBP   2,4-dibromophenol
DBAA   dibromoacetic acid
DBAN   dibromoacetonitrile
DBCAA   dibromochloroacetic acid
DCAA   dichloroacetic acid
DCAN   dichloroacetonitrile
di-HAN   dihaloacetonitrile
DOC   dissolved organic carbon
DPD   *N,N*-diethyl-*p*-phenylenediamine, indicator component
EBMUD   East Bay Municipal Utility District (CA)
ECD   electron capture detector
EC10   Exposure dose at which adverse effect is observed in 10% of the population
GC   gas chromatography
HAA5   sum of regulated haloacetic acids (5 species)
HAA9   sum of all haloacetic acids (9 species)
HAN   haloacetonitrile
HPLC   high-performance liquid chromatography
LC_{50} median lethal concentration
LLE   liquid-liquid extraction
LOQ   limit of quantitation
MBAA   monobromoacetic acid
2-MBP   2-monobromophenol
MCAA   monochloroacetic acid
MCL   maximum contaminant limit
MDL   method detection limit
MGD   millions of gallons per day
MS/MS   tandem mass spectrometry
MTBE   methyl *tert*-butyl ether
NOM   natural organic matter

OC	organic carbon
PTFE	polytetrafluoroethylene or Teflon®
RO	reverse osmosis
SPE	solid-phase extraction
$SUVA_{254}$	specific UV absorption at 254 nm
TAME	*tert*-amyl methyl ether
TBAA	tribromoacetic acid
2,4,6-TBP	2,4,6-tribromophenol
TCAA	trichloroacetic acid
THM	trihalomethane
THM4	sum of trihalomethanes
TOC	total organic carbon
UVA_{254}	UV absorption at 254 nm
v/v	volume per volume

FOREWORD

The WateReuse 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.

A Research 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:

- Definition and addressing of 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 Research 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 Southwest Florida Water Management District, 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.

This publication describes the results of a Foundation-sponsored research study. The main objective of this project was to assess the occurrence of contaminants of concern in water produced by desalination systems. The project also considers the potential impacts of these contaminants on human health in desalinated water and on aquatic organisms in waters that receive desalination concentrate.

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EXECUTIVE SUMMARY

The following list represents a summary of the key findings from experiments that were part of this project—including bench-scale seawater chlorination, pilot plant sampling, and a bench-scale blending study:

- Chlorine disinfection byproducts (DBPs) are produced when seawater is chlorinated under conditions used for desalination pretreatment. Concentrations of DBPs are normally below thresholds for ecological impacts in receiving waters. After dilution with ambient waters, as typically occurs in desalination plant outfalls, these compounds are unlikely to pose significant risks to aquatic organisms.

- The concentrations of DBPs produced during chlorine pretreatment of seawater exhibit temporal and spatial variation. The concentrations cannot be predicted readily by measurement of commonly used water quality parameters such as UV absorption and dissolved organic carbon. The highest production of DBPs was observed in seawater from tropical regions and in water influenced by terrestrial runoff.

- Low-molecular-weight and uncharged DBPs, such as chloroform and bromochloroacetonitrile, are not completely rejected by the desalination RO membranes. As a result, trihalomethanes and haloacetonitriles were detected in pilot plant RO permeate when chlorine pretreatment was used. In contrast, ionized compounds, such as haloacetic acids, were completely rejected. The concentrations of DBPs in desalinated water are considerably lower than those specified by applicable drinking water guidelines.

- Changes in the speciation and concentrations of DBPs produced when desalinated water is blended with surface water can be attributed to the increase in concentration of bromide and the decrease in organic DBP precursors that occur when surface water is blended with desalinated water. Upon blending, a higher proportion of brominated DBPs is produced. Overall, the total concentration of DBPs normally decreases because of dilution of the organic DBP precursors. However, the dilution can be less than predicted by simple volumetric averaging because the addition of bromide results in the production of HOBr, which is more reactive than HOCl.

CHAPTER 1

INTRODUCTION

Recent improvements in membrane technology have decreased the costs and technical challenges associated with reverse osmosis (RO) systems (Alspach and Watson, 2004). As a result, the worldwide capacity of seawater desalination systems approximately doubled between 1994 and 2004 (Cooley et al., 2006) and additional capacity is being planned in populated coastal areas in California, Spain, and Australia. Aside from the relatively high costs for power and concerns associated with RO concentrate (retentate) disposal, most utilities consider desalination to be a reliable technology with few impediments to implementation. In fact, the high quality of water produced by RO systems has been touted as an advantage of desalination plants relative to other water sources, such as wastewater effluent. Despite the widespread success of existing desalination plants and the excellent performance of RO membranes in removing salts and chemical contaminants, the large investments in desalination being contemplated by utilities around the world necessitate a careful examination of the potential occurrence of chemicals that pose human health or ecological risks in water produced by desalination systems.

RO membranes effectively remove most organic compounds from water, rejecting over 95% for dissolved organic carbon (DOC) and most chemical contaminants of regulatory concern (Bellona et al., 2004). However, incomplete removal has been reported for neutral, low-molecular-weight compounds. Such compounds are produced when seawater is chlorinated in intake structures or prior to filtration, and some of these compounds, such as trihalomethanes (THMs), pose human health risks. Furthermore, desalinated seawater is enriched in bromide relative to other anions. When product water from seawater desalination is blended with other water sources, the presence of elevated concentrations of bromide results in the formation of bromide-containing disinfection byproducts, such as bromate (following ozonation) and bromoform (following chlorination). Desalination plants discharge relatively large volumes of concentrate that contain substances rejected by the membranes that could pose risks to aquatic organisms in receiving waters. If organic contaminants are present in the discharge from desalination plants at concentrations that pose risks to aquatic organisms, additional dilution or treatment might be required.

The main objective of this project is to assess the occurrence of contaminants of concern in water produced by desalination systems. The project also considers the potential impacts of these contaminants on human health in desalinated water and on aquatic organisms in waters that receive desalination concentrate. The project includes a comprehensive review of chlorine disinfection byproducts in desalination systems; studies of their formation after chlorination of seawater from different locations; removal of chlorine disinfection byproducts in a pilot-scale seawater desalination system; and the formation of disinfection byproducts after chlorination of desalinated water, before and after blending with water from other sources.

CHAPTER 2

FORMATION, FATE, AND EFFECTS OF DISINFECTION BYPRODUCTS IN DESALINATION SYSTEMS

2.1 CONTAMINANTS OF CONCERN IN SEAWATER DESALINATION SYSTEMS

The construction of large numbers of seawater desalination systems that is likely to occur over the next few decades could have significant impacts on public health and aquatic ecosystems. While the potential impacts on aquatic habitat and greenhouse gas emissions from desalination plants are being considered as part of the debate on the merits of desalination (for example, Cooley et al., 2006; Dickie, 2007), issues related to water quality have received relatively little attention. To identify potential areas of concern and technologies that could be used to minimize adverse impacts, literature on chemical contaminants in seawater and desalination systems was reviewed.

Chemical contaminants of concern for desalination systems could originate in seawater. Such compounds would pose a concern if they passed through the RO treatment system or if their concentrations increased above levels of concern in the RO concentrate. With respect to compounds in seawater that pose risks to potable water supplies, a review of the literature did not reveal any anthropogenic compound or compound of marine origin that posed risks not already faced by managers of freshwater supplies. In fact, dissolved chemical contaminants of industrial origin tend to be present at relatively low concentrations in seawater compared to those encountered in freshwater (Dewulf and Van Langenhove, 1997). Compounds unique to seawater that might pose a risk to potable water supplies, such as algal toxins, are either charged or have molecular weights high enough to assure efficient removal in RO systems (Van Dolah et al., 2001; Carmichael, 2001). While chemical contaminants derived from seawater might be concentrated in RO retentate, most modern seawater desalination plants produce concentrate in which salt recovery is around 50% (Fritzmann et al., 2007) and therefore the concentration of such contaminants would increase by only a factor of around 2 during the desalination process. Under those conditions, the concentrations would likely decrease to their original values as the concentrate is diluted near the outfall. While it is conceivable that conditions occurring in the desalination plant could alter the form or bioavailability of contaminants (for example, by releasing algal toxins from intact cells during treatment), chemical contaminants from seawater were not investigated further in the project.

Chemicals added during the desalination process are another potential source of contaminants in product water or concentrate streams. In modern seawater desalination plants, coagulation and flocculation agents (for example, iron and aluminum salts), sulfuric acid, antiscaling agents, and membrane-cleaning agents are either added continuously or intermittently during the membrane cleaning process (Fritzmann et al., 2007). The environmental risks associated with the discharge of iron, aluminum and sulfate are generally assumed to be minimal in comparison to the risks linked to the discharge of salts in the desalination concentrate. The antiscaling agents and cleaning agents contain organic compounds, such as polycarbonic acids, phosphonates, and chelating agents (for example, EDTA). Assessment of the potential risks associated with these compounds suggests that they will not cause adverse impacts in

the receiving waters under conditions typically employed for seawater desalination facilities (Trieb, 2007). As a result of the modest nature of the anticipated risks and the availability of previous research, these issues were not investigated further.

A final source of chemical contaminants in seawater desalination systems is related to the formation of disinfection byproducts during the treatment process as oxidants or disinfectants are added to intake seawater. Chlorine is the oxidant that is most frequently used in desalination systems. It is added to seawater intakes either intermittently or continuously to prevent biofouling (Brehant et al., 2002). It is also added to seawater prior to filtration to increase filter run times and to control biofouling (Ali and Riley, 1989; Applegate et al., 1989; El Din et al., 2000; Khordagui, 1992). Additionally, chlorine is used to disinfect desalinated water and to provide a residual disinfectant in potable water distribution systems (Hafsi et al., 2004; Alsaleh and Alhaddad, 1994). Other oxidants, such as chlorine dioxide and chloramines, have been used for similar purposes in desalination plants, but they are currently employed to a lesser extent than chlorine is. As a result, the alternative disinfectants were not addressed as part of our study.

Each of these oxidants can generate disinfection byproducts when added to seawater or desalinated water. The disinfection byproducts identified as most relevant to seawater desalination systems are discussed in the following sections and in a review article derived from this research project (Agus et al., 2009). To obviate the need for chemical oxidants or disinfectants prior to RO, modern seawater desalination systems often employ strainers and microfilters that require only occasional treatment for biofouling control (Vedavyasan, 2007). While such systems are becoming increasingly popular, chlorination is routinely practiced in many existing desalination plants. Because new technologies that do not require chlorine may pose other constraints on desalination plants (for example, microfiltration systems are less effective in responding to episodes of elevated turbidity), the use of chemical oxidants in pretreatment is likely to remain attractive for future designs if they do not pose unacceptable environmental risks (Fritzmann et al., 2007).

2.2 CHLORINE DISINFECTION BYPRODUCTS

One can add chlorine to water, either as Cl_2, which disproportionates to form HOCl and Cl^- (reaction [1]), or as NaOCl, which dissociates to form OCl^- (reaction [2]). Both HOCl and its conjugate base, OCl^-, are produced (reaction [3]). Under conditions encountered in seawater (namely, pH = 8.1), OCl^- is the predominant form of Cl[I] present. When chlorine is added to natural waters, Cl[I] slowly disappears as it oxidizes reduced organic and inorganic constituents of the raw water. Some of the reactions with dissolved organic compounds result in the formation of toxic byproducts.

$$Cl_2 + H_2O = HOCl + H^+ + Cl^- \tag{1}$$

$$NaOCl = Na^+ + OCl^- \tag{2}$$

$$HOCl = H^+ + OCl^- \qquad K_a = 10^{-7.6} \tag{3}$$
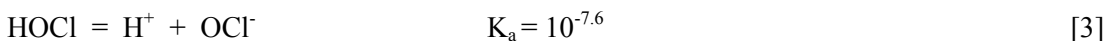
Many of the toxic chlorination byproducts contain chlorine substituents because Cl[I] undergoes electrophilic substitution reactions in which Cl replaces the H atom in an organic compound. However, some byproducts produced when chlorine is added to natural waters contain either bromine or iodine, depending on the halide anion concentrations in the source

water. The formation of brominated or iodinated byproducts attributable to the production of HOBr or HOI when Cl[I] reacts with Br⁻ or I⁻ (reactions [4] and [5]) follows:

$$HOCl + Br^- = HOBr + Cl^- \tag{4}$$

$$HOCl + I^- = HOI + Cl^- \tag{5}$$

With respect to their reactivity with organic compounds, Br[I] and I[I] tend to be more reactive than Cl[I]. Thus, waters that contain elevated concentrations of Br⁻ and I⁻ tend to yield higher concentrations of halogenated byproducts upon chlorination (Hua et al., 2006). For seawater desalination, this is a concern for two reasons. First, seawater contains about 65,000 μg of Br⁻/L, which is about 3 orders of magnitude higher than concentrations encountered in freshwater. As a result, chlorination of seawater results in the formation of relatively high concentrations of a suite of brominated compounds. Second, desalinated water produced by RO tends to be enriched in bromide relative to freshwater with similar dissolved-solid content. For example, desalinated water produced by RO desalination plants typically contains around 650 μg of Br⁻/L (Magara et al., 1996), whereas the median and 90th percentile Br- concentrations among all surface waters in the United States is around 12 and 35 mg/L, respectively (Obolensky and Singer, 2005). In fact, Br⁻ concentrations in desalinated seawater are comparable to some of the highest concentrations reported in potable water supplies (Agus et al., 2009). The potential formation of bromine-containing byproducts in seawater and desalinated water is discussed in the following sections.

The presence of iodide is less of a concern in seawater desalination systems because the concentration of iodide in seawater is usually much lower than that of bromide. In addition, the biogeochemistry of iodine is more dynamic, with formation and volatilization of I_2 and oxidation of I⁻ to IO_3^- depleting iodide ions in surface waters (Fuge and Johnson, 1986). As a result, iodinated byproducts are not expected to be present at elevated concentrations in chlorinated seawater intakes or desalinated waters. Furthermore, I⁻ is rejected more effectively during seawater RO than are bromide and chloride. Iodinated byproducts could be a concern when desalination technology is used to treat certain brackish waters, because some geologic deposits are enriched in iodide (Xu and Drewes, 2006).

2.2.1   THMs

THMs are a family of compounds that contain one carbon atom, one hydrogen atom, and three halogens. The formation of chloroform (namely, $CHCl_3$) in chlorinated surface waters was first reported in the 1970s (Rook, 1974). Later studies demonstrated the formation of bromoform ($CHBr_3$), iodoform (CHI_3), and THMs with different halogens (for example, $CHClBr_2$) in chlorinated surface waters (Hua et al., 2006; Krasner et al., 1996; Bichsel and von Gunten, 2000). The THMs have been the subject of numerous investigations over the past 30 years because they are among the most prominent of the identifiable disinfection byproducts and because they are known to cause adverse health effects. Several epidemiological studies have suggested a correlation between concentrations of THMs in drinking water and adverse reproductive outcomes (Nieuwenhuijsen et al., 2000; Hall et al., 1981). However, there is not a clear consensus on whether adverse health outcomes are attributed to the THMs because other disinfection byproducts of human health concern also are present in chlorinated waters and because their concentrations are likely to be correlated with the concentrations of THMs.

In recognition of the concerns associated with the presence of THMs in drinking water, numerous regulatory agencies have set standards or guidelines for these compounds in drinking water. For total THMs, standards and guidelines of 80 and 100 µg/L have been established by the U.S. Environmental Protection Agency (USEPA) and European Union (EU), respectively (Agus et al., 2009). Guidelines also have been set for individual THMs in recognition that the different compounds do not exhibit identical toxicity.

Because of the content of THMs, discharges from seawater desalination plants may potentially pose ecological risks similar to those of discharges from wastewater treatment plants and water reclamation facilities. Concerns associated with the effects of THMs in coastal waters were first investigated in the 1970s, when continuous chlorination of power plant cooling water was subject to scrutiny. Certain marine organisms (for example, mussels) are sensitive to chloroform and bromoform with median lethal concentration (LC_{50}) values around 1000 µg/L (Helz and Hsu, 1978). In recognition of concerns associated with the discharge of THMs in chlorinated water, the USEPA set surface water criteria under the California Toxics Rule of 46 µg/L for bromodichloromethane, 34 µg/L for dibromochloromethane, and 360 µg/L for bromoform.

Numerous studies have demonstrated that chlorination of seawater under conditions encountered in seawater intakes or during seawater pretreatment results almost exclusively in the formation of bromoform (Agus et al., 2009). In general, the concentration of bromoform produced when seawater is chlorinated depends upon the chlorine dose, which is normally expressed as the product of the concentration and contact time (C•t). Desalination plants typically employ initial chlorine concentrations between 0.2 and 4 mg of Cl_2/L and contact times between 15 and 30 min or C•t values between 3 and 120 mg/L min. Under these conditions, between 10 and 100 µg of bromoform/L is produced (Ali and Riley, 1989; El Din et al., 2000; Helz and Hsu, 1978; Jenner et al., 1997; Allonier et al., 1999; Abarnou and Miossec, 1992). These levels of bromoform are not likely to pose significant concerns for drinking water produced by seawater desalination because even partial removal during RO treatment would reduce the concentrations below the regulatory guidelines. These levels of bromoform also would be unlikely to pose significant risks in marine waters where seawater desalination concentrate is discharged because they would normally be below regulatory guidelines for surface water discharges before mixing with seawater. For example, an RO treatment plant operating at a recovery of 50% would discharge concentrate containing between 20 and 200 µg of bromoform/L, which would be below the effect threshold for sensitive species even before dilution with the receiving water.

Previous studies on the chlorination of seawater have been limited to a few geographic regions (for example, the Atlantic and Pacific coasts of North America and the Persian Gulf) and in relatively pristine coastal waters. It is possible that higher concentrations of bromoform could be produced when waters from other locations are chlorinated. For example, the production of up to 225 µg of bromoform/L was reported after an oil spill near a seawater intake, which led researchers to hypothesize that organic contaminants in crude oil could serve as bromoform precursors (El Din et al., 2000). While this issue has not been investigated in detail, the formation of bromoform and other chlorine disinfection byproducts is often correlated with the concentration of DOC (Krasner et al., 1996). As a result, desalination plants located in highly eutrophic waters or in locations with substantial amounts of pollution might yield higher concentrations of bromoform upon chlorination. Additional research is needed to evaluate the spatial and temporal variability of bromoform production

following chlorination, especially in regions where few previous measurements have been made (for example, along the coast in densely populated regions of Asia).

Only a small fraction of the THMs produced during pretreatment are detected in desalinated water. For plants employing distillation, loss of THMs occurs because the THMs are too volatile to be captured in the condensers (Ali and Riley, 1989; El Din et al., 2000; McGuire Environmental Consultants, 2004). For full-scale seawater desalination plants employing RO, rejection of THMs typically exceeds 99% (Agus et al., 2009). As a result, THMs produced during pretreatment are mainly an issue of concern for the receiving waters.

As mentioned previously, desalinated water normally contains a relatively high concentration of bromide, which often results in the production of higher concentrations of THMs (Hua et al., 2006). However, desalinated seawater does not contain high concentrations of natural organic matter (namely, humic and fulvic acids) that serve as precursors for formation of THMs. Therefore, relatively low concentrations of THMs are produced when desalinated seawater is disinfected with free chlorine or when free chlorine is used as a residual disinfectant in the potable water distribution system (Ali and Riley, 1990; Fayad, 1993). One possible scenario of concern with respect to THM formation in desalinated water systems involves the blending of desalinated water with organic-matter-rich water from other sources. When organic-matter-rich waters are blended with desalinated water, the concentration of THMs produced will decrease because the concentration of THM precursors decreases from dilution with desalinated water, which is low in organic matter. However, the decrease may be less than expected by volumetric averages because the elevated bromide concentrations in the desalinated water can enhance the formation of brominated THMs in the chlorinated blended water. For example, a laboratory study conducted by McGuire Consultants indicated the formation of THMs at concentrations that were approximately 30% higher than what was predicted when a 1:1 mix of Colorado River water and desalinated water was created prior to chlorination (McGuire, 2004).

2.2.2   HAAs

The haloacetic acids (HAAs) are a family of substituted acetic acids with the structural formula CH_aX_bCOOH, where a is 0, 1, or 2; X is a halogen; and b is 1, 2, or 3. This family of compounds became a concern after the initial discovery of THMs led researchers to study the production of disinfection byproducts and their formation mechanisms (Christman et al., 1983). After analytical methods capable of detecting low-molecular-weight organic acids were used to study chlorinated drinking water, it became clear that the concentrations of HAAs were comparable to or slightly lower than those of the THMs. HAAs also have been studied extensively over the past 20 years because they have been linked to cancer and reproductive failures in rodents (Bull et al., 1990; DeAngelo et al., 1996; Bhat et al., 1991; Linder et al., 1994; Tully et al., 2005).

To address concerns about the potential for exposure to HAAs in drinking water, the USEPA established a maximum contaminant limit (MCL) of 60 μg/L for the sum of the concentrations of five of the HAAs (namely, the HAA5: monochloroacetic, dichloroacetic, trichloroacetic, monobromoacetic, and dibromoacetic acids). Guidelines have also been set for individual chlorinated HAAs by the USEPA and the World Health Organization.

The HAAs also could pose risks to aquatic ecosystems. In particular, phytoplankton and aquatic macrophytes appear to be particularly sensitive to HAAs (Lewis et al., 2004; Hanson and Solomon, 2004). A review of available literature indicated that the most sensitive species

for which data are available is the green alga *Scenedesmus subspicatus*, which showed a decrease in growth at concentrations of monochloroacetic acid and monobromoacetic acid of 7 and 20 µg/L, respectively (Kuhn and Pattard, 1990). Additional research is needed to assess the phytotoxicity of other HAAs.

At the high bromide concentrations of seawater, brominated HAAs (mainly dibromoacetic acid) usually account for a higher percentage of the HAAs produced during chlorination. However, unlike the THMs, chlorine-containing compounds (for example, dichloroacetic acid and bromodichloroacetic acid) still are detected at significant concentrations when seawater is chlorinated (Allonier et al., 1999; Fabbricino and Korshin, 2005; Kristiansen et al., 1996). Under conditions typical of seawater intakes, the concentrations of HAAs typically range from 5 to 10 µg/L, with dibromoacetic acid and bromochloroacetic acid accounting for the majority of the HAAs produced (Allonier et al., 1999; Dalvi et al., 2000).

HAAs formed during seawater pretreatment are efficiently removed by desalination plants. In distillation treatment plants, HAAs are removed well (Dalvi et al., 2000) presumably because charged compounds remain behind with the distillation concentrate. HAAs also are removed well by seawater RO plants, with rejections over 98% (Agus et al., 2009). When desalinated water is blended with organic-matter-rich water prior to chlorination, the types of HAAs produced will shift towards compounds with more bromine substituents (Thibaud et al., 1988; Pourmoghaddas et al., 1993). However, data on the formation of HAAs in blended seawater are not available.

2.2.3   Halophenols

Halophenols (namely, substituted phenols containing between one and five halogen groups) represent another important class of chlorine disinfection byproducts. However, unlike the THMs and HAAs, this family of compounds tends to be a concern because its extremely low odor threshold concentrations can affect the aesthetics of potable water. For example, the odor threshold concentration for halophenols ranges from 0.0005 to 2 µg/L, while the guidelines for protection of human health from adverse health effects are greater than 100 µg/L (Agus et al., 2009).

Because of their low odor threshold concentrations, the formation of halophenols has been studied in detail. The reactions of HOCl, HOBr, and HOI with phenol and halogenated phenols are relatively rapid (Lee and Morris, 1962; Gallard and von Gunten, 2002). When chlorine is added during water treatment, halophenols are produced from aromatic substituents in natural organic matter. In many situations, the phenol ring undergoes sequential halogen substitution followed by ring cleavage, which can lead to the formation of other disinfection byproducts, including THMs and HAAs (Christman et al., 1983; Gallard and von Gunten, 2002). The accumulation of halophenols is typically limited to situations when relatively low doses of chlorine are applied or when competing reactions quickly remove chlorine from solution (for example, formation of chloramines when ammonia is present). Because the hydroxy substituent on the phenol can stabilize intermediate structures through resonance, phenols tend to undergo halogen substitution in the *ortho* and *para* positions. Therefore, the most prevalent types of halophenols are replaced in the 2-, 4-, or 6-position.

Although data are not available on the concentrations of halophenols produced when seawater is pretreated with chlorine, available data from power plants that apply chlorine to seawater to control biofouling indicate the formation of between 0.1 and 0.4 µg of

halophenols/L with 2,4,6-tribromophenol accounting for the majority of the products (Jenner et al., 1997; Allonier et al., 1999). While these concentrations approach the odor threshold, the presence of brominated phenols in desalinated water does not appear to be a major concern because phenols are rejected efficiently by RO membranes (Nghiem et al., 2004). However, rejection of phenolic compounds in membranes is often less than expected on the basis of molecular weight because the combination of a hydrophobic compound and a phenolic substituent can lead to dissolution of the compound into the membrane. For example, one study reported only about 80% rejection of estradiol by nanofiltration membranes that were capable of achieving nearly complete removal of lower- molecular-weight compounds that did not have phenolic functional groups (Nghiem et al., 2004).

2.2.4   HANs

Haloacetonitriles (HANs) are low-molecular-weight compounds with a structure of H_aX_bCCN, where *a* is equal to 0, 1, or 2; *X* is a halogen; and *b* is 1, 2, or 3. HANs are produced when natural waters undergo chlorination. However, the compounds are unstable and undergo base-catalyzed hydrolysis and reactions with chlorine (Hua et al., 2006). As a result, the compounds are formed during the initial stages of chlorination followed by a decrease in concentration as they are exposed to chlorine (for example, in a water distribution system). The dihalogenated species (for example, dichloroacetonitrile and dibromoacetonitrile) are more stable than the other members of this family of compounds, and as a result, they are the most frequently detected HANs in water systems (Richardson et al., 2003). In general, the concentrations of HANs produced during chlorination are considerably lower than those of the THMs or the HAAs.

Despite their relatively low concentrations, HANs have been a significant concern among scientists studying the potential human health effects of chlorine disinfection byproducts because the compounds exhibit considerable genotoxicity (Muellner et al., 2007). In recognition of the potential risks posed by these compounds, the USEPA set drinking water guidelines for dichloroacetonitrile (6 µg/L) and dibromoacetonitrile (20 µg/L).

The form of HAN produced upon chlorination shifts from dichloroacetonitrile to dibromoacetonitrile as the concentration of bromide increases. In freshwater containing moderately high concentrations of bromide (namely, >100 µg/L), dibromoacetonitrile accounts for the majority of the HANs produced during chloramination (Hua et al., 2006; Obolensky and Singer, 2005). In seawater, dibromoacetonitrile is the predominant HAN, with formation of between 0.3 and 3.4 µg/L in seawater cooling systems for power plants that use chlorine (Jenner et al., 1997; Allonier et al., 1999).

No data are available on the removal of HANs in seawater desalination plants.

CHAPTER 3

FORMATION OF CHLORINE DISINFECTION BYPRODUCTS UPON CHLORINATION OF SEAWATER

3.1 OBJECTIVES

As indicated by a review of previous research summarized in Chapter 2 and in Agus et al. (2009), several different chlorine disinfection byproducts of concern are formed when seawater is chlorinated as part of the pretreatment that frequently occurs prior to desalination. Previous data on the concentrations of disinfection byproducts produced upon seawater chlorination were collected in a limited number of geographic locations, such as the Middle East and the North Atlantic. The few available studies that consider the effect of different types of disinfection byproduct precursors on byproduct formation suggest that the nature of the OC can play a role in the total concentrations of disinfection byproducts formed upon chlorination (Fabbricino and Korshin, 2005). Furthermore, data from the Persian Gulf suggest that concentrations of chlorine disinfection byproducts produced upon chlorination of gulf waters tend to be higher than those measured in the Atlantic or Pacific Ocean. It is difficult to determine whether these differences are attributable to variations in the concentrations of organic matter, differences in experimental procedures (for example, chlorination dose and temperatures), or variations in the concentrations of disinfection byproduct precursors in these different locations. To address these issues, seawater samples from five locations were subjected to chlorination at doses and a contact time comparable to conditions encountered at desalination plants.

3.2 SAMPLE LOCATIONS

Seawater grab samples were collected from the locations listed in Table 3.1. Seawater samples from California were collected in 4-L amber bottles. Water samples from Florida and Singapore were collected in 12-L high-density polyethylene (HDPE) containers. The samples were shipped with cold packs and arrived at temperatures under 5 $^{\circ}$C. Seawater samples were filtered with 0.45-μm-pore-size disk filters and stored at temperatures below 10 $^{\circ}$C. Although the three locations in California are not far from each other, they capture significant differences in seawater quality that occur within one geographic region, with San Diego representing low-productivity water, Monterey Bay located in a strong upwelling, and San Francisco Bay representing estuarine waters near a highly urbanized area. The samples from Singapore and Panama City represent waters with higher nutrient loading and higher primary productivity.

Table 3.1. Seawater Sampling Locations

Location	Location Description	Latitude	Longitude
Monterey, CA	Coastal seawater, Pacific	37˚ 34' 55" N	122˚ 58' 37" W
San Diego, CA	Coastal seawater, Pacific	33˚ 08' 21" N	117˚ 20' 16" W
San Francisco Bay, CA	Estuarine water, Pacific	37˚ 51' 39" N	122˚ 19' 35" W
Singapore	Estuarine water, Pacific	1˚ 18' 30" N	103˚ 52' 27" E
Panama City, FL	Estuarine water, Atlantic	30˚ 12' 0" N	85˚ 40' 48" W

3.3   EXPERIMENTAL METHODS

Within 72 h of receipt, the samples were chlorinated at initial chlorine concentrations of either 0.5 mg of Cl_2/L (low dose) or 2 mg of Cl_2/L (high dose). Chlorination was conducted at ambient temperature (23 ± 2 ^{o}C) in the containers used for the subsequent extraction of disinfection byproducts—40-mL amber glass vials for THMs and HANs, 60-mL clear glass vials for HAAs, and 1-L amber glass bottles for phenols. After 30 min, the samples were quenched with excess (0.5-mL) 1 M sodium bisulfite. All samples were chlorinated in duplicate. In addition, one unchlorinated sample, one unchlorinated Milli-Q water sample, and one chlorinated Milli-Q water sample were included with each chlorination experiment, which normally included chlorination of samples from one location at two doses. Matrix spikes were analyzed monthly on months when chlorination experiments were carried out. THM, HAN, and HAA samples were usually chlorinated on the same day, while halophenol experiments were conducted on separate days. A total of 18 samples with various chlorination conditions were analyzed for eight water quality parameters and at least 21 disinfection byproducts from the five locations. Samples were analyzed for disinfection byproducts and water quality parameters as described below.

3.3.1   Analysis of Water Quality Parameters

Conductivity was measured using a Hach SensIon 7 meter and pH was measured using a Denver Instrument UB-10 meter. Total dissolved solids were analyzed using Standard Method 2540C with drying at 180 ^{o}C for at least 2 h (Greenberg et al., 1992).

DOC was analyzed using a Shimadzu 5000A TOC analyzer with a low-sensitivity platinum catalyst. DOC was quantified by two internal calibration curves using four potassium hydrogen phthalate standards ranging in concentration from 0 to 6 mg C/L and from 0 to 18 mg C/L. The calibration curves were linear with r^2 values of 0.999. The detection limit for DOC was 0.65 mg of C/L.

UVA_{254} was measured on a Perkin-Elmer Lambda 14 spectrophotometer with a 1-cm path length. UV absorbance and DOC measurements were used to calculate the specific UV absorption at 254 nm ($SUVA_{254}$) value of the seawater samples.

Total chlorine residuals were measured immediately after dosing and at 30 min. Residual analysis was conducted using Standard Methods 4500 Cl⁻ F, the *N,N*-diethyl-*p*-phenylenediamine (DPD) ferrous titration method (Greenberg et al., 1992).

Chloride was analyzed by ion chromatography (Dionex DX 120) using an AS14 anion-exchange column and a suppressed conductivity detector. Bromide and iodide anions were analyzed by high-pressure liquid chromatography (HPLC) and a photodiode array detector (Waters Alliance 2695). Bromide and iodide were quantified at 194 and 226 nm, respectively. Bromide concentrations could not be measured from seawater samples because of interference from the chloride peak, even in samples diluted by a factor of 1000. External calibration curves (all with r^2 above 0.995) were used for quantification with four standards for each anion in the following concentration ranges: 5 to 20 g/L for Cl⁻, 50 to 200 μg/L for Br⁻, and 25 to 100 μg/L for I⁻.

3.3.2   Analysis of Chlorine Disinfection Byproducts

THMs and HANs were analyzed by gas chromatography with an electron capture detector (GC/ECD) (Varian 3800) using EPA Method 551.1 (1995). The analytes were extracted by liquid-liquid extraction (LLE) using 3 mL of pentane and 35 mL of sample. 1,2-Dibromopropane was used as a surrogate standard. Typical recovery for LLE of THMs and HANs ranged from 80 to 120%. The injection volume for GC analysis was 2.0 μL, and a 30-m J&W Scientific DB-5 (internal diameter, 0.25 mm; thickness, 0.25 μm) GC column was used for separation. THMs and HANs were quantified by external calibration using standards ranging in concentration from 20 to 100 μg/L. For quantification, the five-point calibration curves used for the four THMs and three di-substituted HANs were linear, with r^2 values above 0.98. The method detection limits, listed in Table 3.2, were determined by analyzing identical low concentration samples and multiplying the standard deviation of the identical samples by 3.14 (the Student *t* value). Limits of quantitation (LOQs) for this analysis are three times the method detection limit.

Iodoform was analyzed using the same extraction and analytical method during preliminary seawater chlorination experiments but was not detected in any samples at concentrations above the method detection limit.

Table 3.2. Method Detection Limits for Chlorine Disinfection Byproducts

Method No.	Compound	Method Detection Limit (μg/L)
Method 551.1	Chloroform	1.1
	Bromodichloromethane	1.1
	Dibromochloromethane	1.1
	Bromoform	1.1
	Dichloroacetonitrile	0.20
	Bromochloroacetonitrile	0.20
	Dibromoacetonitrile	0.49
Method 552.3	Chloroacetic acid	0.24
	Dichloroacetic acid	0.51
	Bromoacetic acid	0.21
	Trichloroacetic acid	0.48
	Bromochloroacetic acid	0.45
	Bromodichloroacetic acid	0.70
	Dibromoacetic acid	0.65
	Dibromochloroacetic acid	0.19
	Tribromoacetic acid	0.42
SPE-GC/MS	2,4,6-Trichlorophenol	0.090
	2-Bromophenol	0.045
	2,6-Dibromophenol	0.086
	2,4,6-Tribromophenol	0.11
	2,4,6-Trichloroanisole	0.11
	2,4,6-Tribromoanisole	0.11

Nine HAAs were analyzed by GC/ECD using a modified version of EPA Method 552.3 (2003). The analytes were extracted by LLE using 4 mL of methyl *tert*-butyl ether (MTBE) or *tert*-amyl methyl ether (TAME) from a 40-mL sample (acidified with 2 mL of concentrated H_2SO_4). The ether extracts were then derivatized with 3-mL 10% H_2SO_4/CH_3OH for 4 h to produce the esters of the HAAs. Purge-and-trap-grade CH_3OH (Aldrich) was used for esterification. Derivatization was conducted at 50 $^{\circ}$C for MTBE or 60 $^{\circ}$C for TAME in a water bath. 2,3-Dibromopropionic acid was used as the surrogate standard and was added prior to extraction and derivatization. Typical recovery for the method ranged from 80 to 110% using ester standards of HAAs. The injection volume for GC analysis was 2.0 μL. HAAs were quantified by external calibration using standards ranging in concentration from 20 to 100 μg/L. Five-point calibration curves were calculated for the nine HAAs and were linear with r^2 values above 0.97. The detection limits for Method 552.3 analytes are listed in Table 3.2.

Halophenols were analyzed by GC/tandem mass spectrometry (GC/MS/MS) in a Varian 3900 GC with a Saturn 2100T ion trap mass spectrometer. 2-Bromophenol, 2,6-dibromophenol,

and 2,4,6-tribromophenol were detected in the chlorinated seawater samples. 2,4,6-Trichlorophenol, 2,4,6-trichloroanisole, and 2,4,6-tribromoanisole were included in the analysis but were not detected in any sample at levels above the detection limits (Table 3.2). The analytes were extracted by solid-phase extraction (SPE) using 250 mg of isolute-ENV resin packed into silanized 6-mL glass cartridges between two Teflon frits. Before extraction, the SPE resin was conditioned by running with 5 mL of CH_3OH, 5 mL of Milli-Q H_2O, and 5 mL of pH 4 Milli-Q H_2O through the cartridge at a flow rate of approximately 2 mL/min.

Prior to SPE, water samples were acidified to a pH of 4 to ensure that all halophenols were present in their neutral, protonated forms. The natural ionic strengths of different sample types varied considerably, a variance that could have affected the recoveries of SPE by isolute-ENV. Thus, prior to extraction, reagent-grade salt (NaCl) was added to seawater, intake, feed, and permeate samples to match the salinity of RO concentrate from the pilot plant (~70 g/L). Deuterated d^5-trichloroanisole (0.5 µg/L) was used as the surrogate standard and was added prior to SPE. One liter of sample was passed through the SPE cartridge at a flow rate of approximately 10 mL/min.

Immediately after loading of the resin, the cartridge was washed with 2 mL of a 30:70 acetone:Milli-Q H_2O solution and then dried for at least 1 min. The analytes were then eluted with at least 6 mL of 50:50 acetone:methylene chloride. The eluent then was spiked with 2,3,5-trichlophenol as an internal standard and dried to about a 1-mL volume using a gentle stream of ultra-pure N_2. Typical recovery for the method ranged from 70 to 130%, with better yields observed for tribrominated compounds. The injection volume for GC analysis was 2.0 µL, and a 30-m Agilent HP5-MS (internal diameter, 0.25 mm; thickness, 1.0 µm) GC column was used for separation. Halophenols and haloanisoles were quantified by external calibration using standards ranging in concentration from 100 to 600 ng/L. The seven-point calibration curves were calculated for the four halophenols and two haloanisoles and were linear with r^2 values above 0.980. The detection limits for the halophenol and haloanisole method are listed in Table 3.2.

3.4 RESULTS

Results from the different analytical methods are summarized in the following sections.

3.4.1 Water Quality Parameters

Inorganic water quality parameters (Table 3.3) indicate that the samples used in the chlorination experiments were relatively uniform and appear to be consistent with the reported composition of coastal seawater. As noted in the experimental section, the concentrations of bromide for these samples were not reported because of the interference of chloride in HPLC analysis. Given the consistency of inorganic parameters in these samples with other marine locations, we expect the bromide levels in these samples to range between 60 and 65 mg/L. With respect to chlorination, the variation of bromide levels between different seawater samples is not expected to significantly affect the formation and speciation of byproducts since the variations in concentrations are expected to be small compared to the high absolute concentration of bromide.

Table 3.3. Water Quality Parameters of Seawater Samples Used in Bench-Scale Chlorination Experiments

Sample Location or Datum Type	Sample Date	pH	Conductivity (µS/cm)	Total Dissolved Solids (ppm)	Chloride (g/L)	Iodide (µg/L)
Mean (± SD)		7.3 ± 0.1	45,700 ± 3000	34,100 ± 2000	18.9 ± 1.4	62 ± 3
SF Bay	1/28/2008	7.3	42,100	31,200	17.1	57
Moss Landing	11/6/2007	7.2	43,200	33,200	18.3	64
Carlsbad summer	7/15/2007	7.4	48,500	36,000	20.1	64
Carlsbad winter	3/28/2008	7.5	48,200	34,800	19.2	57
Panama City	3/28/2008	7.2	49,300	36,700	21.0	63
Singapore 1	3/20/2008	7.4	43,200	32,000	17.5	63
Singapore 2	7/11/2008	—[a]	45,400	34,600	18.9	63

[a]Sample was acidified to a pH of 2 at the sampling point.

In contrast to the inorganic water quality parameters, the nature and concentration of organic matter in the seawater samples varied considerably by location and season (Table 3.4). The concentrations of DOC in samples from California were lower (0.91 to 1.9 mg/L) than those in samples from Singapore and Panama City (2.8 to 4.4 mg/L). Organic carbon from phytoplankton activity is affected by solar irradiation, water temperature, and nutrient availability. Other factors influencing the DOC levels in these coastal regions are mixing and freshwater runoff. The higher DOC concentrations in the samples from Singapore and Panama City are most likely related to the combination of these different factors.

Differences in $SUVA_{254}$ in seawater are related to the extent of the terrestrial or marine contribution to OC (Fabbricino and Korshin, 2005). The highest $SUVA_{254}$ values in Pacific Ocean seawater samples—correlated to high chromophoric dissolved organic matter (CDOM) content—were detected in the San Francisco Bay sample and the wet weather sample from Carlsbad. These samples were likely influenced by terrestrial runoff, which often has high SUVA values (Fabbricino and Korshin, 2005). The Monterey (Moss Landing) and Carlsbad dry weather samples had lower $SUVA_{254}$ values, indicating the influence of autochthonous carbon. The Moss Landing sample was collected following an algal bloom in the nearby Monterey Bay, while algal blooms are common off the coast of San Diego Bay, near where the Carlsbad sample was collected.

Both samples from Singapore had a higher DOC content than did the California samples (2.8 and 3.4 mg/L). The southernmost end of the South China Sea has warm water temperatures (annual mean = 27 $^{\circ}$C) and high solar irradiation to support phytoplankton. Additionally, many parts of the South China Sea receive carbon inputs from rivers with high levels of agricultural and urban runoff. However, the $SUVA_{254}$ values calculated for the Singapore samples were relatively low, suggesting that the more important carbon contribution came from autochthonous phytoplanktonic activity.

Among the seawater sampling locations, the highest DOC level was reported in the Panama City sample, which was located in St. Andrews Bay. The bay lies along the northeast coast of Gulf of Mexico, which has moderately warm temperatures (annual mean 22 $^{\circ}$C) and

Table 3.4. DOC and UVA$_{254}$ of Seawater Samples

Sample Location	Sample Date	DOC (mg/L)	UVA$_{254}$ (cm^{-1})	SUVA$_{254}$ (m^{-1} L/mg)
SF Bay	1/28/2008	1.9	0.061	3.16
Moss Landing	11/6/2007	1.6	0.024	1.45
Carlsbad summer	7/15/2007	0.91	0.014	1.49
Carlsbad winter	3/28/2008	1.5	0.054	3.58
Panama City	3/28/2008	4.4	0.085	1.91
Singapore 1	3/20/2008	2.8	0.034	1.18
Singapore 2	7/11/2008	3.4	0.051	1.47

contributions from a number of major rivers and urban corridors. The elevated carbon content could have been due to both algal activity and runoff from the nearby coastal communities. The SUVA$_{254}$ value at this location was moderately high, indicating a mix of allochthonous OC and autochthonous OC.

Total residual chlorine content of seawater samples was measured immediately after chlorine addition and after 30 min of chlorination. For the initial concentration of 0.5 mg of Cl$_2$/L, the total residual measured at the beginning of the experiment ranged between 0.4 and 0.5 mg of Cl$_2$/L. After 30 min of contact time, the chlorine residual ranges between 0 and 0.2 mg of Cl$_2$/L. For the high initial concentration of 2.0 mg/L, the initial total residual chlorine concentration was between 1.5 and 2.0 mg of Cl$_2$/L, which decreased to between 0.3 and 1.0 mg of Cl$_2$/L after 30 min. The average C•t values were 10 ± 3 mg of Cl$_2$/L•min for the low-dose samples and 36 ± 6 mg of Cl$_2$/L•min for the high-dose samples.

3.4.2   THMs

As expected, bromoform (CHBr$_3$) was the predominant THM produced upon chlorination of seawater, accounting for over 78% of the total THM production (Figure 3.1). In about half of the samples, bromoform was the only THM detected. Dibromochloromethane (CHBr$_2$Cl) was detected in half of the samples at concentrations of about an order of magnitude lower than those of bromoform. Dichlorobromomethane (CHBrCl$_2$) and chloroform (CHCl$_3$) were detected only in the winter sample from San Diego chlorinated at an initial concentration of 2.0 mg of Cl$_2$/L. As discussed in Chapter 4, these compounds were observed prior to chlorination in some samples from this site and may have been produced at the adjacent power plant.
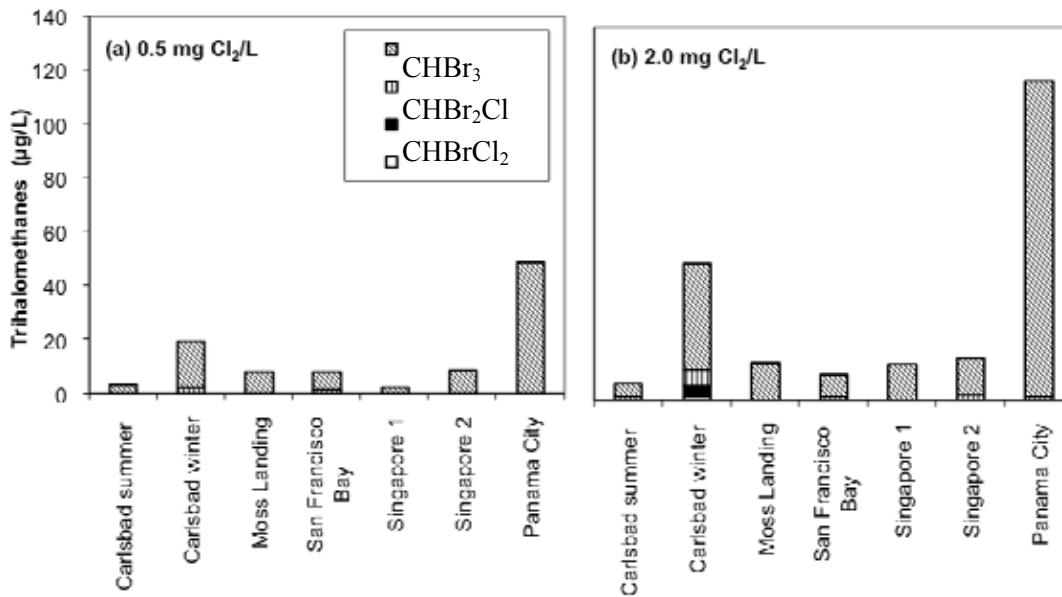
Figure 3.1. THM concentrations in seawater samples chlorinated at (a) 0.5-mg Cl₂/L and (b) 2.0-0mg Cl₂/L initial concentrations.

At the low chlorine dose (namely, 0.5 mg of Cl_2/L), the total concentration of THMs ranged from 5 to 50 μg/L. The highest concentration of total THMs was detected in the sample from Panama City, which is the sampling site that also had the highest concentration of DOC (4.4 mg of C/L). Furthermore, the wintertime sample collected from San Diego, which contained significantly higher DOC than did the summertime sample (namely, 1.5 mg of C/L versus 0.91 mg of C/L), produced about twice as high a concentration of total THMs upon chlorination. However, the relationship between DOC and THM formation was not identical among the different sites. For example, the first sample from Singapore produced the lowest concentration of THMs upon chlorination, even though it had relatively high DOC content (namely, 2.8 mg/L). These results suggest that the nature of the OC in seawater is not identical in different regions and that, while DOC may be a useful surrogate for THM formation under the different conditions encountered at one site, it may not be useful for predicting THM formation at different locations. Additionally, the nature of OC in intake water varies not only between regions but also between different seasons within the same region.

The concentration of bromoform produced increased when the initial chlorine concentration increased to 2 mg of Cl_2/L. The concentration of total THMs increased by approximately a factor of 2, even though the chlorine dose increased by approximately a factor of 4. Therefore, THM production was not directly related to the initial chlorine dose. As was the case for the low-dose chlorination, no clear relationship was observed between the DOC content and the formation of THMs. However, some trends were evident. For example, the Panama City sample, with the highest organic content, also produced the highest concentration of THMs.

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3.4.3 HAAs

The concentrations of HAAs formed upon chlorination of seawater ranged from 4 to 11 μg/L for low-dose chlorination and from 17 to 31 μg/L for high-dose chlorination (Figure 3.2). The concentration of total HAAs increased by approximately a factor of 4 as the initial chlorine concentration increased from 0.5 to 2.0 mg of Cl_2/L. Monobromoacetic acid (MBAA) and bromochloroacetic acid (BCAA) were the most prevalent acids detected in the chlorinated seawater, each accounting for about 30% of the total HAAs in most samples.
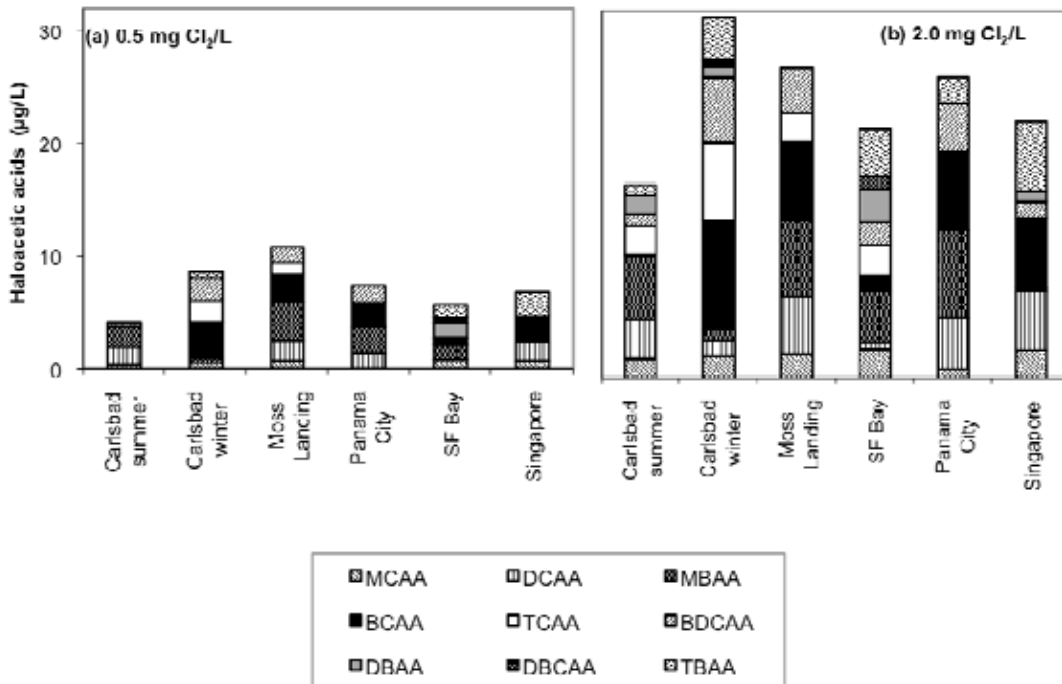
Figure 3.2. Nine HAAs in seawater samples chlorinated at (a) 0.5-mg Cl_2/L and (b) 2.0-mg Cl_2/L initial concentrations.

The total concentration of HAAs produced upon chlorination did not exhibit much variation among the different sites. In samples chlorinated at an initial concentration of 2.0 mg of Cl_2/L, the highest and lowest concentrations were detected in samples from Carlsbad that were collected under different seawater conditions. The low concentration in the Carlsbad summer sample also had the lowest DOC concentration. Other than this observation, no relationship was observed between the total concentration of HAAs and the DOC concentration.

3.4.4   Halophenols
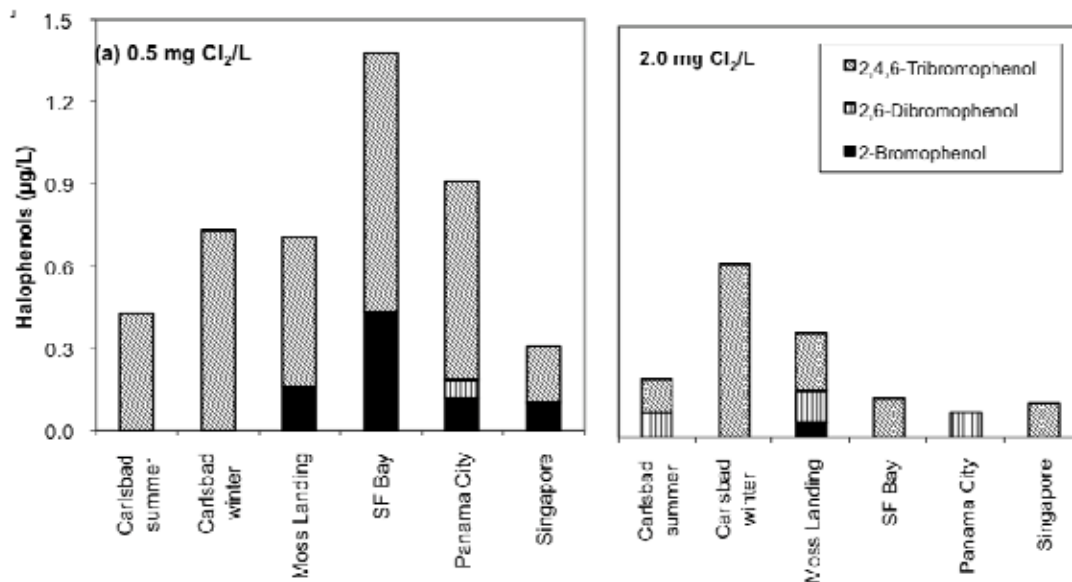
Figure 3.3. Bromophenols in seawater samples chlorinated at (a) 0.5-mg Cl$_2$/L and (b) 2.0-mg Cl$_2$/L initial concentrations.

Brominated phenols were detected in all of the chlorinated seawater samples at concentrations ranging from 0.09 to 1.4 µg/L (Figure 3.3). In all cases, 2,4,6-tribromophenol was the predominant halophenol, with concentrations ranging from 0.1 to 0.9 µg/L, accounting for over 80% of the total halophenols formed for low-dose samples and over 55% of the halophenols for the high-dose samples. An exception to this is detected in the Panama City sample with 2.0 mg of Cl$_2$/L, where the dibrominated form was dominant. 2,6-Dibromophenol was the second most prevalent halophenol and was detected in more than half the samples at concentrations ranging from 0.09 to 0.4 µg/L. 2-Bromophenol was detected in only two of the 14 samples at concentrations around 0.05 µg/L.

At an initial chlorine concentration of 0.5 mg of Cl$_2$/L, there was no clear relationship between halophenol concentration and DOC concentration. With the exception of the sample from Singapore, which contained less than half of the halophenol concentration of the other samples, the concentration of total halophenols varied by less than a factor of 2 among the 14 samples. Halophenol concentration decreased at the higher chlorine dose as the halophenols were further transformed by chlorine. For most samples, concentrations of total halophenols at the higher Cl$_2$ dose were less than those observed at the low Cl$_2$ dose.

3.4.5 HANs
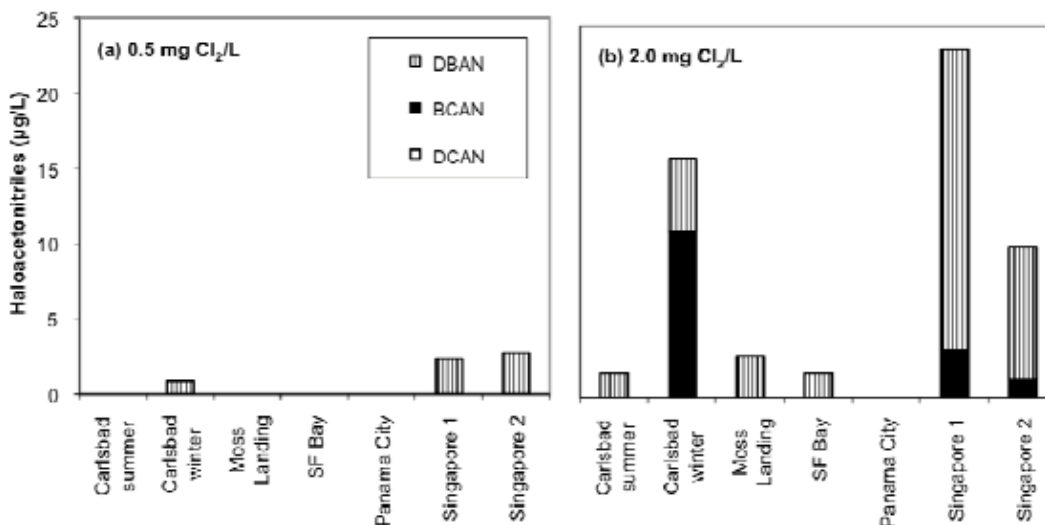
Figure 3.4. HANs in seawater samples chlorinated at (a) 0.5-mg Cl$_2$/L and (b) 2.0-mg Cl$_2$/L initial concentrations.

Total HANs formed during chlorination of seawater ranged from below detection to 2.7 µg/L at low dose and up to 23 µg/L at high dose (Figure 3.4). Dibromoacetonitrile (DBAN) was the most prevalent HAN, detected at concentrations ranging from 1.6 to 20 µg/L. Bromochloroacetonitrile (BCAN) was detected in three samples at concentrations between 1.2 and 11 µg/L. Dichloroacetonitrile (DCAN), as well as mono- and tri-HANs, was not detected above the detection limit (namely, 0.2 µg/L) in any sample.

Chlorination at an initial concentration of 2.0 mg of Cl$_2$/L produced considerably higher concentrations of HANs than at an initial concentration of 0.5 mg of Cl$_2$/L. The relatively high concentration of HANs detected in the Singapore samples suggests that HAN precursors were present in these samples at elevated concentrations. Both Singapore samples contained moderately high DOC levels. These samples also produced lower concentrations of THMs and HAAs than did the Panama City seawater sample, which had comparable concentrations of DOC and a similar SUVA$_{254}$.

3.5 DISCUSSION

3.5.1 Comparison with Previous Studies

In general, the concentrations of chlorine disinfection byproducts detected after chlorination were consistent with reported data from full-scale seawater desalination plants and power plants that use low doses of chlorine during pretreatment. For example, bromoform accounted for the majority of the THMs produced at power plants and desalination plants, with concentrations ranging from 10 to 50 µg/L at locations in North America and Europe and concentrations between 70 and 100 µg/L in the Middle East (Allonier et al., 1999; Ali and Riley, 1990). At a low chlorine dose (initial concentration of 0.5 mg of Cl$_2$/L), we also found bromoform to be the predominant THM with concentrations ranging from 10 to 50 µg/L

(Figure 3.1). Previous studies also have shown that significantly higher concentrations of THMs can be produced when seawater from some locations is chlorinated. For example, 490 μg of THMs/L (mainly bromoform) was produced when an initial chlorine concentration of 2.5 mg of Cl_2/L was applied at a desalination plant in Tampa Bay, FL (Agus et al., 2009). This finding is qualitatively consistent with our observation of the highest concentrations of bromoform (namely, 120 μg/L) when the sample from Panama City (which is located approximately 550 km from Tampa Bay) was chlorinated at an initial concentration of 2.0 mg of Cl_2/L. These findings support our observations that THM production varies among regions and cannot be simply predicted from water quality parameters like DOC or $SUVA_{254}$.

Our finding that monobromoacetic acid and bromochloroacetic acid were the predominant HAAs formed is inconsistent with previous studies in which more highly halogenated compounds (for example, dibromoacetic and bromodichloroacetic acid) accounted for the majority of the HAAs (Agus et al., 2009). However, the chlorine contact time that we employed (namely, 30 min) was considerably shorter than those at power plants and full-scale desalination plants, because our experiments were designed to mimic conditions at the Carlsbad desalination pilot plant. Additional halogen incorporation into HAAs may occur at longer chlorination contact times. Furthermore, we also detected slightly lower total concentrations of HAAs than reported in previous studies in these chlorination experiments because of the shorter contact time.

Halophenols detected in chlorinated seawater were somewhat more concentrated than in previous studies, where 2,4,6-tribromophenol was the predominant halophenol detected at concentrations up to 0.4 μg/L in chlorinated cooling water from coastal power plants (Allonier et al., 1999). The concentration of total halophenols decreased at higher initial chlorine concentrations, as would be expected for the sequential halogenation at the *ortho* and *para* sites of a phenol followed by ring cleavage (Acero et al., 2005). Thus, the higher concentrations observed in cooling water were probably related to longer contact times.

The chlorination of cooling water at the coastal power plant also provided the only comparison of HAN concentrations (namely, observed concentrations of 0.3 to 3.4 μg/L) to the HAN concentrations from our experiment with chlorination of seawater. The previous data were consistent with our findings, except for the winter samples from Carlsbad and the two samples from Singapore, which contained total HAN concentrations of up to 23 μg/L (Figure 3.4). In chlorinated Lake Kinneret (Israel) water, total HAN concentrations up to 12 μg/L were detected (Heller-Grossman et al., 1999). In a USEPA survey of drinking water treatment plants, the median concentration reported for the sum of HANs was 3 μg/L, with a maximum of 14 μg/L (Krasner et al., 2006). The aforementioned studies indicated that the di-HANs were the most prevalent HANs detected following chlorination and that the presence of bromide in the source water increased HAN production.

3.5.2 Relationship of disinfection byproduct formation to organic precursor concentration
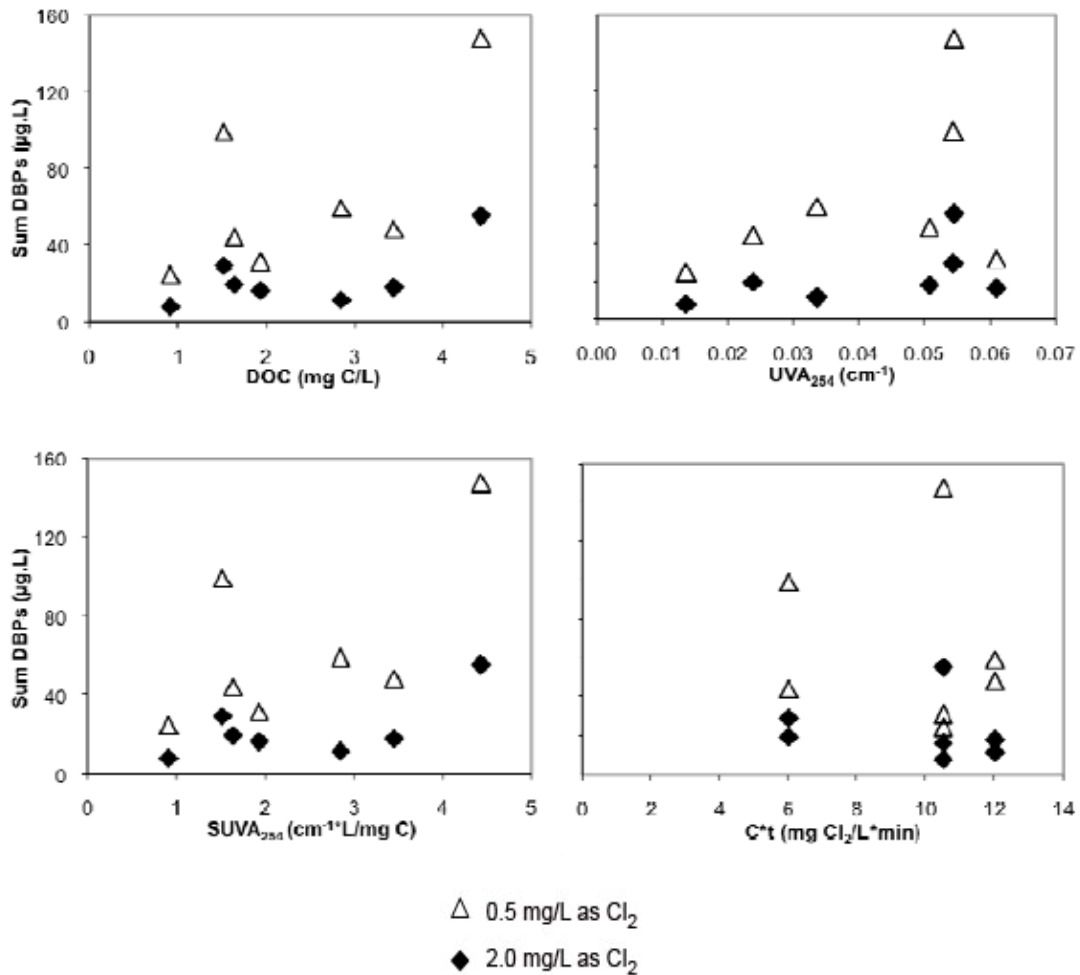
Figure 3.5. Relationships between the sum of THMs, HAAs, HANs, and bromophenols in seawater samples, chlorinated at 0.5-mg Cl$_2$/L and 2.0-mg Cl$_2$/L initial concentrations, and other parameters: DOC, UVA$_{254}$, SUVA$_{254}$, and chlorine dose.

As mentioned in Results, no simple correlation between the formation of chlorine disinfection byproducts and parameters of organic precursors was observed. In Figure 3.5, the sum of THMs, HAAs, HANs, and bromophenols detected in the chlorinated seawater is plotted against UVA, DOC, SUVA, and C•t. Because concentrations of THMs and HAAs were normally much higher than those of the HANs and halophenols, this relationship is dominated by THMs and HAAs. Because of the extremely high bromide levels expected in seawater samples from all locations, HOBr is present as the dominant oxidant during all of the bench-scale experiments. The modest variation between bromide levels in each seawater sample is not likely to be responsible for the variability.

The seawater samples in our experiments varied in the nature and concentrations of dissolved organic compounds present. Natural organic matter (NOM) associated with coastal water had

been observed to contain higher byproduct formation potential than weathered NOM from the open ocean, so terrestrial influence and mixing at each sampling site can also contribute to the variability (Fabbricino and Korshin, 2005). Characteristics of NOM that may influence the formation and speciation of disinfection byproducts include aromaticity, presence of reactive moieties, and nitrogen content (Westerhoff et al., 2004). Measuring $SUVA_{254}$ determines only one of these characteristics (namely, aromaticity), which did not show a strong correlation with disinfection byproduct precursors. Beyond the straightforward $SUVA_{254}$ measure, other analytical methods—including nuclear magnetic resonance spectroscopy—are needed to better identify the presence and concentration of reactive sites in the organic precursor. It is possible that a relationship might have been apparent if we had observed a larger number of samples encompassing a wider range of OC content and $SUVA_{254}$ values.

CHAPTER 4

FORMATION AND FATE OF CHLORINE DISINFECTION BYPRODUCTS IN A PILOT-SCALE DESALINATION PLANT

4.1 OBJECTIVES

Previously published data on chlorine disinfection byproduct production during seawater pretreatment (Chapter 2) and laboratory studies on the chlorination of seawater under conditions approximating those encountered in seawater (Chapter 3) indicate that disinfection byproducts that pose potential threats to human health and aquatic ecosystems are produced during chlorine pretreatment. Previously published data from full-scale treatment plants also suggest that many of the chlorine disinfection byproducts are rejected efficiently by seawater RO membranes. However, previous studies do not address the full suite of compounds that pose potential risks, nor do they provide a good understanding of the formation and removal of specific compounds under different conditions. To provide a better understanding of the performance of seawater desalination plants with respect to removal of chlorine disinfection byproducts, a study was conducted at a pilot-scale seawater desalination plant. As part of this study, disinfection byproduct formation and removal were monitored at different points in the plant during two seasons in which intake water quality varied.

4.2   PILOT PLANT OPERATIONS

The experiments were performed at the Poseidon Resources pilot-scale desalination plant in Carlsbad, CA (Figure 4.1).
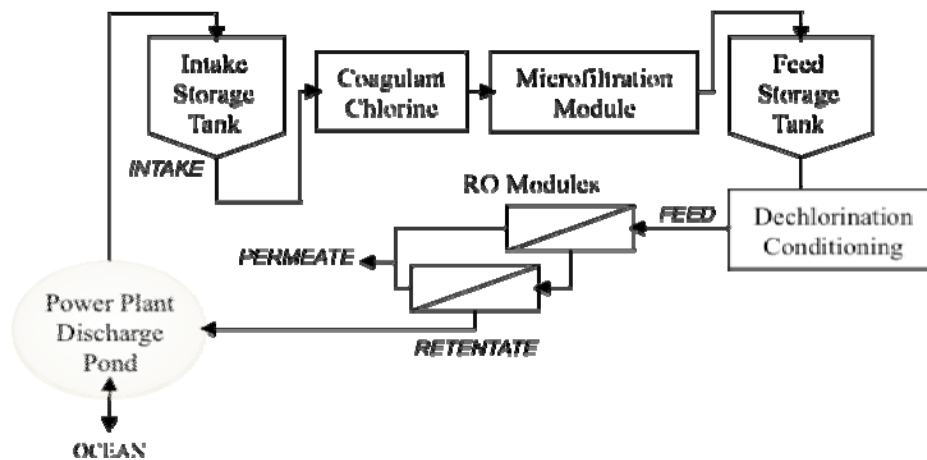
Figure 4.1. Simplified process schematic of the Carlsbad desalination pilot plant, including sampling points for intake seawater, RO feed, RO permeate, and RO retentate (brine).

In the configuration employed during the study, the 0.026-million-gallon-per-day (0.026-MGD) (1.2-L/s) pilot plant employed microfiltration prior to RO. Intake seawater was taken from the discharge pond of the adjacent power plant's cooling system and stored in a 500-gal tank. The power plant used chlorine for biofouling control. As a result, low levels of chlorine disinfection byproducts were sometimes detected in the inlet water prior to pretreatment. Dosing of chlorine occurred immediately after the intake water storage tank. The estimated hydraulic retention time between the point of chlorination and the location where chlorine was quenched with sodium bisulfite, prior to RO, was 28 min. On each day of the study, the plant was equilibrated for 2 to 4 h at a 0.5-mg Cl_2/L initial chlorine concentration before samples were collected. Following collection of samples at the low chlorine dose, the initial chlorine concentration was adjusted to 2.0 mg of Cl_2/L and the system was equilibrated again for 2 to 4 h before sampling. During the study, the pilot plant was operated by Dan Marler of Poseidon Resources, Inc.

Samples were collected at the pilot plant during the fall and late winter of 2007–2008. Fall samples (namely, October 5, 12, 17, and 30, 2007) represented the dry period with low phytoplankton productivity, while winter samples (namely, February 12 and 19, March 28, and April 29, 2008) captured conditions in which the intake lagoon was influenced by terrestrial runoff. Sampling during the late winter was conducted only following storm conditions. Samples of inlet water, postchlorination RO feed, post-RO permeate, and RO retentate at two chlorine doses (0.5-mg and 2.0-mg Cl_2/L initial chlorine concentrations) were collected during each round of study. Samples were collected in 1-L glass bottles with Teflon-lined caps. The samples were placed on ice and shipped by overnight courier to UC–Berkeley, where they were extracted within 24 h of collection. Samples were analyzed for water quality parameters and chlorine disinfection byproducts using the methods described in Experimental Methods.

4.3 RESULTS

Results of analyses of water quality parameters and chlorine disinfection byproducts are included in the following sections.

4.3.1 Water Quality Parameters

Data on water quality parameters indicated that, with the exception of DOC, the quality of the feed seawater to the pilot plant was consistent throughout the two different study periods (Table 4.1). The plant operated with a recovery of 40% on October 5 and a recovery of 50% on the other days. Throughout the study, the final product water had a total-dissolved-solid content of 310 ± 50 mg/L and a mean bromide concentration of 350 ± 80 μg/L, which is in the lower end of the range reported for full-scale seawater desalination plants.

As a result of the increased primary productivity, the mean concentration of DOC increased from 2.05 mg of C/L during the fall to 4.00 mg of C/L during the winter (Figure 4.2). Most of the OC was rejected during RO, as indicated by the low concentrations of DOC measured afterward in the permeate. DOC concentrations in the permeate were close to or below the limit of detection (namely, 0.65 mg/L).

The average $SUVA_{254}$ detected in the intake, feed, and concentrate samples was 2.0 ± 0.9 cm^{-1}•L/mg. $SUVA_{254}$ decreased dramatically in the permeate samples to 0.7 ± 0.3 cm^{-1}•L/mg. For permeate samples where DOC was reported below the detection limit, the value of half the detection limit was used to calculate $SUVA_{254}$.

Table 4.1. Water Quality Parameters in Samples from the Desalination Pilot Plant[a]

Parameter	Unit	Intake	Feed	Retentate	Permeate
pH		7.63 ± 0.30	7.60 ± 0.16	7.52 ± 0.28	8.60 ± 0.54
Temperature	^{o}C	19.8 ± 2.3	20.7 ± 2.0	21.3 ± 2.1	25.3 ± 1.7
Chloride	g/L	18.9 ± 1.4	19.4 ± 2.0	37.8 ± 6.8	0.25 ± 0.08
Bromide	mg/L	NA	NA	NA	344 ± 76
Iodide	µg/L	63 ± 3	62 ± 3	118 ± 11	ND
Conductivity	µS/cm	51,100 ± 800	51,300 ± 1000	89,700 ± 1300	204 ± 18
TDS	mg/L	35,800 ± 2100	36,000 ± 1400	72,300 ± 3200	310 ± 50
Salinity	^{o}/oo	35 ± 2	35 ± 2	71 ± 3	<0.5

[a]NA = not analyzed; ND = not detected above detection limit; TDS, total dissolved solids.
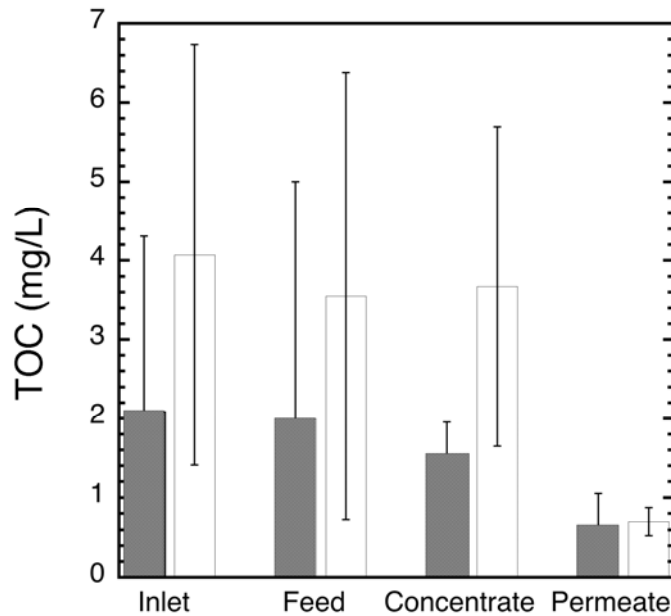
Figure 4.2. Mean and standard deviation of concentrations of total OC measured at the pilot-scale desalination plant during fall (filled bars) and winter (hollow bars) conditions.

4.3.2 THMs

As indicated in Figure 4.2, the inlet samples collected during the fall typically had lower concentrations of OC than those collected during the winter. In particular, the final two water samples (namely, March 28 and April 29), which were collected during an algal bloom, contained 7.4 and 5.4 mg of C/L. As a result of the elevated concentrations of OC, the winter samples typically produced more THMs after they were chlorinated (Figures 4.3 to 4.6) with

bromoform concentrations up to approximately 65 µg/L in the feed water to the RO membranes (Figure 4.3). Bromoform concentrations were higher in the samples with an initial concentration of 2.0 mg of Cl_2/L than they were in the samples with an initial concentration of 0.5 mg of Cl_2/L. Concentrations of other THMs were typically lower than those of bromoform (Figures 4.4 to 4.6) with two exceptions. In the first winter sample (namely, February 12), chloroform concentrations between 35 and 45 µg/L were detected in intake water. The source of the chloroform is uncertain, but we suspect it was produced during maintenance operations at the power plant. Concentrations of chloroform also were higher than those of bromoform in the high-chlorine-dose sample from February 28 (Figure 4.4). However, elevated chloroform concentrations were not detected in the intake.

For most of the samples, THM concentrations in the RO permeate were below the limit of quantification (hollow circles in Figures 4.3 to 4.6). When THMs were detected in the permeate, the concentrations of the individual compounds were always below 15 µg/L. As expected, the concentrations of THMs in the retentate were higher than those in the RO feed, indicating that the compounds were rejected during RO. On the basis of the conductivity data, which indicated that the plant was operating at 50% salt recovery, we expected the concentrations of THMs in the concentrate to be approximately twice as high as the concentration in the RO feed (assuming nearly complete rejection of THMs during RO). The lower-than-expected concentrations of THMs could be attributable to volatilization of the compounds during collection. However, additional research would be needed to confirm this hypothesis.
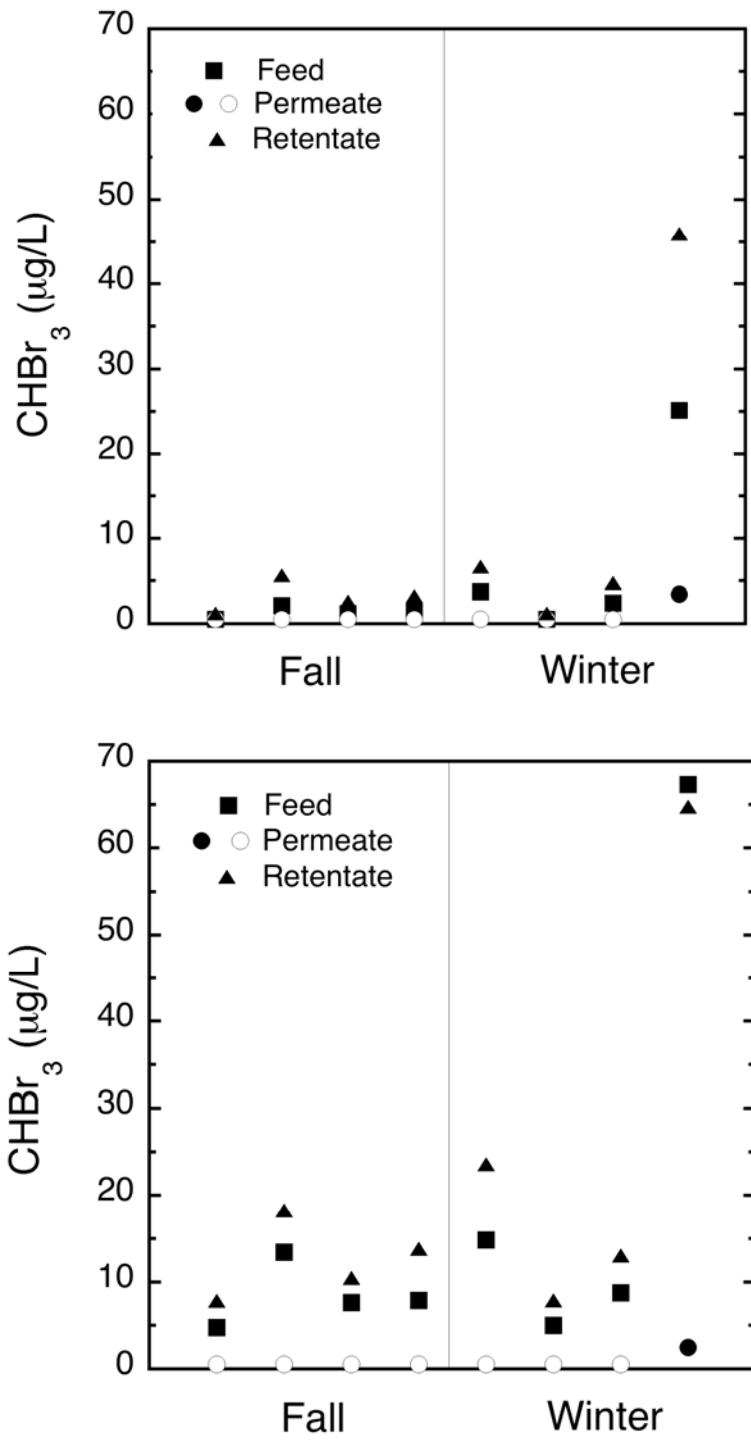
Figure 4.3. Bromoform in samples from the desalination pilot plant at 0.5-mg Cl₂/L (top) and 2.0-mg Cl₂/L (bottom) initial concentrations. Hollow symbols indicate concentrations below the limit of quantification and are plotted at half of the limit of detection.
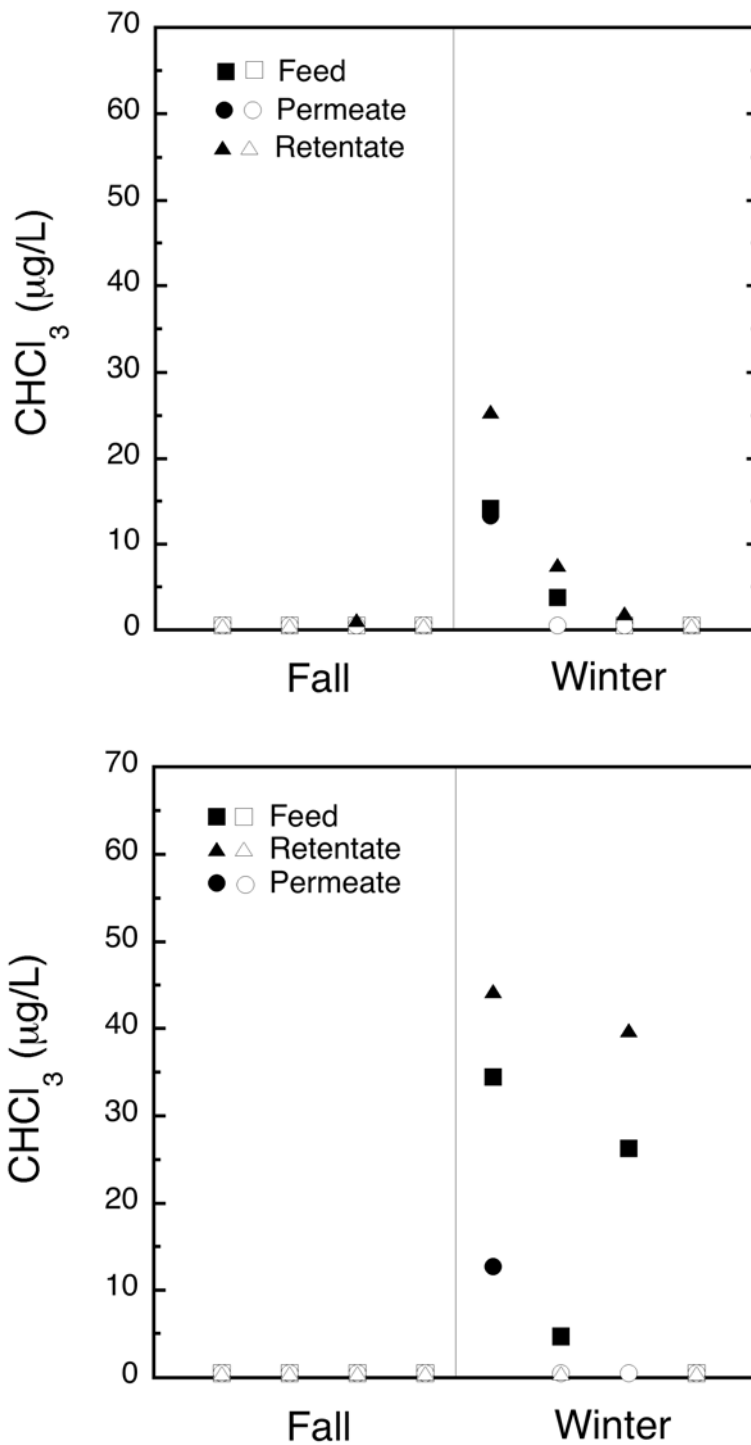
Figure 4.4. Chloroform in samples from the desalination pilot plant at 0.5-mg Cl₂/L (top) and 2.0-mg Cl₂/L (bottom) initial concentrations. Hollow symbols indicate concentrations below the limit of quantification and are plotted at half of the limit of detection.
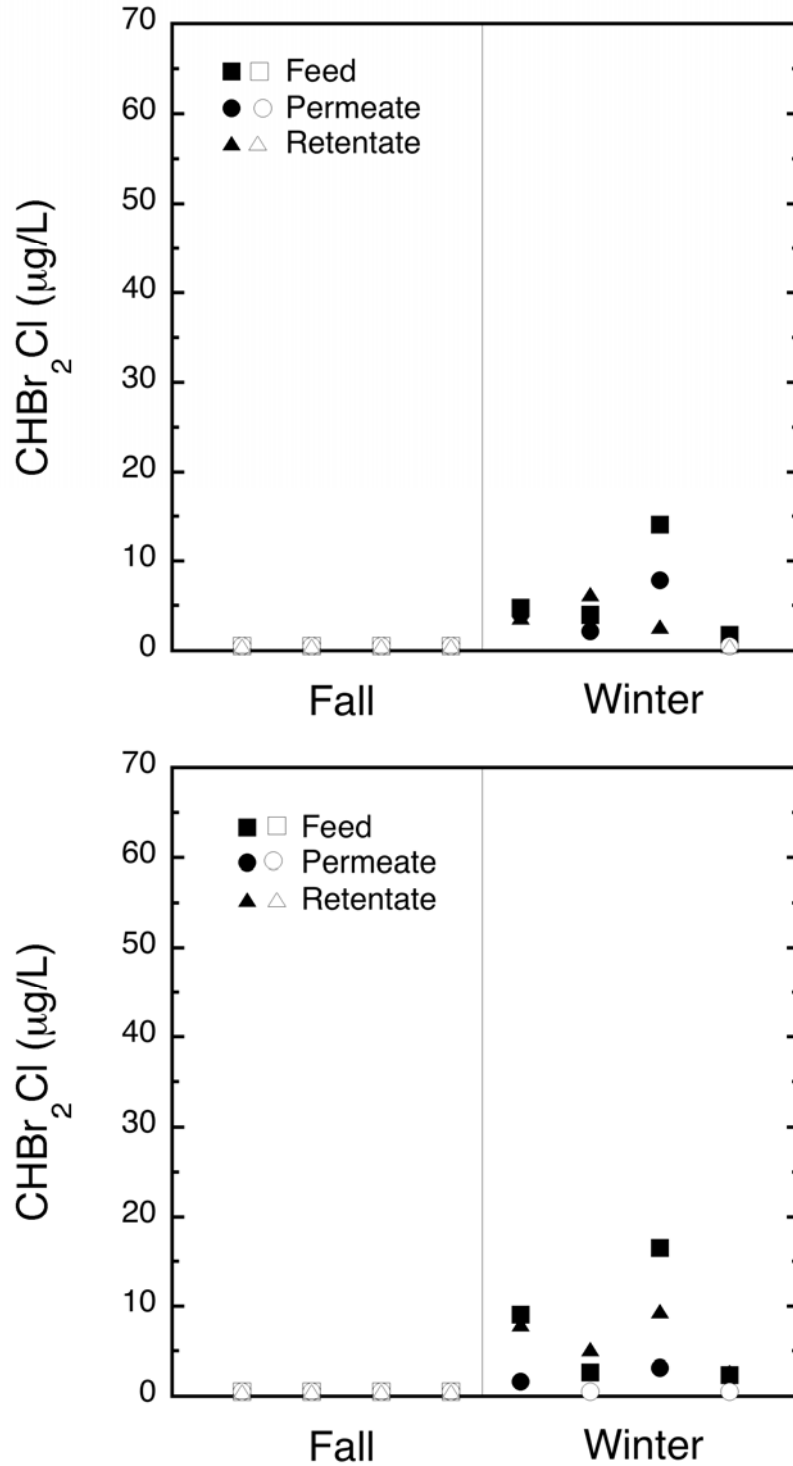
Figure 4.5. Dibromochloromethane in samples from the desalination pilot plant at 0.5-mg Cl_2/L (top) and 2.0-mg Cl_2/L (bottom) initial concentrations. Hollow symbols indicate concentrations below the limit of quantification and are plotted at half of the limit of detection.
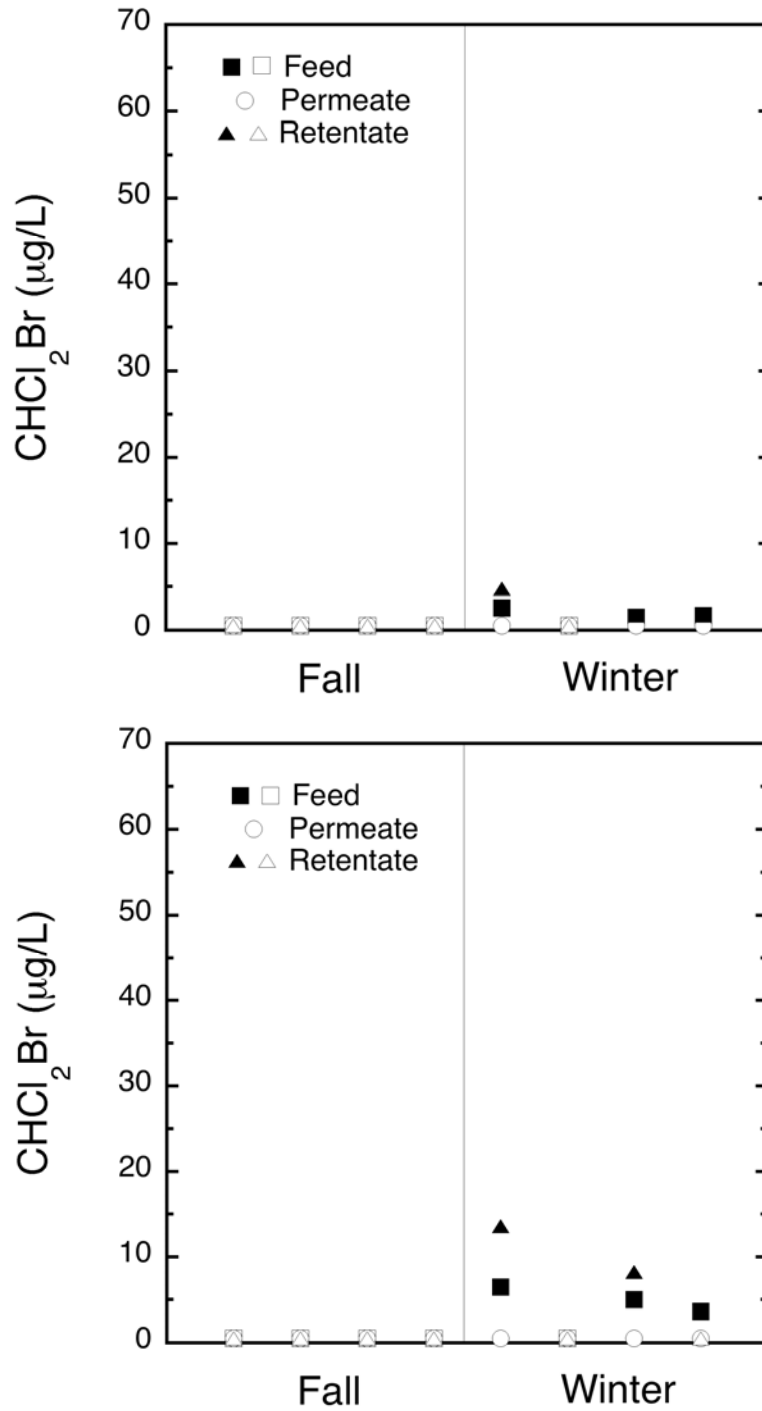
Figure 4.6. Bromodichloromethane in samples from the desalination pilot plant at 0.5-mg Cl₂/L (top) and 2.0-mg Cl₂/L (bottom) initial concentrations. Hollow symbols indicate concentrations below the limit of quantification and are plotted at half of the limit of detection.

4.3.3 HAAs

HAAs exhibited behavior similar to that observed for the THMs. Among the nine HAAs measured, monobromoacetic acid (MBAA), dichloroacetic acid (DCAA), and trichloroacetic acid (TCAA) were the most prominent species (Figures 4.7 to 4.15). In general, concentrations of HAAs increased as the initial chlorine concentration increased from 0.5 mg of Cl_2/L to 2 mg of Cl_2/L, and concentrations were similar between the fall and winter samples.

As expected, most of the HAAs were removed during RO treatment. As a result of the nearly complete rejection of the compounds, the concentrations of HAAs in the retentate were approximately twice as high as the concentrations measured in the inlet water. Despite the excellent rejection of HAAs, three of the lower-molecular-weight compounds (namely, monochromoacetic acid [MCAA], DCAA, and MBAA) were detected in the permeate at concentrations below 10 μg/L. None of the other higher-molecular-weight HAAs was present in the permeate above the limit of quantification.
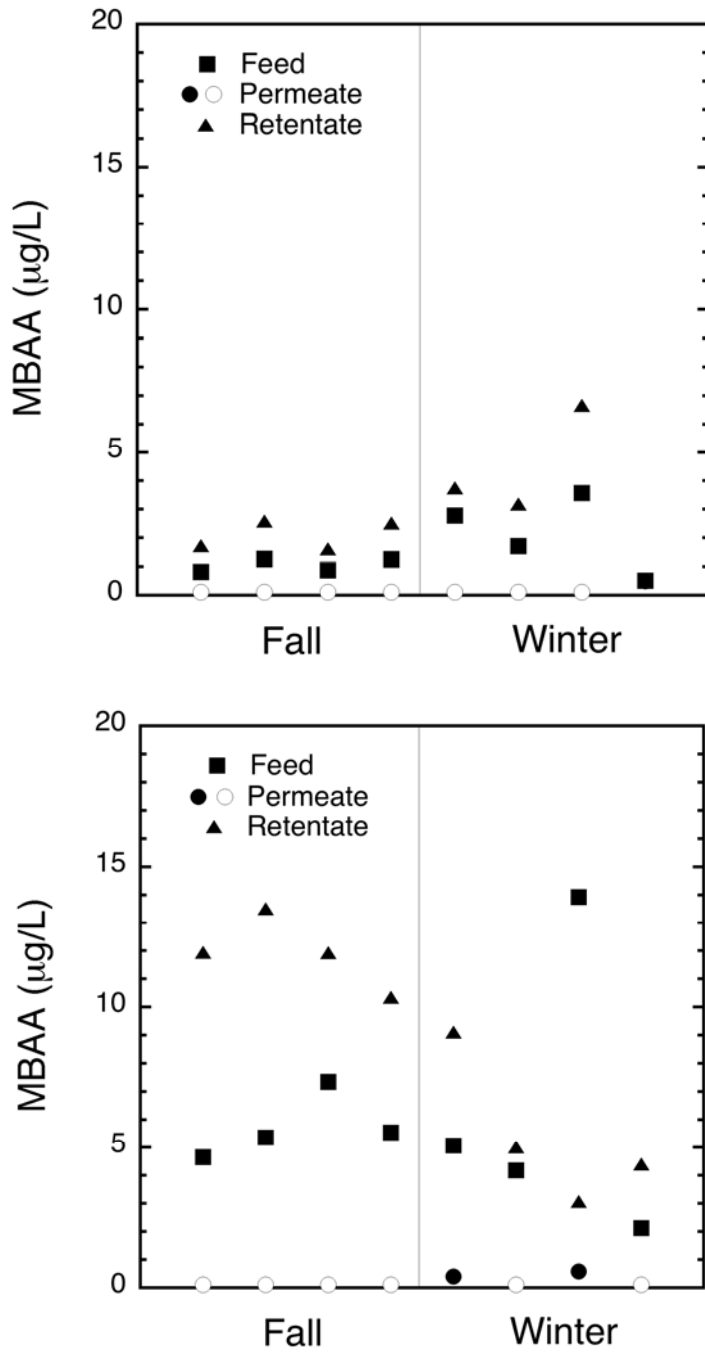
Figure 4.7. Monobromoacetic acid (MBAA) in samples from the desalination pilot plant at 0.5-mg Cl₂/L (top) and 2.0-mg Cl₂/L (bottom) initial concentrations. Hollow symbols indicate concentrations below the limit of quantification and are plotted at half of the limit of detection.
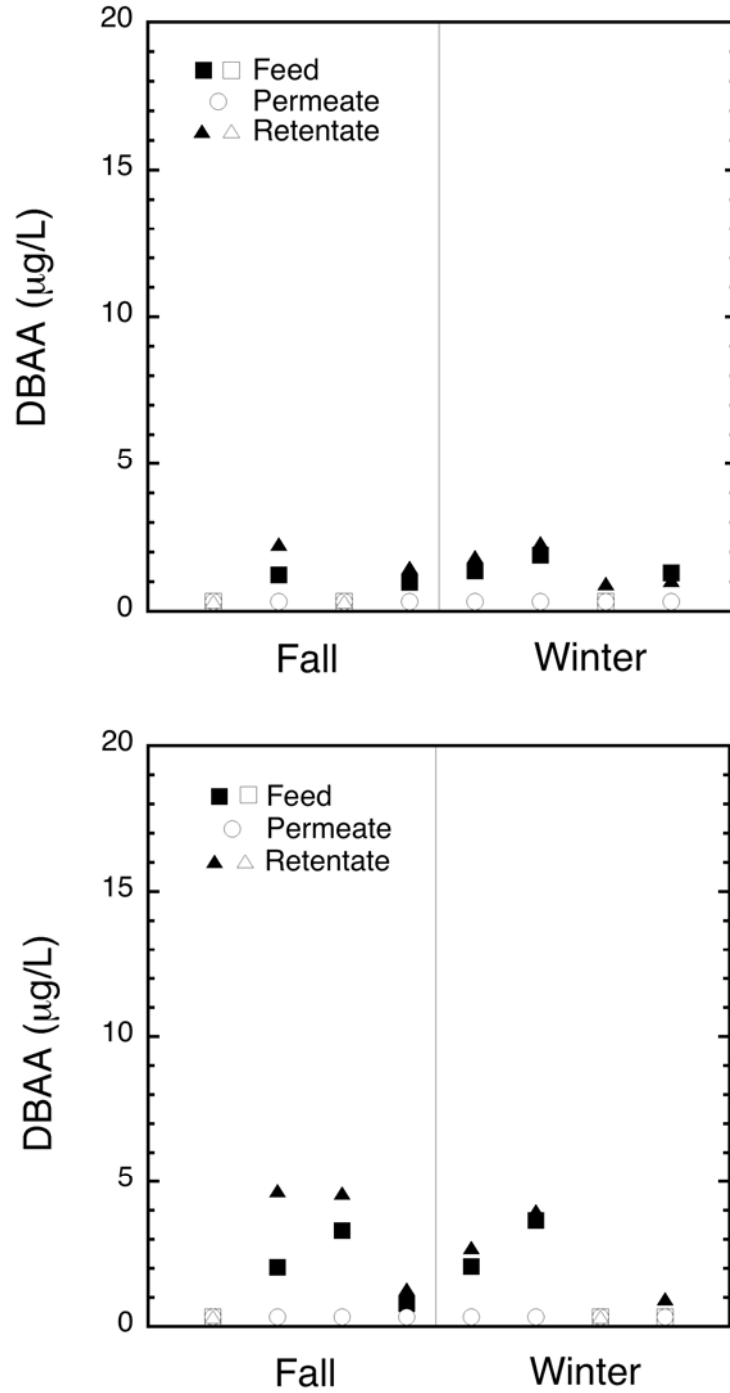
Figure 4.8. Dibromoacetic acid (DBAA) in samples from the desalination pilot plant at 0.5-mg Cl$_2$/L (top) and 2.0-mg Cl$_2$/L (bottom) initial concentrations. Hollow symbols indicate concentrations below the limit of quantification and are plotted at half of the limit of detection.
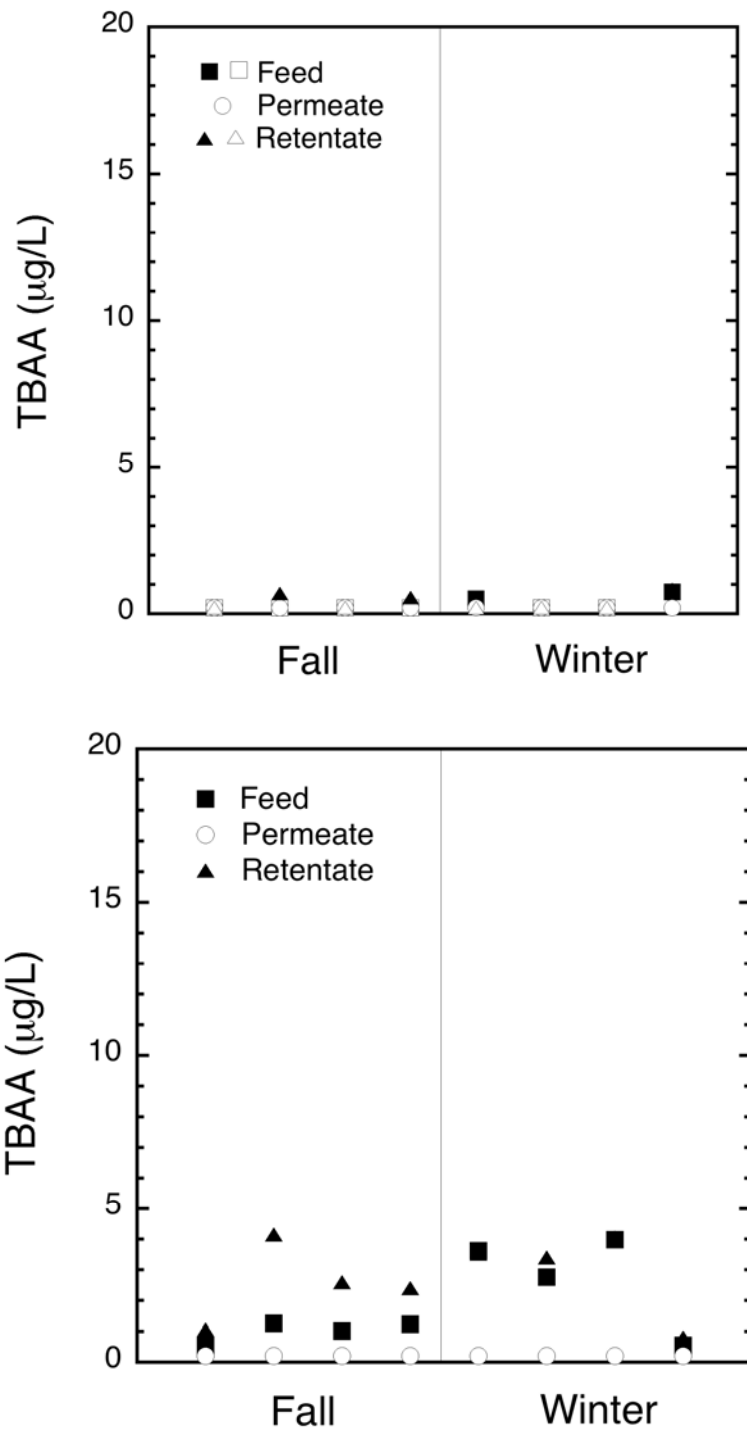
Figure 4.9. Tribromoacetic acid (TBAA) in samples from the desalination pilot plant at 0.5-mg Cl₂/L (top) and 2.0-mg Cl₂/L (bottom) initial concentrations. Hollow symbols indicate concentrations below the limit of quantification and are plotted at half of the limit of detection.
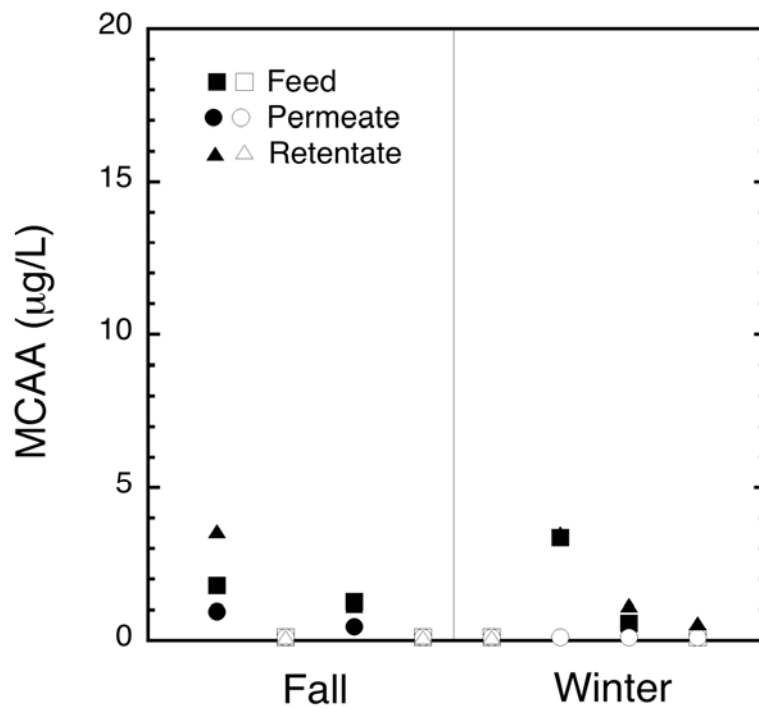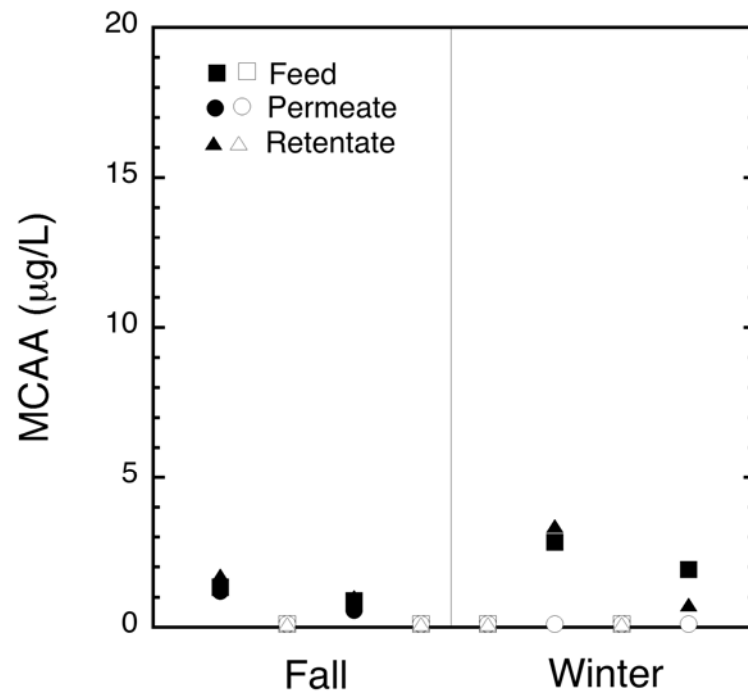
Figure 4.10. Monochloroacetic acid (MCAA) in samples from the desalination pilot plant at 0.5-mg Cl_2/L (top) and 2.0-mg Cl_2/L (bottom) initial concentrations. Hollow symbols indicate concentrations below the limit of quantification and are plotted at half of the limit of detection.
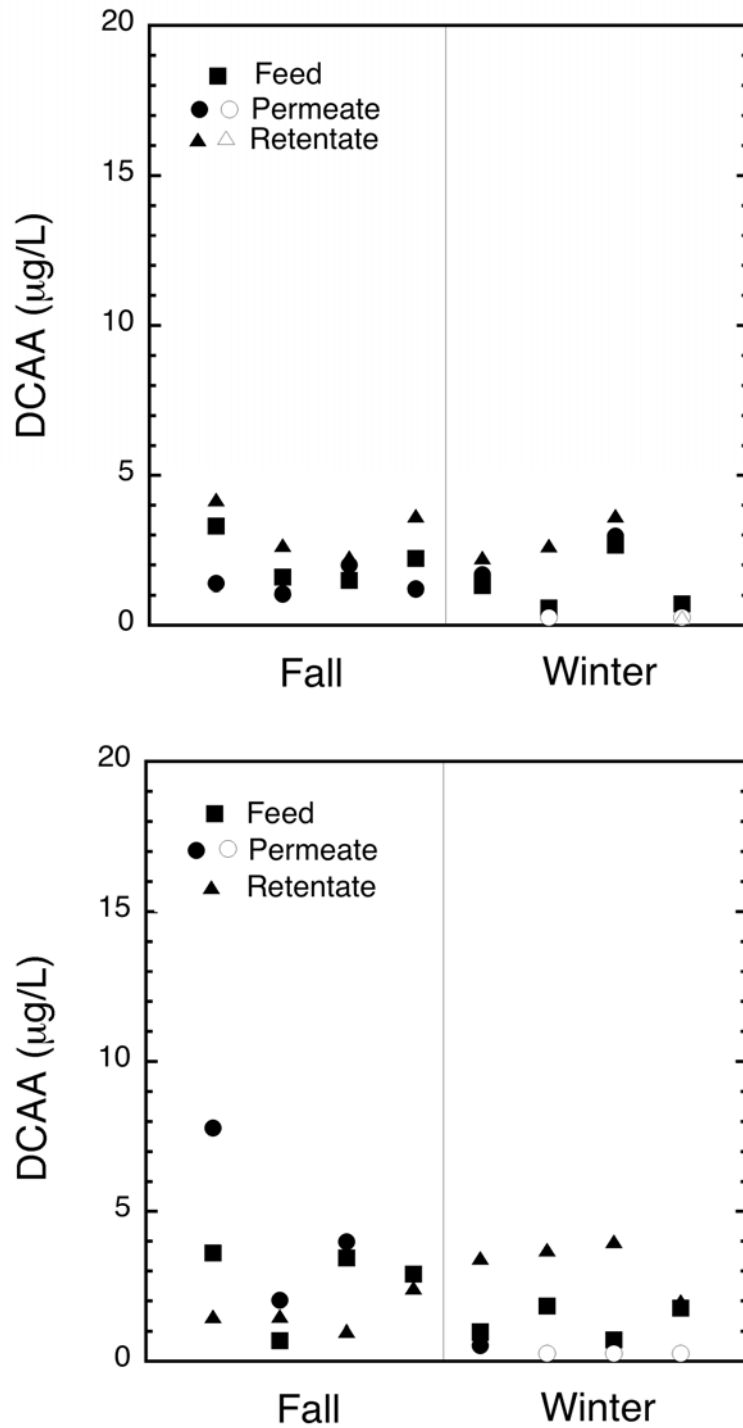
Figure 4.11. Dichloroacetic acid (DCAA) in samples from the desalination pilot plant at 0.5-mg Cl₂/L (top) and 2.0-mg Cl₂/L (bottom) initial concentrations. Hollow symbols indicate concentrations below the limit of quantification and are plotted at half of the limit of detection.
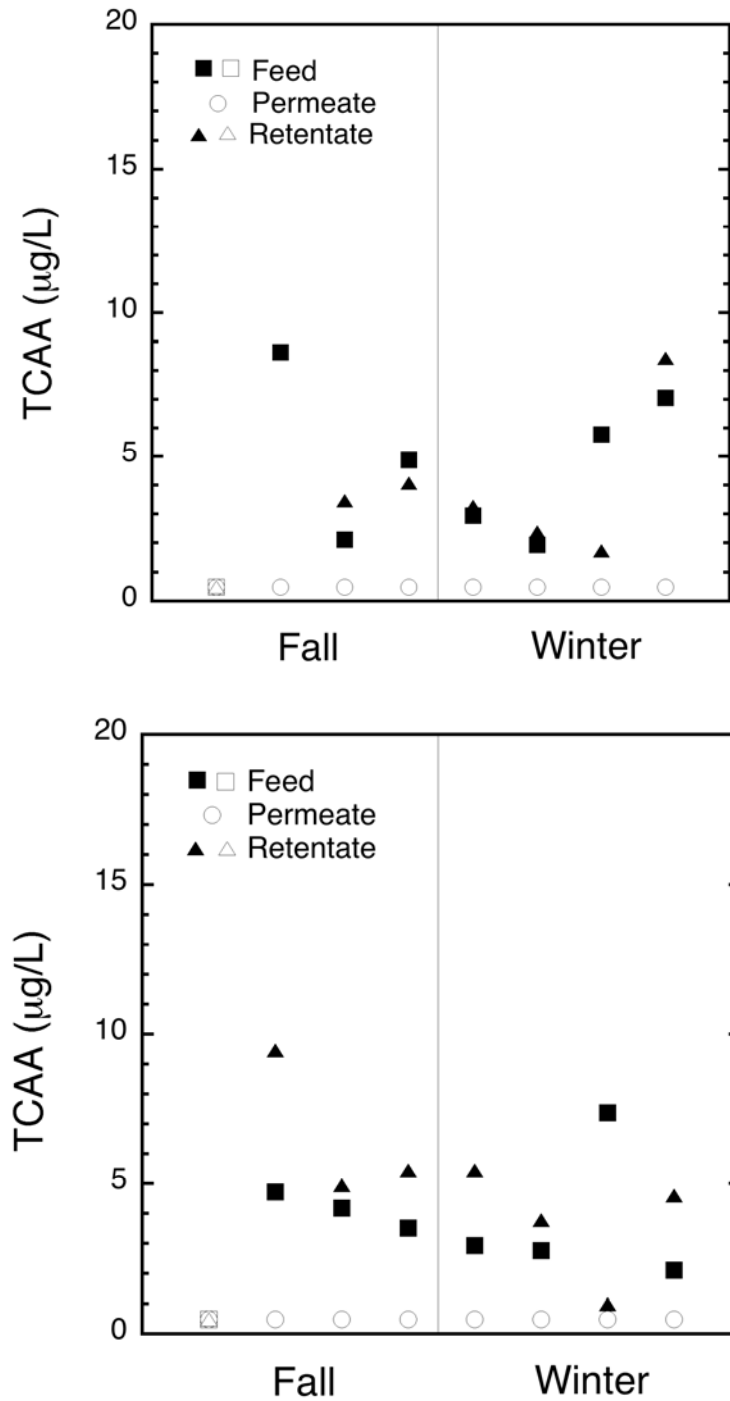
Figure 4.12. Trichloroacetic acid (TCAA) in samples from the desalination pilot plant at 0.5-mg Cl₂/L (top) and 2.0-mg Cl₂/L (bottom) initial concentrations. Hollow symbols indicate concentrations below the limit of quantification and are plotted at half of the limit of detection.
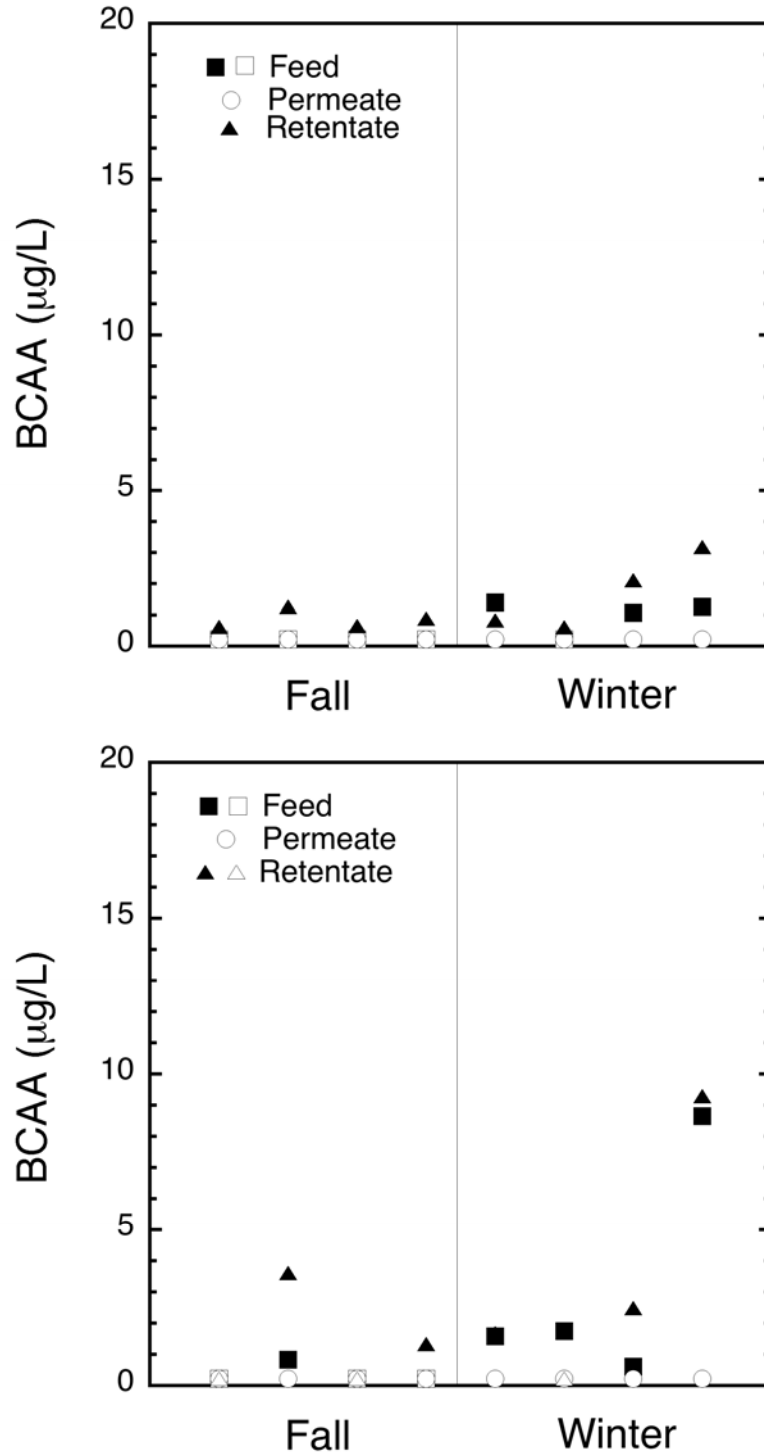
Figure 4.13. Bromochloroacetic acid (BCAA) in samples from the desalination pilot plant at 0.5-mg Cl$_2$/L (top) and 2.0-mg Cl$_2$/L (bottom) initial concentrations. Hollow symbols indicate concentrations below the limit of quantification and are plotted at half of the limit of detection.
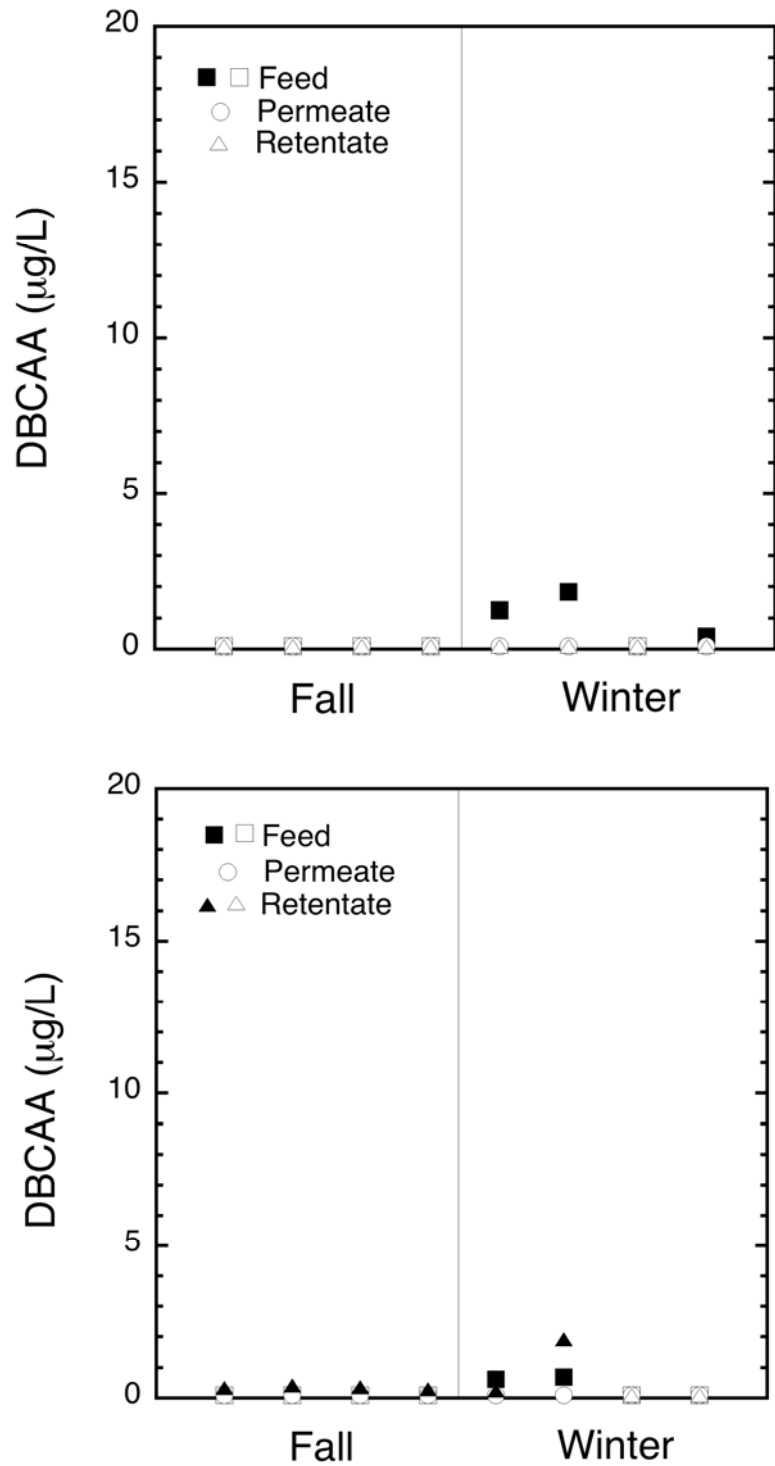
Figure 4.14. Dibromochloroacetic acid (DBCAA) in samples from the desalination pilot plant at 0.5-mg Cl$_2$/L (top) and 2.0-mg Cl$_2$/L (bottom) initial concentrations. Hollow symbols indicate concentrations below the limit of quantification and are plotted at half of the limit of detection.
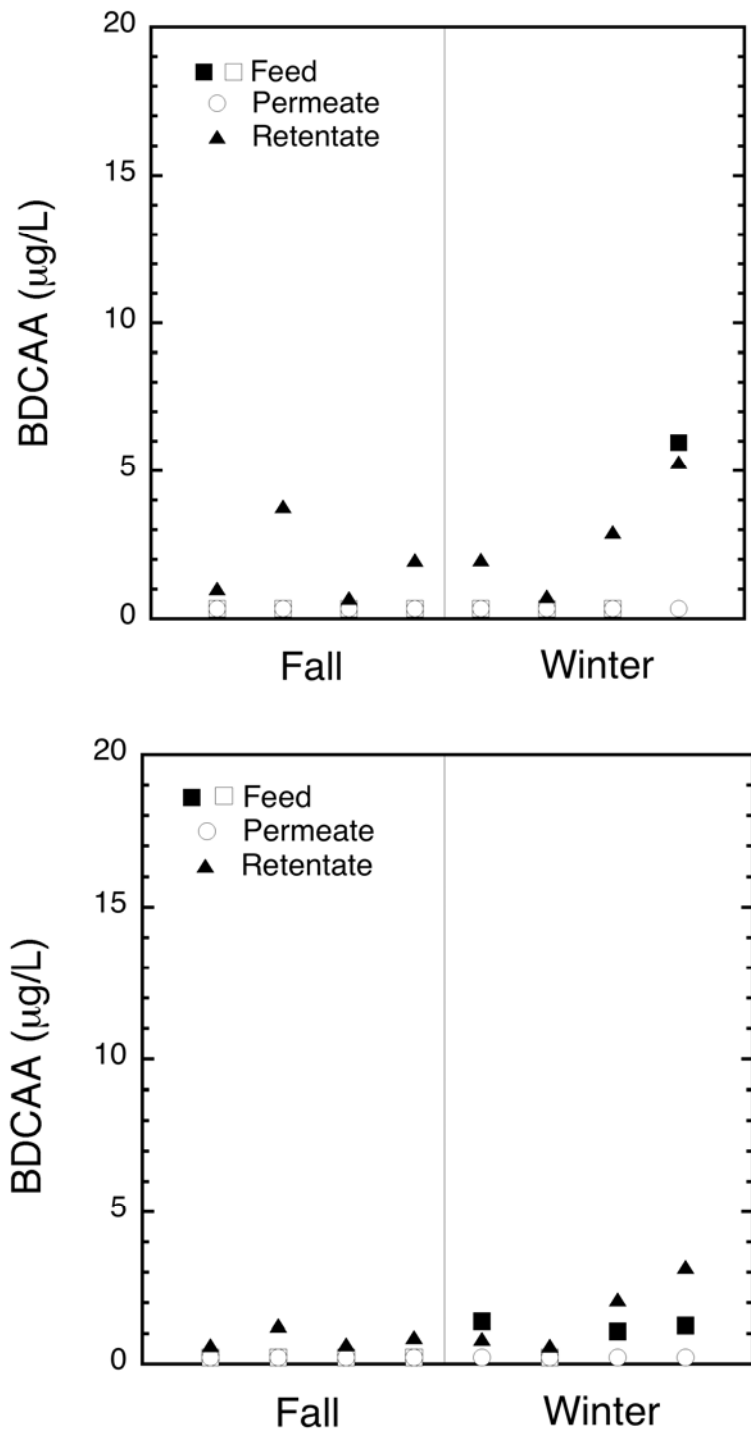
Figure 4.15. Bromodichloroacetic acid (BDCAA) in samples from the desalination pilot plant at 0.5-mg Cl$_2$/L (top) and 2.0-mg Cl$_2$/L (bottom) initial concentrations. Hollow symbols indicate concentrations below the limit of quantification and are plotted at half of the limit of detection.

4.3.4 Halophenols

As expected, brominated phenols were produced when seawater was chlorinated (Figures 4.16 to 4.18). 2,4,6-Tribromophenol was the predominant halophenol with concentrations up to approximately 0.7 μg/L in the RO feed water. Maximum concentrations of approximately 0.5 and 0.1 μg/L were detected after chlorination for 2,6-dibromophenol and 2-bromophenol, respectively. In general, concentrations of halophenols decreased as the initial chlorine concentration increased, because the sequential substitution of halogens results in further oxidation of the halophenols to THMs and HAAs. A weak temporal relationship was observed for halophenol production, with higher concentrations observed during winter.

As expected, the halophenols were removed during RO. Concentrations of halophenols in the retentate were usually about twice as high as the concentrations detected in the RO feed water, which is consistent with the conductivity data. Halophenols were never detected at concentrations above the limit of quantification in the RO permeate.
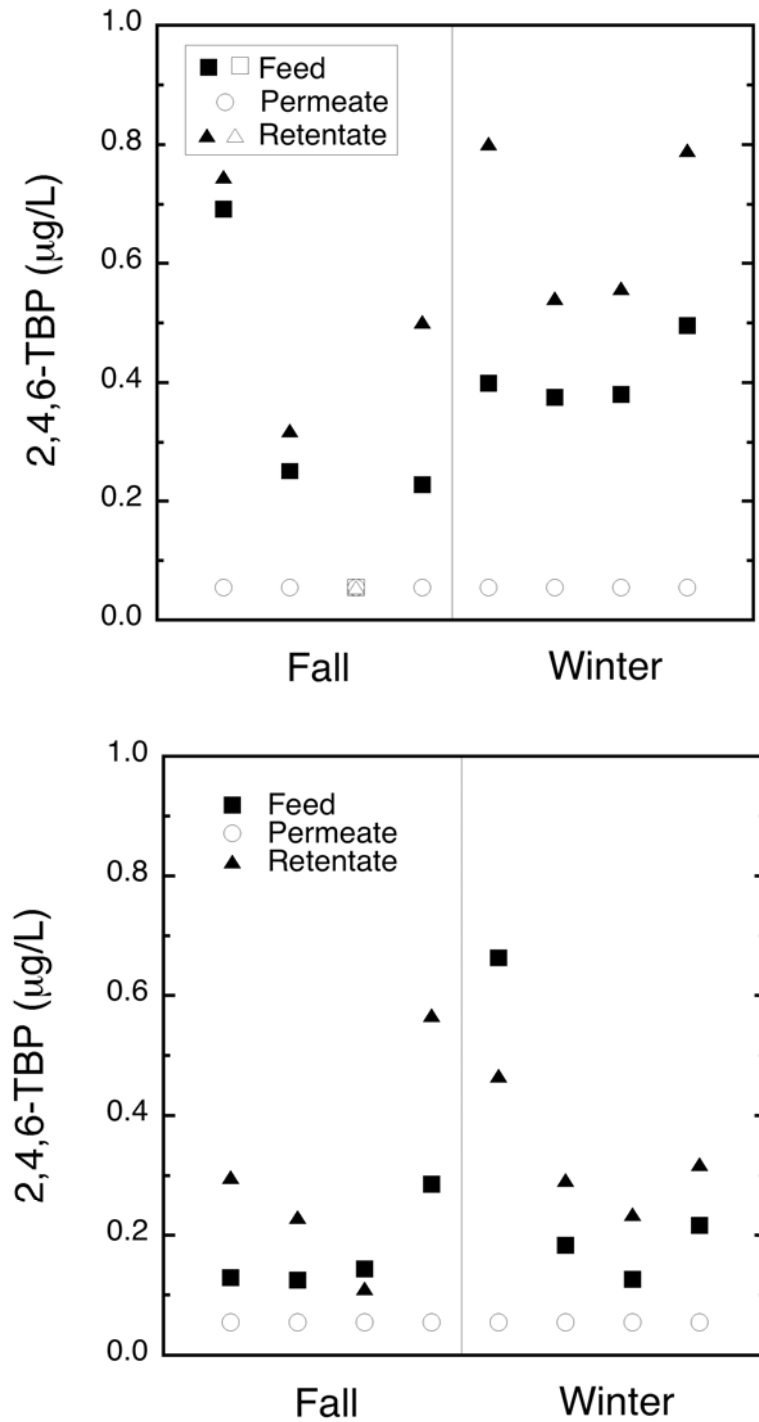
Figure 4.16. 2,4,6-Tribromophenol (2,4,6-TBP) in samples from the desalination pilot plant at 0.5-mg Cl₂/L (top) and 2.0-mg Cl₂/L (bottom) initial concentrations. Hollow symbols indicate concentrations below the limit of quantification and are plotted at half of the limit of detection.

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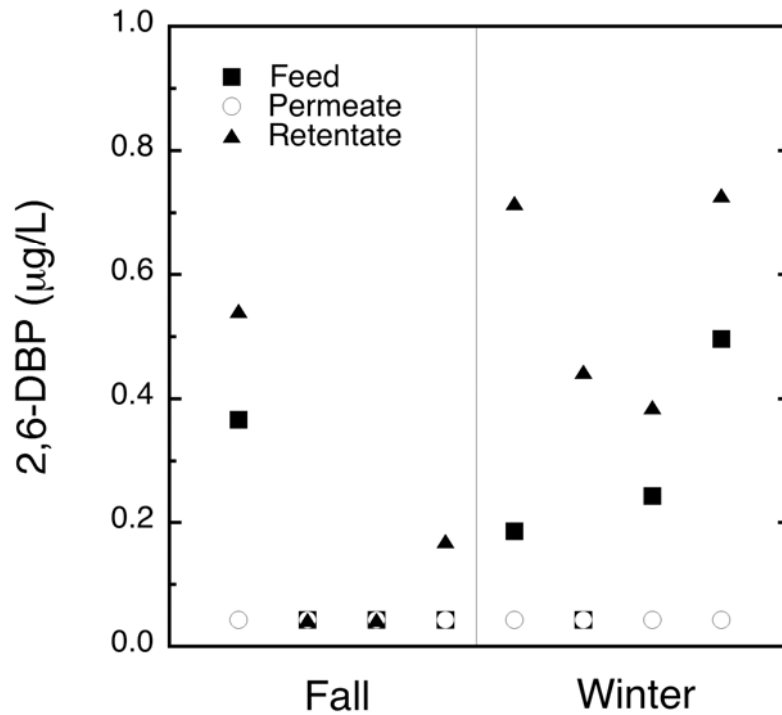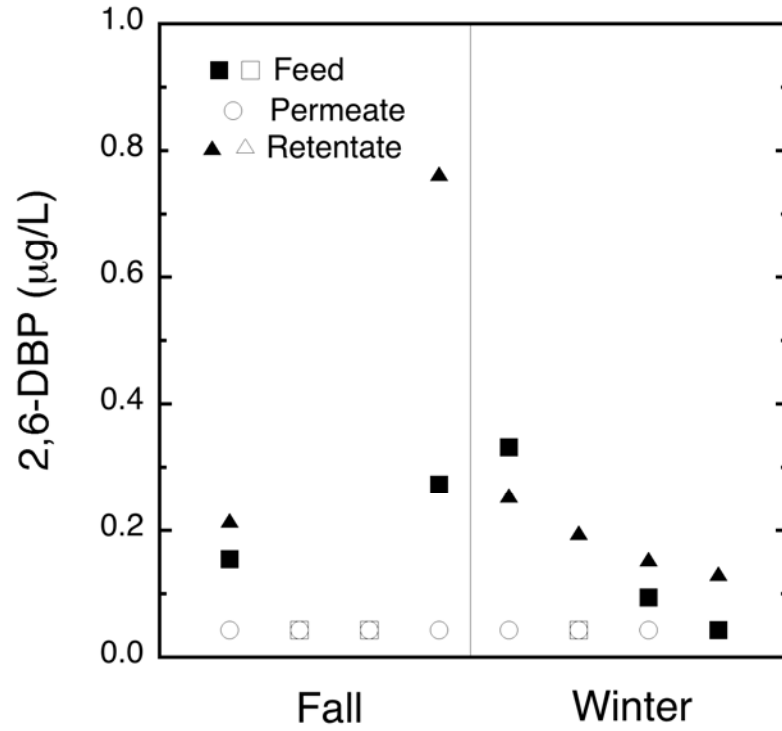
Figure 4.17. 2,6-Dibromophenol (2,6-DBP) in samples from the desalination pilot plant at 0.5-mg Cl_2/L (top) and 2.0-mg Cl_2/L (bottom) initial concentrations. Hollow symbols indicate concentrations below the limit of quantification and are plotted at half of the limit of detection.
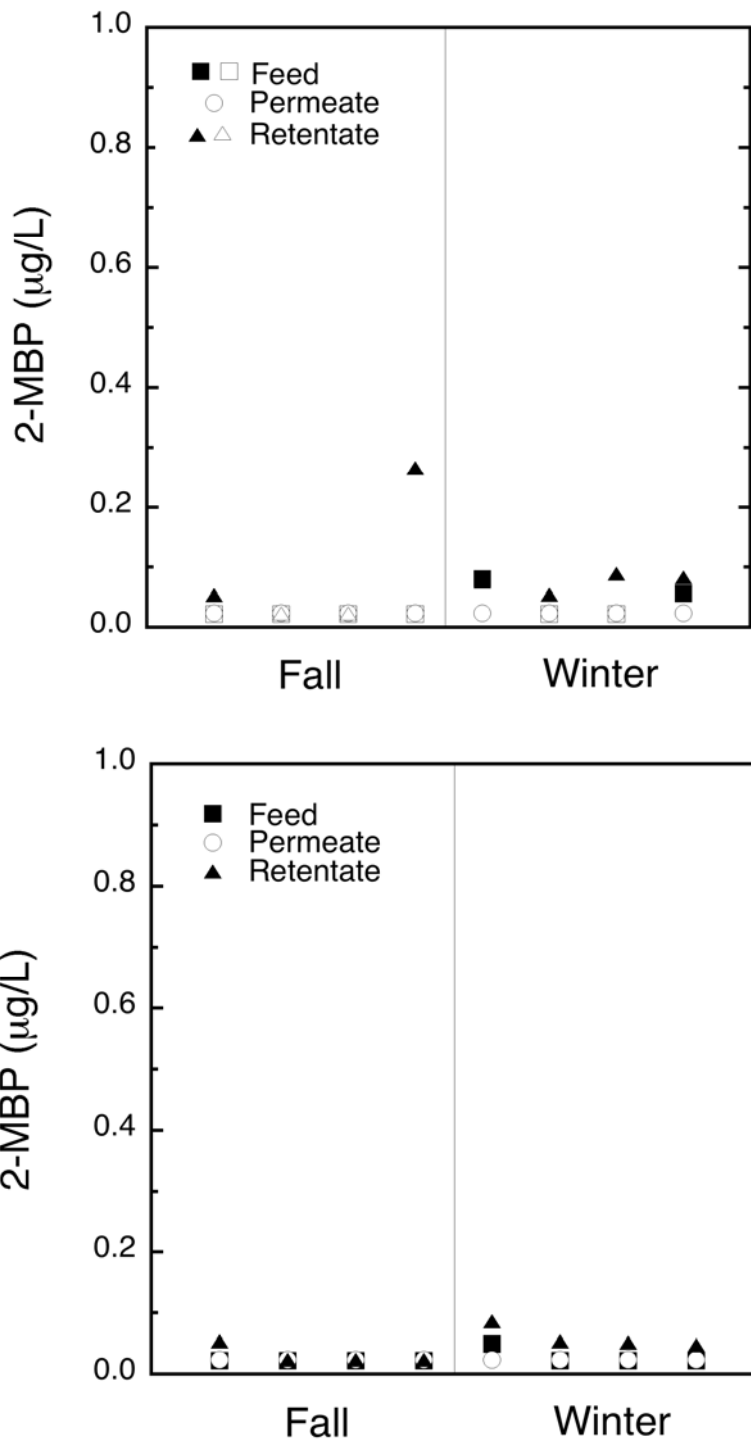
Figure 4.18. 2-Monobromophenol (2-MBP) in samples from the desalination pilot plant at 0.5-mg Cl$_2$/L (top) and 2.0-mg Cl$_2$/L (bottom) initial concentrations. Hollow symbols indicate concentrations below the limit of quantification and are plotted at half of the limit of detection.

4.3.5 HANs

Dibromoacetonitrile and bromochloroacetonitrile were detected at similar concentrations in chlorinated inlet water (Figures 4.19 and 4.20). Dichloroacetonitrile was never detected in the chlorinated seawater samples. Concentrations of HANs prior to RO were as high as 3.5 µg/L. In general, higher concentrations of dibromoacetonitrile were detected at the higher initial chlorine concentration and higher concentrations of both compounds were detected during winter.

The HANs were detected in half of the RO permeate samples at concentrations up to 0.8 µg/L. In several cases, the concentrations of HANs were approximately equal to or slightly higher than those detected before RO. If one uses only those samples in which HANs were present at concentrations above the limit of quantification in the feed water and half the limit of detection for the permeate samples in which HANs were not detected, the removal of dibromoacetonitrile during RO ranges from 20 to 93% with a median of 78%. If one uses the same approach for dibromoacetonitrile, the overall removal ranges from 0 to 95% with a median of 59%.
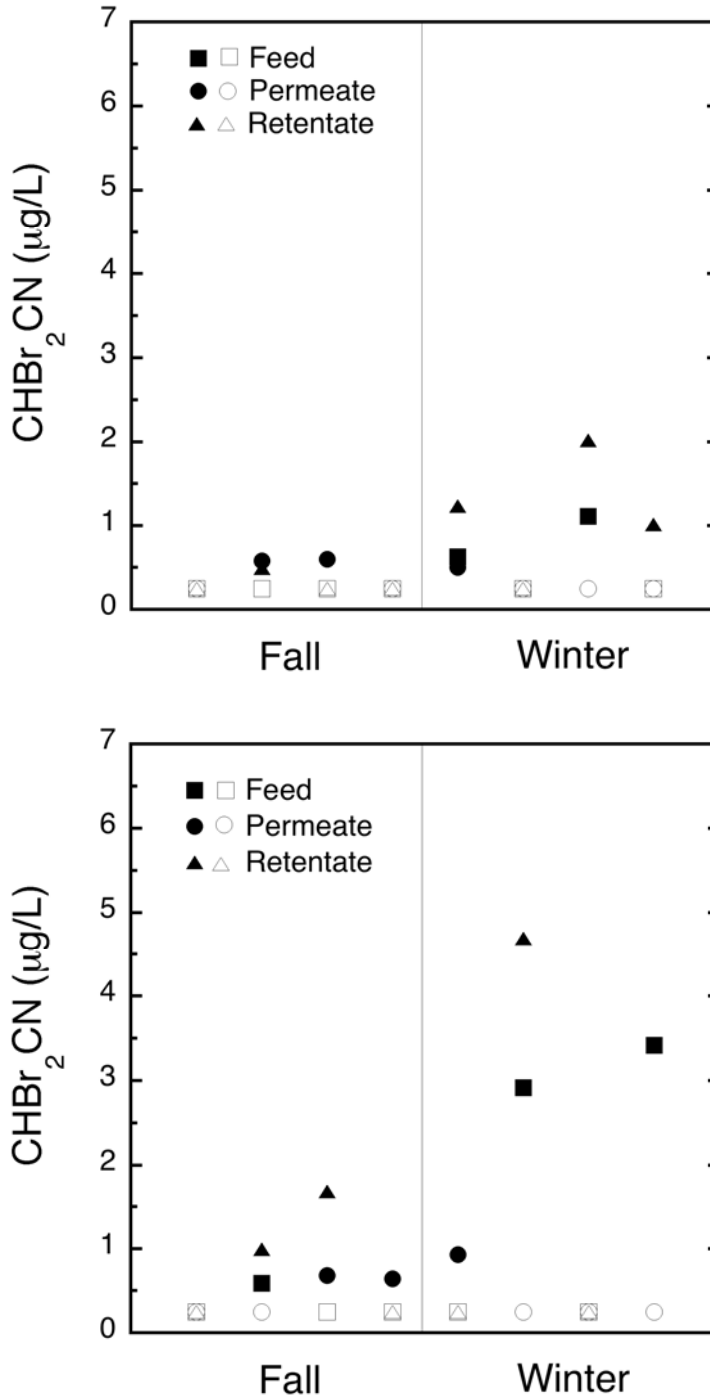
Figure 4.19. Dibromoacetonitrile (CHBr₂CN) in samples from the desalination pilot plant at 0.5-mg Cl₂/L (top) and 2.0-mg Cl₂/L (bottom) initial concentrations. Hollow symbols indicate concentrations below the limit of quantification and are plotted at half of the limit of detection.
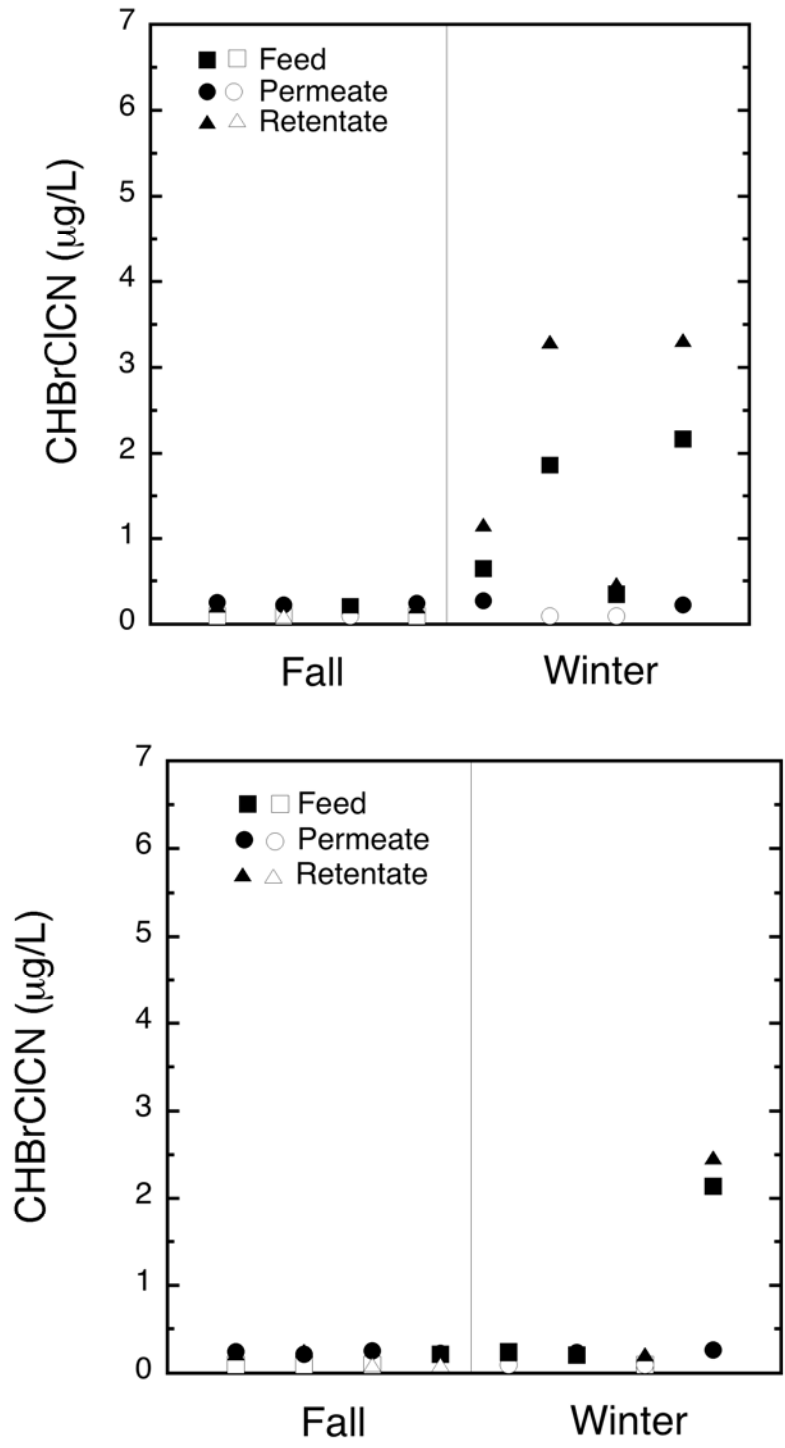
Figure 4.20. Bromochloroacetonitrile (CHBrClCN) in samples from the desalination pilot plant at 0.5-mg Cl₂/L (top) and 2.0-mg Cl₂/L (bottom) initial concentrations. Hollow symbols indicate concentrations below the limit of quantification and are plotted at half of the limit of detection.

4.4 DISCUSSION

4.4.1 Comparison with Potable Water Standards and Guidelines

As indicated in the previous section, chlorination of seawater during pretreatment resulted in the formation of chlorine disinfection byproducts. As a result of the relatively high quality of the inlet seawater at this location and the short time of contact between chlorine and seawater, the concentrations of disinfection byproducts formed during pretreatment were relatively low. A comparison between the data collected during the study and relevant drinking water standards and guidelines (Table 4.2) indicated that the chlorinated feed water would meet all relevant disinfection byproduct guidelines and standards prior to RO treatment. When these data are considered along with information on the removal of disinfection byproducts during RO, it appears that the planned desalination plant will be able to meet disinfection byproduct standards and guidelines with little risk of exceeding the standards or guidelines if chlorine is applied under the conditions employed in this study.

Table 4.2. Comparison of Observed Disinfection Byproduct Concentrations (μg/L) in Desalinated Water with Relevant Standards and Guidelines

Disinfection Byproduct[a]	Concn of Disinfection Byproduct Found at 0.5 Mg of Cl$_2$/L		Concn of Disinfection Byproduct Found at 2.0 Mg of Cl$_2$/L		Guideline
	Maximum	**Median**	**Maximum**	**Median**	
THMs	18	3.5	16	1.8	80
HAAs	4.3	2.3	8.5	3.1	60
Dibromoacetonitrile	0.60	0.25	0.93	0.42	20

[a]For THMs and HAAs, concentrations of compounds were summed using half the limit of detection for those samples in which the concentration was below the limit of quantification.

The pilot plant study described in this chapter provides additional data on the removal of disinfection byproducts during desalination. These data can be applied to the data from Chapter 3 to make predictions about disinfection byproducts in desalination water that might be produced at other locations employing the same treatment train. Using data from the pilot plant along with data on maximum concentrations of seawater from all of the locations described in Chapter 3, we can predict the maximum expected concentrations of disinfection byproducts if a plant with the configuration used in this study were constructed at locations where more disinfection byproducts were produced during pretreatment (Table 4.3). As part of our analysis, we consider a worst-case scenario using the highest observed measurement in the chlorination experiments reported in Chapter 3. Next, we calculated the median percent removal for the disinfection byproducts using removal data obtained at the pilot plant. For the THMs and HAAs, we assumed that all of the compounds would be removed to the same extent as bromoform and monobromoacetic acid, respectively. We made this assumption because these were the predominant compounds detected from the THM and HAA classes. For all of the disinfection byproducts, we calculated the percent removal, using only data for which the compounds were present at concentrations above the limit of quantification in the RO feed water. For compounds that were present at concentrations below the limit of

detection in the RO permeate, we used half the limit of detection in our calculation. Finally, we used the removal data from the pilot study to predict maximum concentrations in the RO permeate.

Table 4.3. Comparison of Predicted Worst-Case Concentrations (µg/L) of Disinfection Byproducts in Desalinated Water and Relevant Standards and Guidelines

Disinfection Byproduct	Observed RO Feed Maximum	Measured Removal	Guideline	Predicted RO Permeate Maximum	Expected Concn/Guideline
THMs	120	89%[a]	80	13	0.17
HAAs	60	96%[b]	60	2.4	0.04
Dibromoacetonitrile	20	59%	20	8.2	0.41
2,4,6-Tribromophenol	0.8	>78%[c]	0.6	<0.096	<0.16
2,6-Dibromophenol	0.2	>59%	0.0005[d]	<0.082	<160

[a]Measured removal calculated using data for which bromoform was present above the limit of quantification in the feed water.

[b]Measured removal calculated using data for which monobromoacetic acid was present above the limit of quantification in the feed water.

[c]Compound never detected in RO permeate.

[d]Data are compared to the odor threshold. Health effects occur at significantly higher concentrations.

Results from this conservative analysis suggest that none of the compounds that pose potential human health concerns (namely, THMs, HAAs, and dibromoacetonitrile) will be present in the permeate from RO treatment at concentrations above the relevant standards or guidelines. For THMs and HAAs, the maximum predicted concentrations are about an order of magnitude below the relevant standards. For dibromoacetonitrile, the maximum predicted concentration, which is based upon data on chlorination of seawater samples from Singapore and modest removal of dibromoacetonitrile observed at the pilot-scale desalination plant, is equivalent to approximately 40% of that specified by the USEPA drinking water guidelines. The concentrations of HANs formed upon chlorination of seawater from Singapore and Carlsbad during wintertime were significantly higher than those observed for the other locations sampled in this study as well as higher than the data previously reported in the literature. Therefore, the breakthrough of HANs when seawater is chlorinated as part of pretreatment may be a concern under site-specific conditions. Additional research is needed to assess the variation in HAN formation, especially in tropical coastal waters, such as those near Singapore or during wintertime conditions along the coast of Southern California.

For the halophenols, our analysis suggests that 2,4,6-tribromophenol will not be present at concentrations above the odor threshold. We were unable to reach any firm conclusion about the possible presence of 2,6-dibromophenol because the odor threshold for the compound is below the limit of quantification of our analytical method. On the basis of the maximum concentration of the compound detected in the RO feed water, over 99.5% of the compound

would have to be removed for the maximum concentration to be below the reported odor threshold. While the data collected at the pilot plant suggest that the halophenols will be well rejected during RO treatment (namely, none of the compounds was ever detected in the RO permeate), it is still possible that the compound could occasionally be present in desalinated water at concentrations above the reported odor threshold. In our review of the literature, we found no evidence that phenol-like odors have been reported by consumers of desalinated water, suggesting that the concentrations of 2,6-dibromophenol are not often above the odor threshold in desalinated water. Additional research with more sensitive analytical tools and possibly a sensory panel would be needed to resolve this issue.

4.4.2   Comparison with Data on Ecological Effects of Disinfection Byproducts

Disinfection byproducts from pretreatment with chlorine are present in the concentrate outfall from the RO process at concentrations higher than those detected in feed water. Aquatic toxicity data are unavailable for most of the disinfection byproducts analyzed in this study. However, some level of toxicity is available for two THMs and two HAAs. Maximum concentrations predicted from the chlorination experiments described in Chapter 3 as well as those maximum concentrations observed in the pilot plant concentrate outfall are compared to the available ecotoxicity threshold in Table 4.4. Additionally, the state of California established water quality criteria for THMs released into inland surface waters and estuaries to protect aquatic organisms (California Toxics Rule, 2000). These threshold levels are also listed for comparison.

Table 4.4. Comparison of Observed Maximum Disinfection Byproduct Concentrations (µg/L) in RO Concentrate and Concentrations of Concern for Aquatic Organisms

Disinfection Byproduct	Maximum Concentration in Pilot Plant[a]		Maximum Concentration in Chlorinated Seawater[b]	CTR[c] Criteria	Ecotoxicity Threshold Level[d]
	Predicted	Observed			
Chloroform	70	44	3	—	1000
Bromodichloromethane	10	8	8	46	—
Dibromochloromethane	32	9	3	34	—
Bromoform	130	64	240	360	1000
Monochloroacetic acid	6	4	5	—	7
Monobromoacetic acid	26	15	16	—	20
Trichloroacetic acid	17	19	14	—	>1000

[a]Maximum concentration in RO retentate at the Carlsbad pilot plant. Predicted values were calculated by multiplying the maximum concentration from bench-scale chlorination by 2, assuming 50% recovery at the RO membrane. Observed values are maximum concentrations actually detected in the pilot plant retentate.

[b]Predicted values were calculated by multiplying the maximum concentration after 30 min of chlorination by 2, assuming 50% recovery at the RO membrane.

[c]California Toxics Rule for the protection of aquatic organisms (California Toxics Rule, 2000).

[d]LC_{50} for oyster larvae for THMs; EC_{10} for green algae for monochloroacetic acid and monobromoacetic acid; LC_{50} for fish for TCAA. Relevant concentrations of disinfection byproducts to produce ecological effects on aquatic organisms were compiled by Agus et al. (2009).

The highest concentrations of monochloroacetic acid and monobromoacetic acid observed in some pilot plant concentrate samples approached the concentration observed to produce an adverse effect in green algae (namely, the EC_{10} value). The other threshold levels included in Table 4.4 are lethal doses that are much higher than the concentrations that may produce chronic effects. More toxicity data are needed to fully assess the risks posed by disinfection byproducts in the desalination concentrate outfalls.

It should be noted that desalination plant outfalls are designed to assure adequate dilution in the receiving waters. For example, at the proposed Carlsbad desalination project, the concentrate from the RO system will be discharged with cooling water from the co-located power plant, resulting in a dilution factor of 10. Thus, any adverse impacts of disinfection byproducts in desalination concentrate are likely to be restricted to outfalls that lack adequate dilution near the discharge point.

CHAPTER 5

FORMATION OF DISINFECTION BYPRODUCTS FOLLOWING BLENDING OF RO DESALINATED SEAWATER WITH RAW AND TREATED FRESHWATER

5.1 OBJECTIVES

Previous research on drinking water treatment indicates that elevated concentrations of bromide often lead to increased concentrations of disinfection byproducts upon chlorination (Hua et al., 2006; Krasner et al., 2006; Heller-Grossman et al., 1999). Although desalinated water contains very low concentrations of organic precursors of disinfection byproducts, it typically contains bromide at concentrations up to an order of magnitude above the median level found in freshwater sources (Agus et al., 2009). Because of the relatively high cost of producing desalinated water, there may be occasions when a utility finds it advantageous to blend desalinated water with local freshwater sources that contain relatively high concentrations of disinfection byproduct precursors. Blending with desalinated water may decrease the organic precursor concentration in the water source, but the added bromide could result in higher concentrations of certain disinfection byproducts. To address these issues, desalinated seawater was blended with raw and treated freshwater and subjected to disinfection under conditions typical of a potable water distribution system. The following experiments included raw water for blending to observe an apparent response of bromide addition to organic-matter-rich water. In practice, surface water supplies for blending with desalinated water typically have gone through treatment to remove organic precursors and will produce lower byproduct levels. The formation of disinfection byproducts was monitored and compared with predictions stated upon disinfection byproducts in samples that were chlorinated without blending.

5.2 MATERIALS AND METHODS

5.2.1 Blending Water Sources

Desalinated water used in all of the experiments was collected in 4-L glass bottles from the Carlsbad pilot-scale desalination plant during the last two sampling rounds of the pilot study described in Chapter 4.

Grab samples of untreated freshwater were collected from the Colorado River at Lake Mead, NV. The Colorado River is presently subjected to chlorination after Lake Mead to prevent the spread of an invasive species (quagga mussels). As a result, it was not practical to collect water closer to coastal drinking water treatment plants. The chlorinated near-coastal supplies would introduce an undesirable background of chlorination byproducts in samples for bench-scale experiments. The Colorado River water samples were collected in 12-L HDPE containers and filtered through 0.22-µm-pore-size membranes prior to shipment.

Pilot plant permeate and Colorado River samples were shipped with cold packs and arrived at temperatures under 5 $^{\circ}$C and were stored at temperatures below 10 $^{\circ}$C upon receipt.

Untreated water grab samples were also collected from the San Pablo Reservoir near Orinda, CA, during weekly sampling by the East Bay Municipal Utility District (EBMUD). The

reservoir collects imported water from the Mokelumne River watershed in California's Sierra Nevada mountains along with modest amounts of local runoff from the area surrounding the reservoir. San Pablo Reservoir water samples were collected in 1-L glass bottles and were transported to the laboratory within 24 h of collection.

Chloraminated tap water samples were collected from a cold-water tap at UC–Berkeley after running of the tap water for 2 min. The local utility, EBMUD, practices free chlorine disinfection of intake raw water prior to the addition of a chloramine residual at the Orinda water treatment plant, which is located near the San Pablo Reservoir and serves as the main source of potable water in Berkeley.

5.2.2   Blending and Chlorination Experiments

The chlorination of desalinated water, freshwater, and water blends was designed as a bench-scale experiment to simulate a distribution system with a chlorine residual and a 72-h maximum travel time at ambient temperature.

Prior to initiation of the experiments, the chlorine demand of permeate, freshwater, and blended samples was measured to assure that the total chlorine residual at the maximum incubation period (72 h) would exceed 0.5 mg of Cl_2/L in every sample. Since the raw freshwater samples typically exhibited the highest chlorine demand, the corresponding desalination permeate was chlorinated at the same dose as the freshwater sample. The blended samples were made by mixing the chlorinated raw water and chlorinated desalinated water at a 1:1 ratio (v/v). For Colorado River and San Pablo Reservoir samples, the initial concentration of Cl_2 needed to achieve the desired residual was 4 mg of Cl_2/L.

For experiments with tap water, the total combined residual chlorine concentration in the freshly collected tap water ranged from 2.2 to 2.5 mg of Cl_2/L. As in the raw water experiments, blend samples were made by mixing the tap water and desalinated water with the appropriate disinfectants at a 1:1 ratio (v/v). For one blending experiment, desalinated water was chloraminated to match the total combined residual found in the tap water. Another experiment was conducted in which free-chlorine-containing desalinated water was blended with chloraminated tap water. Under these conditions, the chlorine residuals rapidly break down because of breakpoint chlorination. Because this scenario is unlikely to be employed in a distribution system, the results of these experiments are not discussed in this chapter. Full results are included in Appendix B.

All disinfection experiments were conducted in 1-L amber glass bottles that had been baked at 400 $^{\circ}$C for 3 h to minimize chlorine demand. Chlorine was added as sodium hypochlorite to each 1-L bottle, and the pH was adjusted to 7.5 with 1 N H_2SO_4 for all desalinated water samples. Then each bottle was covered with a polytetrafluoroethylene (PTFE)-lined plastic cap, sealed with PTFE tape, and stored in the dark until the desired incubation period was reached. One chlorinated Milli-Q water sample, one untreated raw water sample, and one untreated desalinated water sample were analyzed for each blending scheme. A total of 20 samples were analyzed for each set of experiments.

The blending experiments were conducted in triplicate. The variation in disinfection byproduct concentration replicates varied by less than 30% for THMs and HANs and 20% for the HAAs. When a compound was not detected in one of the triplicates, a value of half the detection limit is used to calculate the average formation of disinfection byproducts. Halophenols were not analyzed in the blending experiments.

The temperature in the incubation chamber was measured twice daily, and the water temperature was measured at the end of the incubation period. At the start of each experiment, the total OC (TOC), UVA_{254}, and bromide were measured. At the end of the incubation period, for each experimental batch, the samples were quenched with excess (5-mL) 1 M sodium bisulfite and were then analyzed for disinfection byproducts.

5.2.3 Analytical Methods

Samples were analyzed for water quality parameters and chlorine disinfection byproducts using the methods described in Experimental Methods.

5.4 RESULTS

5.4.1 Water Quality Parameters

Water quality parameters measured in the blending experiments are listed in Tables 5.1 and 5.2. The freshwater samples from the Colorado River contained significantly higher concentrations of dissolved ions than did samples from the EBMUD system. The conductivity of Colorado River water was about twice as high as that of the San Pablo Reservoir and tap water samples. The highest bromide concentrations were observed in the desalinated water (mean concentration, 350 μg/L), followed by the Colorado River samples (133 μg/L). Bromide concentrations in the EBMUD water samples were approximately 35% of the concentration detected in the Colorado River samples (namely, ~50 μg/L).

Table 5.1. Water Quality Parameters Measured in Samples of Freshwater, Desalinated Water, and a 1:1 (v/v) Blended Solution Used in Bench-Scale Blending and Disinfection Experiments

Experiment	Sample	Sample Date	pH	Conductivity (μS/cm)	Bromide (μg/L)
Experiment 1	Colorado River water		7.4	514	133
	Desalinated water	3/20/2008	8.0	178	355
	1:1 (v/v) blend		7.6	290	274
Experiment 2	San Pablo Reservoir water		7.6	198	59
	Desalinated water	6/18/2008	8.0	123	388
	1:1 (v/v) blend		7.6	144	208
Experiment 3	Tap water		7.3	134	51
	Desalinated water	6/24/2008	8.0	132	360
	1:1 (v/v) blend		7.4	165	222

The two untreated freshwater samples (namely, from the Colorado River and San Pablo Reservoir) contained moderately high concentrations of DOC (7.6 and 4.7 mg of C/L). The DOC content in desalinated water was usually below the detection limit, while the treated EBMUD tap water contained <1 mg of OC/L. The $SUVA_{254}$ values indicate that the organic content of the water samples were not enriched in aromatic compounds. For one

Table 5.2. DOC Content and UVA$_{254}$ in Freshwater, Desalinated Water, and a 1:1 (v/v) Blended Solution Used in Bench-Scale Blending and Disinfection Experiments

Experiment	Sample	Sample Date	UVA$_{254}$ (cm^{-1})	DOC (mg/L)	SUVA$_{254}$ (m^{-1} L/mg)^a
Experiment 1	Colorado River water		0.086	7.6	1.13
	Desalinated water	3/20/2008	0.004	<0.65	1.23
	1:1 (v/v) blend		0.051	4.0	1.27
Experiment 2	San Pablo Reservoir water		0.092	4.7	1.96
	Desalinated water	6/18/2008	0.006	0.65	0.92
	1:1 (v/v) blend		0.043	3.0	1.44
Experiment 3	Tap water		0.011	1.4	0.77
	Desalinated water	6/24/2008	0.006	<0.65	1.85
	1:1 (v/v) blend		0.009	1.0	0.89

^{a}SUVA$_{254}$ for desalinated water were calculated by using the value of half of the detection limit.

sample, DOC was measured to be around the detection limit. SUVA values for desalinated water were calculated by using the value of half of the detection limit. Blending of raw Colorado River water with desalinated water reduced the DOC concentration by approximately 50%. Since the Colorado River water already had relatively high concentrations of bromide, blending with desalinated water reduced the bromide concentration by only around 20%.

Blending decreased the DOC content in San Pablo Reservoir water by around 40%. However, the addition of desalinated water increased the concentrations of bromide in the blend by a factor of 4. Blending had less of an effect on the DOC concentration in tap water because significant amounts of TOC were removed during water treatment. As a result, blending experiments conducted on untreated waters are likely to overestimate the concentrations of disinfection byproducts created. However, they are useful because they help illustrate trends for disinfection byproduct creation.

5.4.2 Chlorine Decay

Following the addition of chlorine to water from the Colorado River and San Pablo Reservoir and to blended waters, the residual gradually decreased over 72 h (Figure 5.1). In both raw waters, the concentration of chlorine remained relatively constant after the initial rapid decay that occurred in the first 24 h. In the desalinated water, the chlorine concentration decreased by less than 20% over the 72-h contact time. For Colorado River and San Pablo Reservoir waters, residuals in the blend with desalinated water were up to 0.5 mg of Cl_2/L lower than predicted by the volumetric average of the freshwater and desalinated water. The slightly faster-than-expected decrease in chlorine concentration in the blended water may be attributed to the higher reactivity of HOBr, which one would expect to be present at a higher concentration in the blended water.
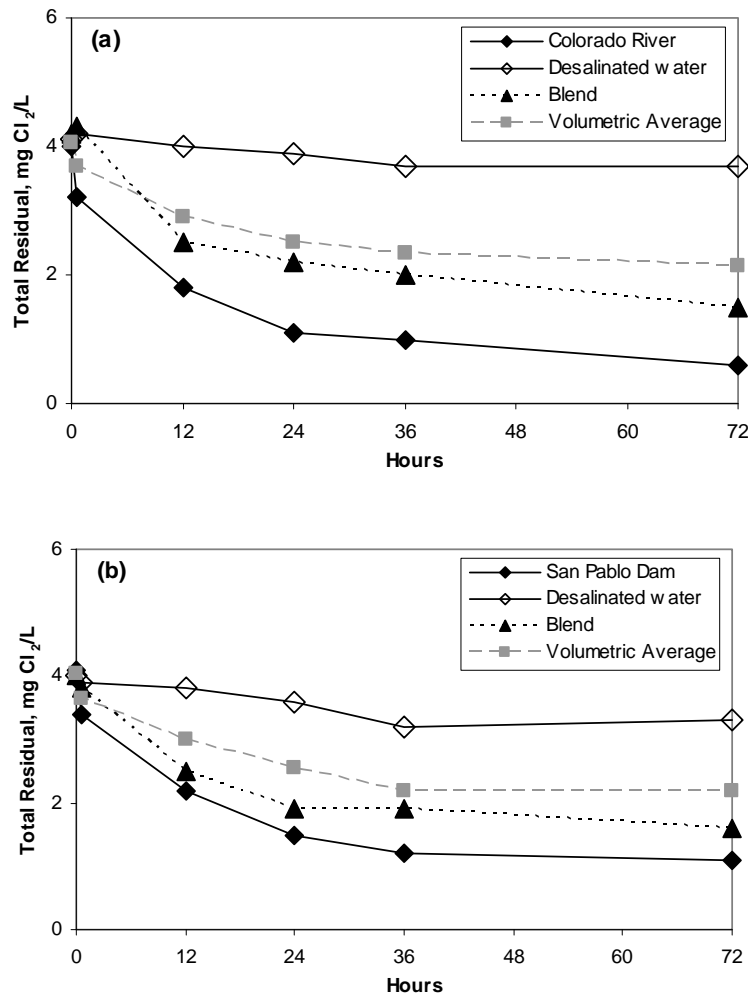
Figure 5.1. Total chlorine residual (mg of Cl_2/L) during chlorination of RO permeate from the desalination pilot plant water blended (1:1 [v/v]) with raw (a) Colorado River and (b) San Pablo Reservoir waters. The volumetric average represents predictions made using data from the two unmixed sources.

Residual chlorine exhibited different trends when chloramines were added to EBMUD tap water (Figure 5.2). After an initial drop in total chlorine residual in the desalinated water, the residual chloramines were stable through the 72-h incubation period. The initial drop of about 1 mg of Cl_2/L, which has been reported previously, is attributable to the formation of highly reactive bromamine species (McGuire, 2004).
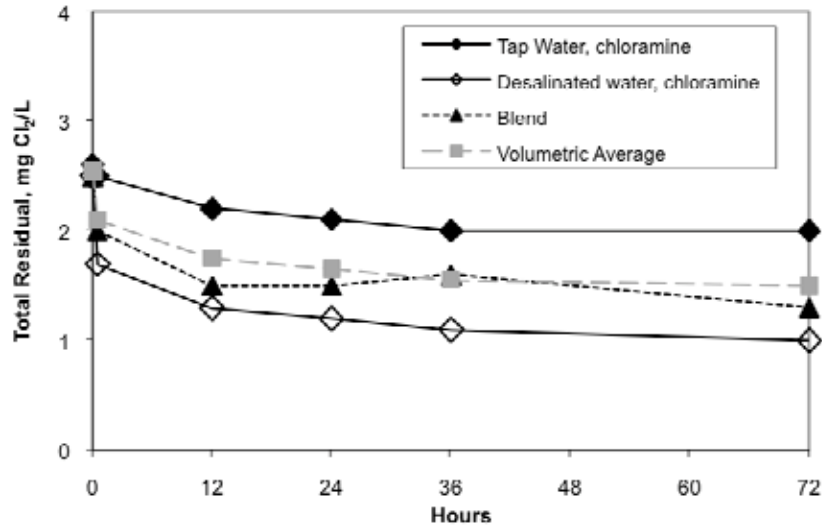
Figure 5.2. Total residuals (mg of Cl_2/L) during blending (1:1 [v/v]) of chloraminated EBMUD tap water with chloraminated RO permeate from the desalination pilot plant. The volumetric average represents predictions made using data from the two unmixed sources.

5.4.3   Disinfection Byproducts

5.4.3.1   THMs

In experiments with untreated Colorado River water, more brominated compounds accounted for a larger fraction of the THMs in the blended water than in chlorinated surface water (Figure 5.3). The most common species of THMs found in the chlorinated Colorado River water were dibromochloromethane (49%) and chloroform (36%). After blending, bromodichloromethane (39%) and dibromochloromethane (41%) were the dominant species detected in the blended water. Bromoform, which was not detected in the Colorado River sample, was present at concentrations up to 20 μg/L (17% of the total THMs) in chlorinated blended water. Predictions made by using the volumetric average (grey squares in Figures 5.3 to 5.6) overestimate the concentrations of chloroform in the blended water and, vice versa, underestimate the brominated compounds.
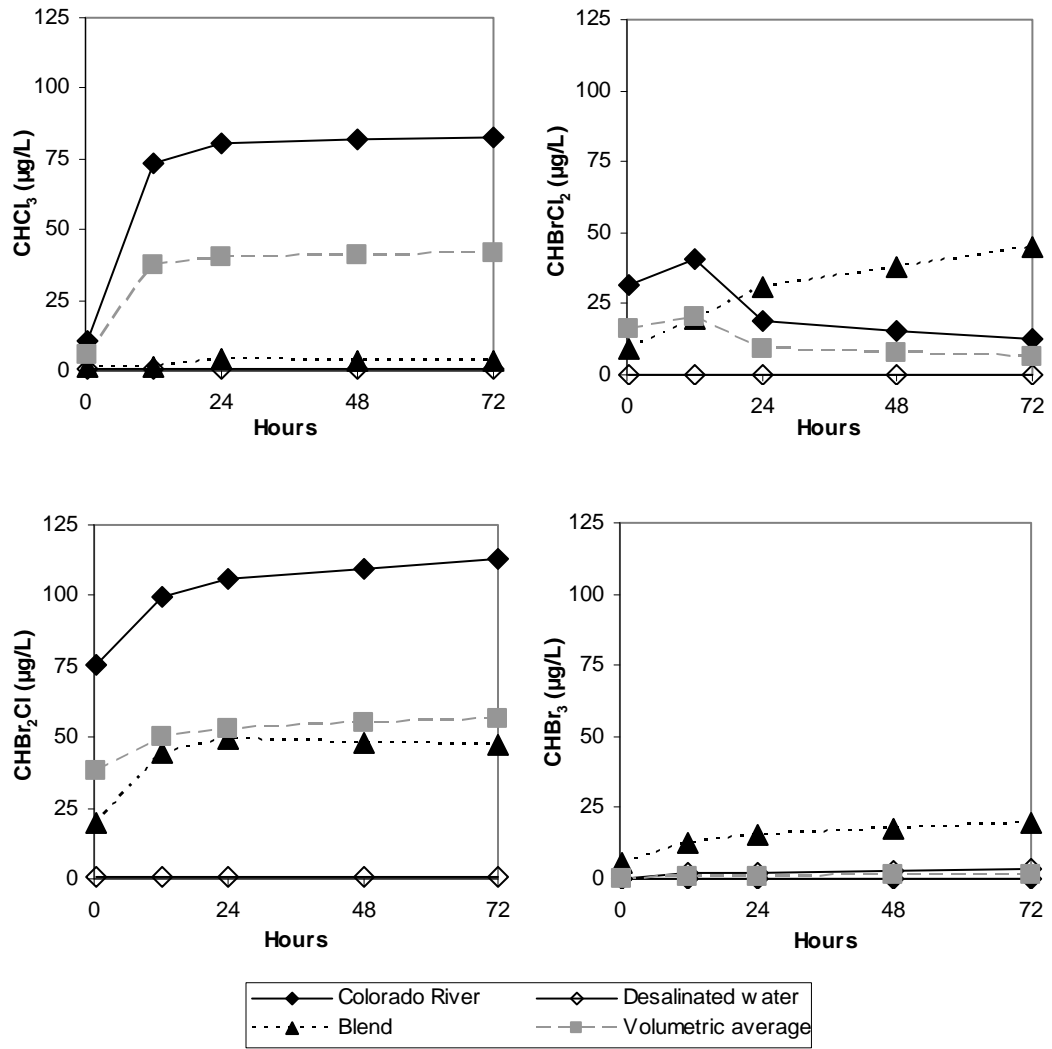
Figure 5.3. Chloroform, bromodichloromethane, dibromochloromethane, and bromoform during chlorination of RO permeate from the desalination pilot plant water blended (1:1 [v/v]) with raw Colorado River water. The volumetric average represents predictions made using data from the two unmixed sources.

We did not observe an increase in total THM production relative to predictions based on the volumetric average of THM concentrations expressed on a mass-per-volume basis in the chlorinated blend of Colorado River water with desalinated water (Figure 5.4). The Colorado River water sample obtained for this experiment already contained a rather high concentration of bromide (133 μg/L). Hence, the effect of the bromide addition from the desalinated water was small. In this analysis, we have used the mass-per-volume basis because water quality regulations often use the mass concentration. However, this approach does not account for the differences in the molecular weights of the individual THMs. An analysis of byproduct formation by a molar basis is addressed in Discussion.
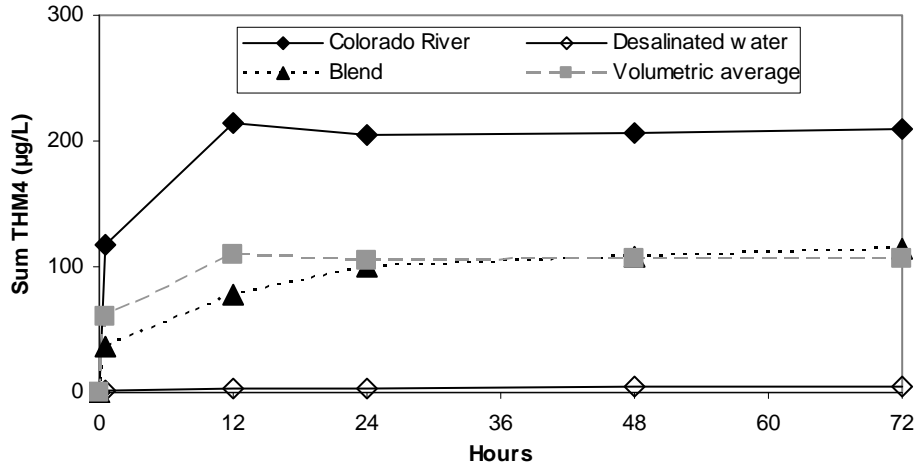
Figure 5.4. Sum of THMs during chlorination of RO permeate from the desalination pilot plant water blended (1:1 [v/v]) with raw Colorado River water. The volumetric average represents predictions made using data from the two unmixed sources.

Because of the lower initial bromide concentration in the San Pablo Reservoir water, the speciation shift from chlorinated to brominated forms of THMs upon blending is more apparent than that observed in the Colorado River water (Figure 5.5). The speciation of THMs in the experiments shifted from mostly chloroform (80%) in the chlorinated San Pablo Reservoir water to mainly bromodichloromethane (75%) in the blended water samples.
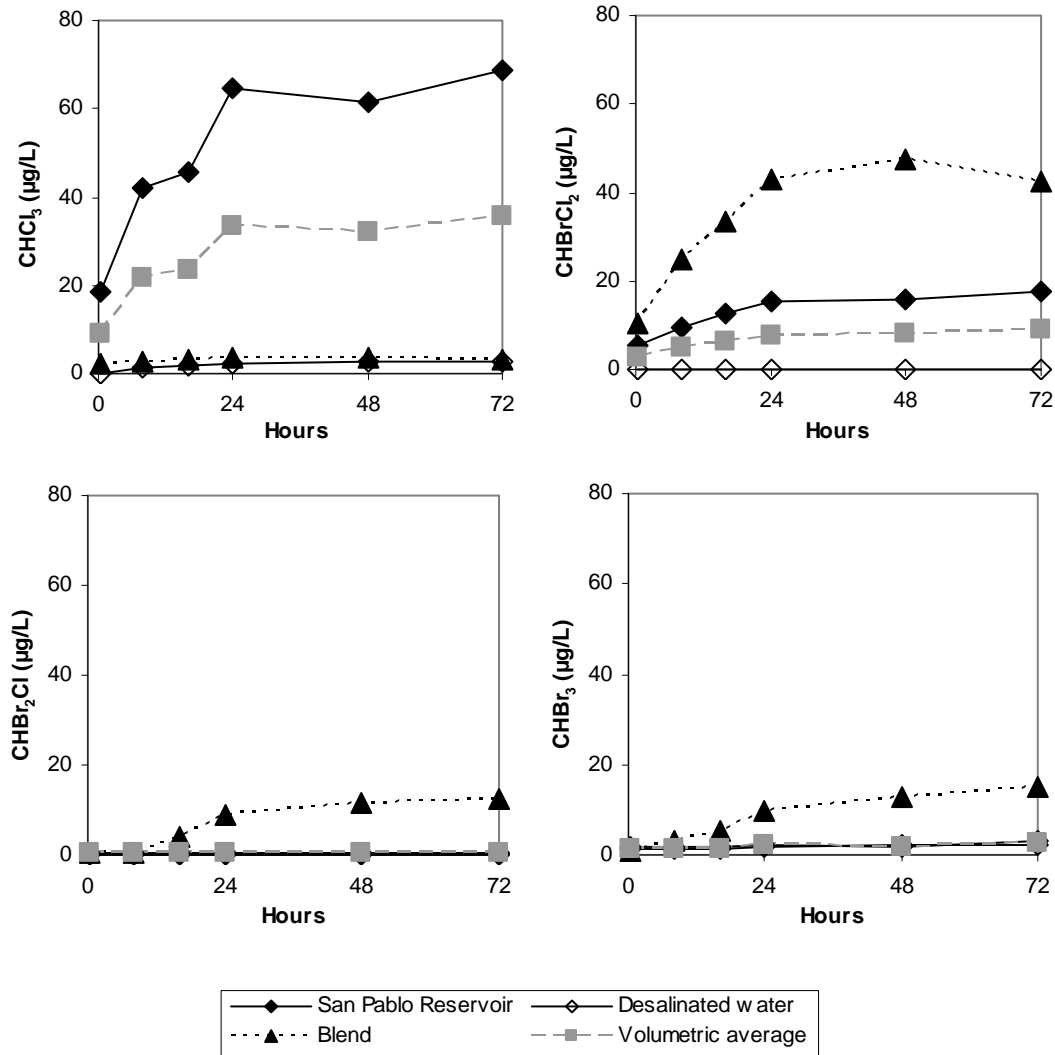
Figure 5.5. Chloroform, bromodichloromethane, dibromochloromethane, and bromoform during chlorination of RO permeate from the desalination pilot plant water blended (1:1 [v/v]) with raw San Pablo Reservoir water. The volumetric average represents predictions made using data from the two unmixed sources.

Total THM production increased significantly above the volumetric average for the blend of San Pablo Reservoir water and desalinated water (Figure 5.6). At the end of the 72-h incubation period, total THMs detected in the blended water were almost equal to those observed in the San Pablo Reservoir water prior to blending.
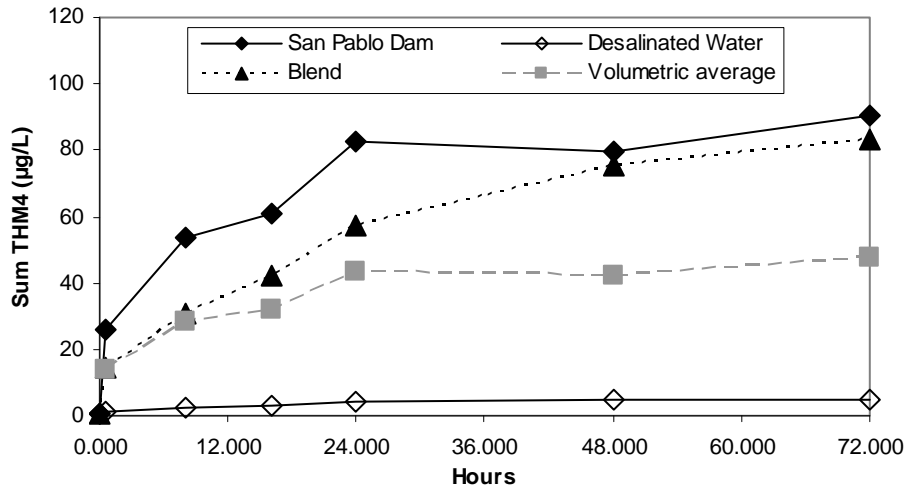
Figure 5.6. Sum of THMs during chlorination of RO permeate from the desalination pilot plant water blended (1:1 [v/v]) with raw San Pablo Reservoir water. The volumetric average represents predictions made using data from the two unmixed sources.

As expected with the use of chloramines, little THM formation was observed in desalinated water, tap water, or blended water (Figures 5.7 and 5.8). Prior to the initiation of the experiment, the tap water collected from the EBMUD source already had relatively low concentrations of THMs (up to 15 μg/L) as a result of free chlorine disinfection in the water treatment plant. The most prominent detected THM in the tap water was chloroform at around 8 μg/L. No increase in THM concentration was observed during the incubation of blended samples.
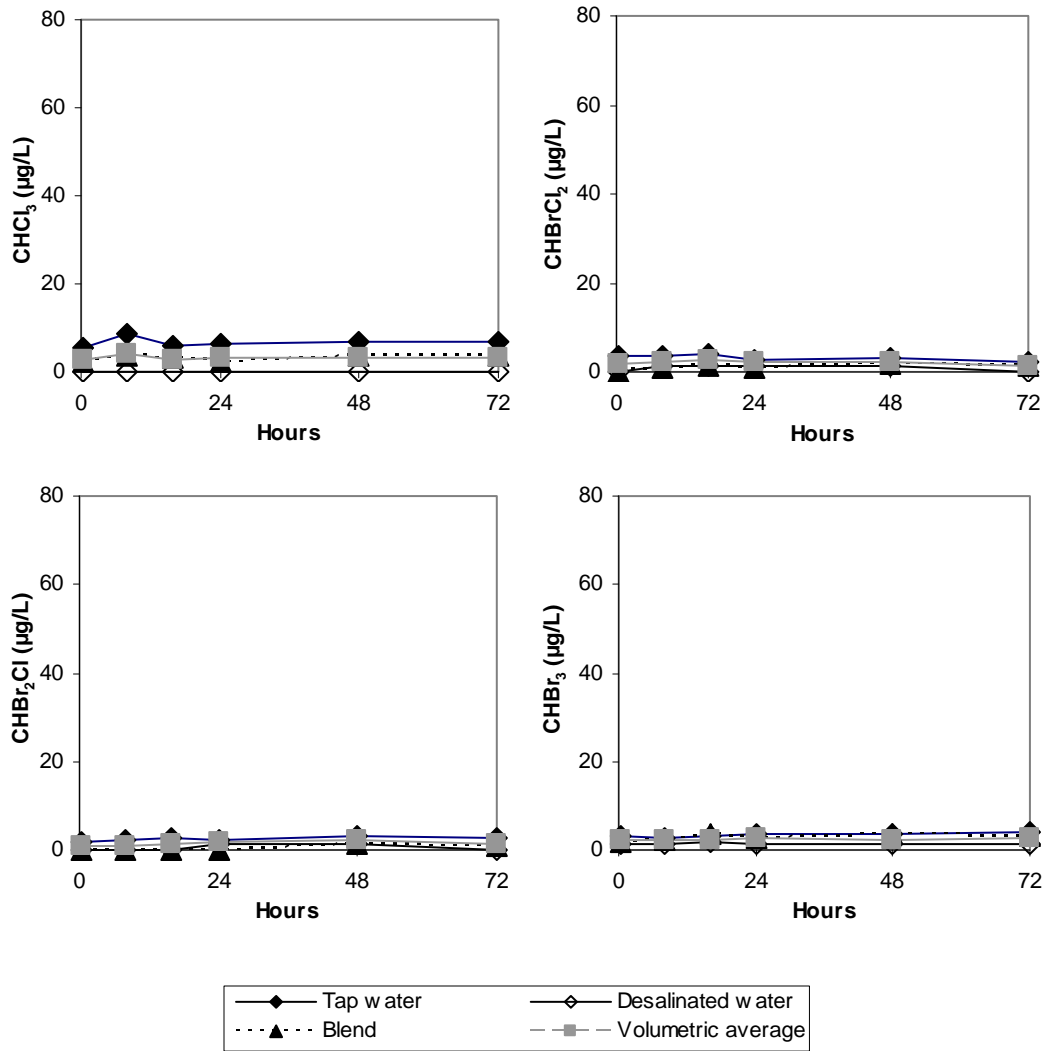
Figure 5.7. Chloroform, bromodichloromethane, dibromochloromethane, and bromoform during blending of chloraminated desalinated water and chloraminated tap water (1:1 [v/v]). The volumetric average represents predictions made using data from the two unmixed sources.
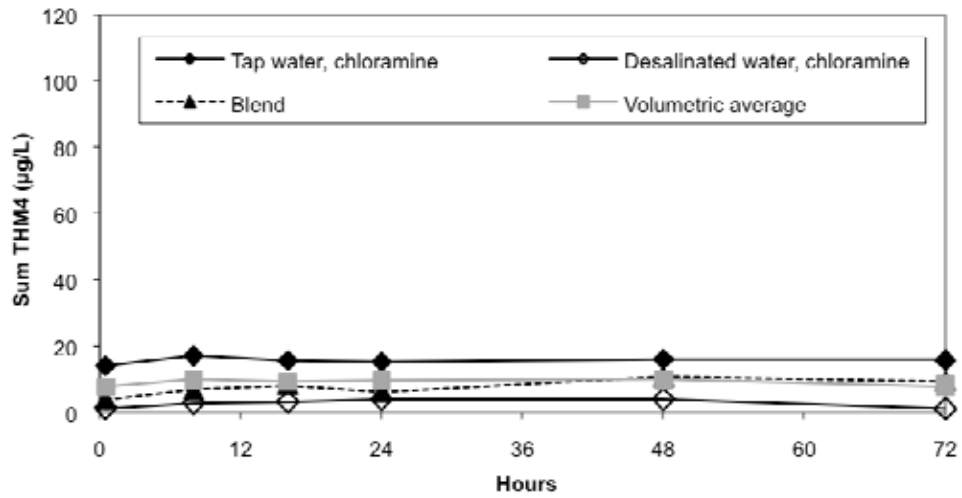
Figure 5.8. Sum of THMs during blending of chloraminated desalinated water and chloraminated tap water (1:1 [v/v]). The volumetric average represents predictions made using data from the two unmixed sources.

5.4.3.2   HAAs

A shift in speciation from chlorinated to brominated HAAs was observed when the untreated Colorado River water blended with desalinated water (Figure 5.9). The most abundant chlorine-containing HAA in the Colorado River samples was trichloroacetic acid (12%), which decreased to 5% of the total HAA9 in the blended water samples. Two brominated HAAs were detected at similar concentrations in the chlorinated Colorado River water—dibromochloroacetic acid (21%) and dibromoacetic acid (17%). In the blended water, brominated HAAs accounted for a larger fraction of the compounds—dibromoacetic acid (20%) and tribromoacetic acid (17%). Again, the shift observed was subtle because of the relatively high bromide concentrations in the Colorado River water. Chlorination of the desalinated permeate produced only about 9 µg of total HAAs/L, with bromodichloroactic acids accounting for 54% of the total HAAs.
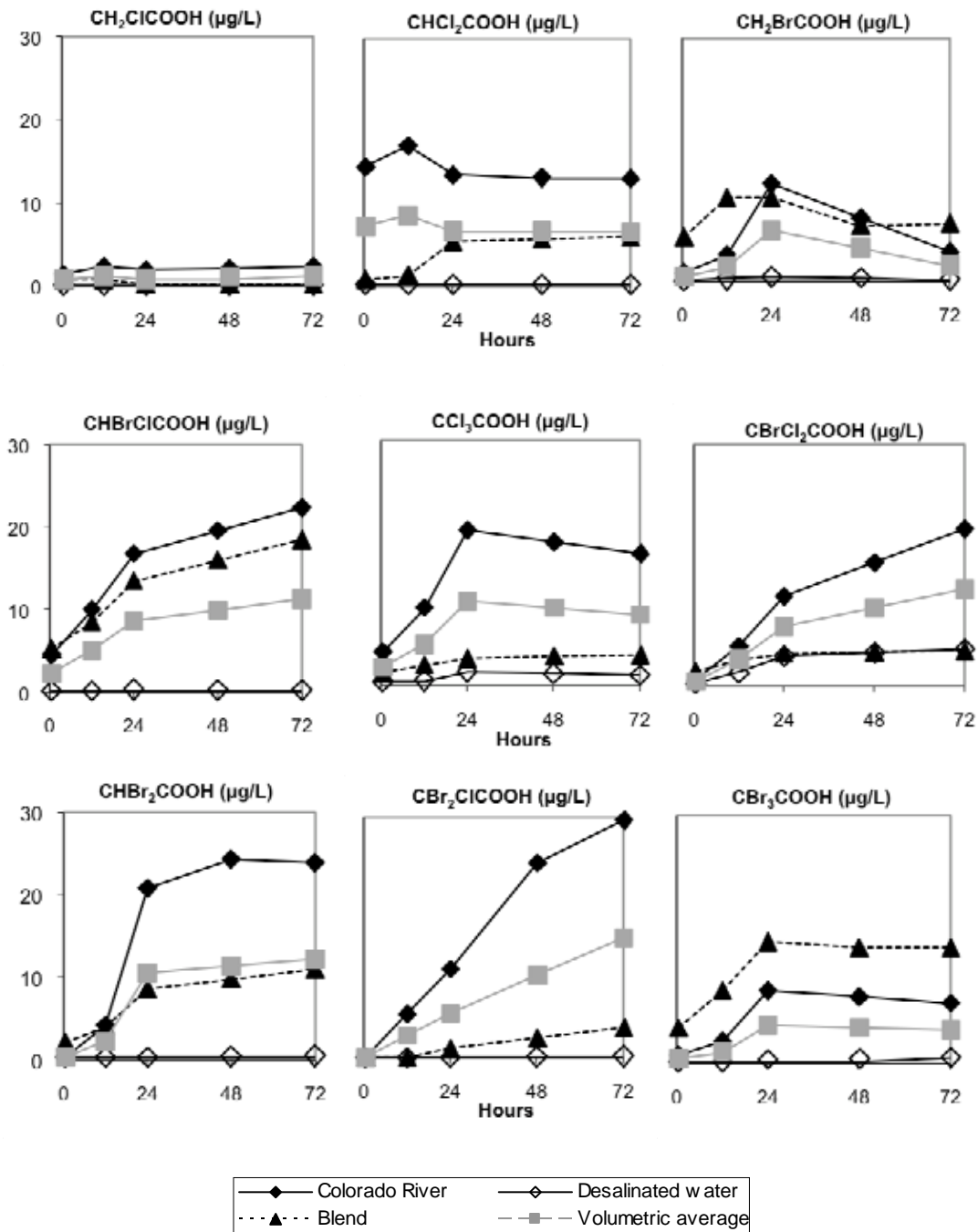
Figure 5.9. Individual HAAs (HAA9) during chlorination of RO permeate from the desalination pilot plant water blended (1:1 [v/v]) with raw Colorado River water. The volumetric average represents predictions made using data from the two unmixed sources.

The sum of the HAAs (namely, HAA9) produced in the blended Colorado River roughly corresponds with the concentration predicted by the volumetric average (Figure 5.10). At the end of the 72-h incubation period, the concentration of HAAs produced after blending desalinated water with raw high-DOC and high-bromide water, expressed in mass-per-volume basis, was approximately half of the value for the Colorado River water.
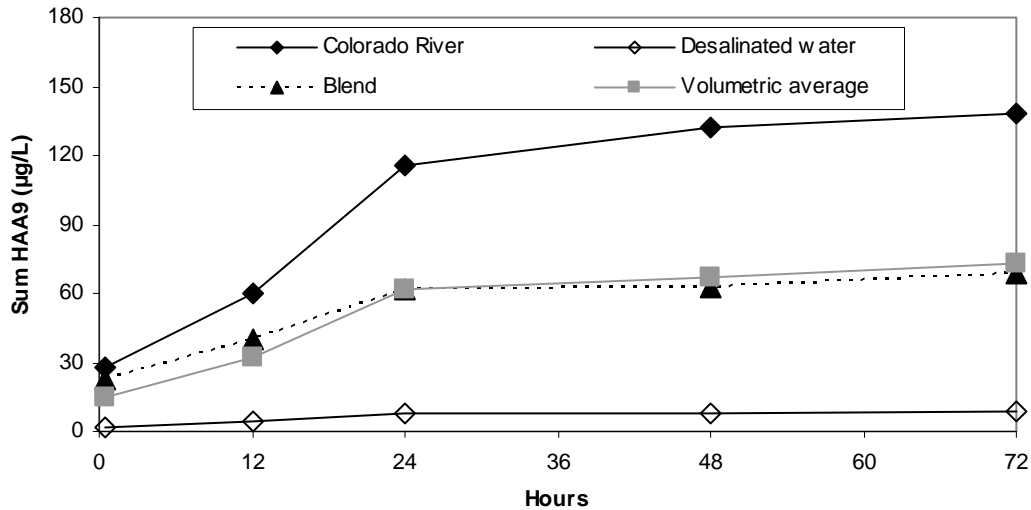
Figure 5.10. Sum of HAAs (HAA9) measured during chlorination of RO permeate from the desalination pilot plant water blended (1:1 [v/v]) with raw Colorado River water. The volumetric average represents predictions made using data from the two unmixed sources.

The effect of bromide addition on HAA speciation was more pronounced in blending with San Pablo Reservoir water (Figure 5.11). The speciation of HAAs shifted from mostly dichloroacetic acid (23%) and trichloroacetic acid (22%) in the chlorinated San Pablo Reservoir water to more brominated species in the blended water. Monobromoacetic acid was observed as the most prominent HAA species (up to 26%) during the first 24 h of the experiments. However, increasing halogen incorporation was observed with longer incubation periods. The prominent acid species detected in the chlorinated blended water at 72 h were bromochloroacetic acid (32%) and bromodichloroacetic acid (23%), while monobromoacetic acids made up only 10% of the sum of HAAs. In chlorinated desalination permeate, bromodichloroacetic acid was the only prominent compound observed at up to 5 µg/L.
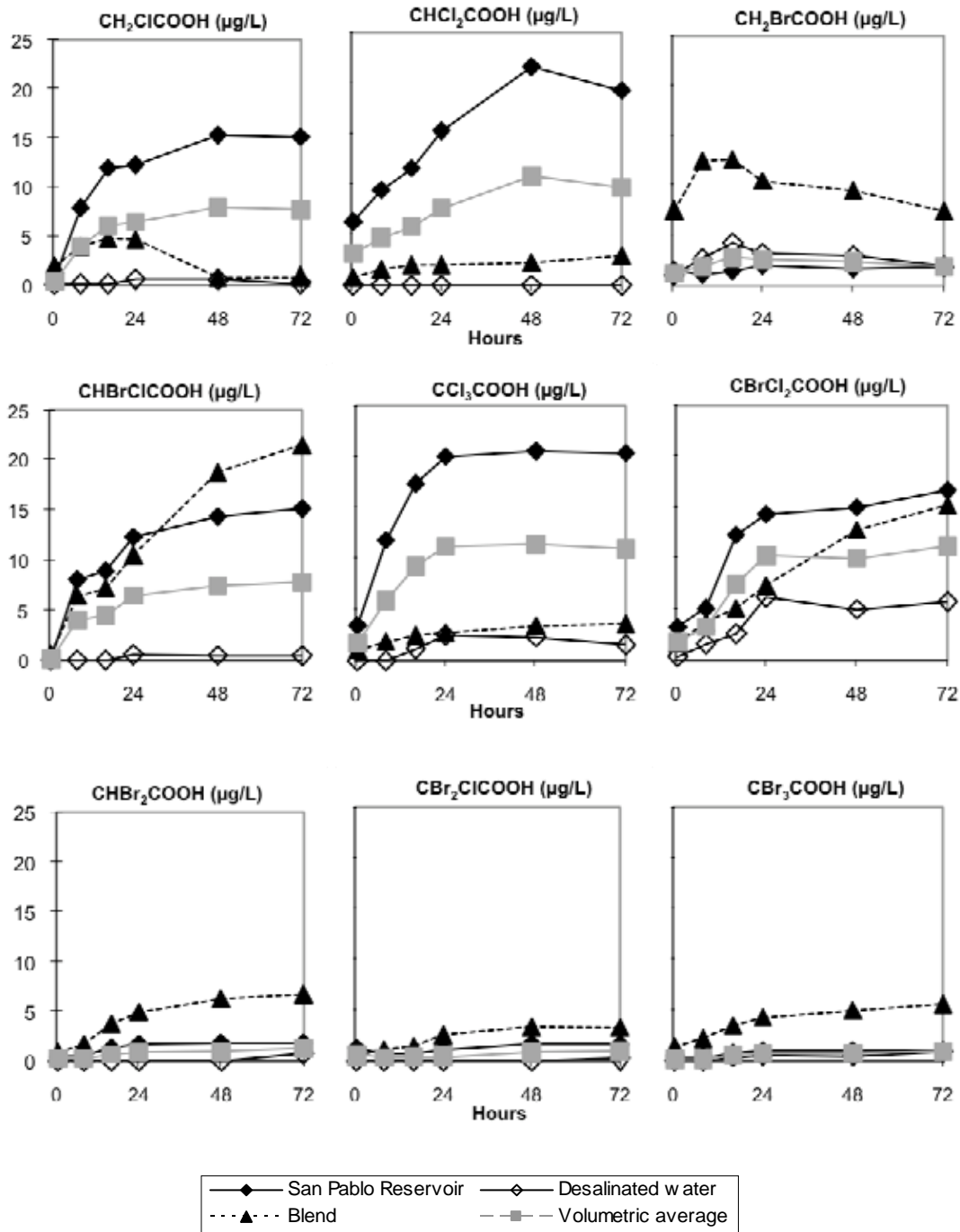
Figure 5.11. Individual HAAs (HAA9) during chlorination of RO permeate from the desalination pilot plant water blended (1:1 [v/v]) with raw San Pablo Reservoir water.
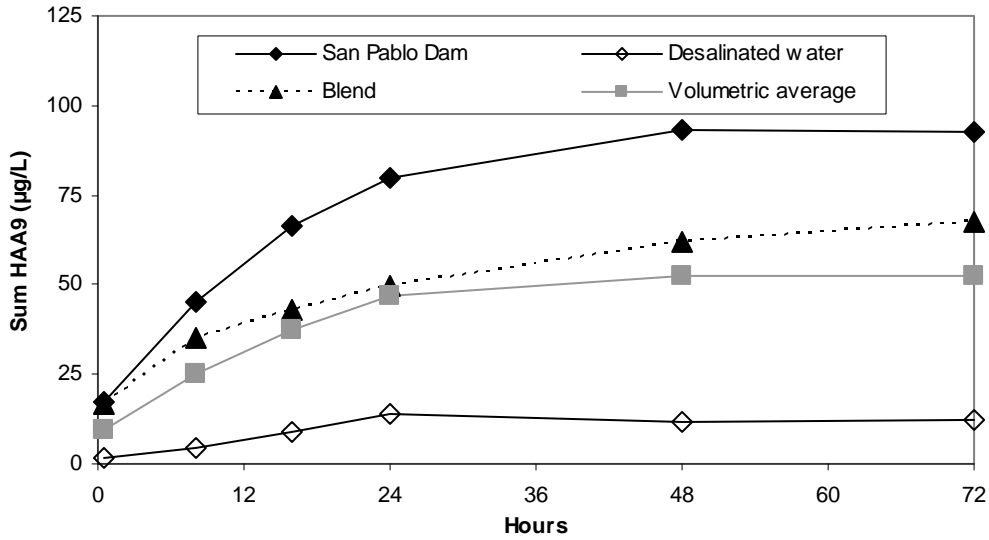
Figure 5.12. Sum of HAAs (HAA9) during chlorination of RO permeate from the desalination pilot plant water blended (1:1 [v/v]) with raw San Pablo Reservoir water.

HAA production on a mass basis increased above the volumetric average for the blend of San Pablo Reservoir water and high-bromide desalinated water (Figure 5.12). At the end of the 72-h incubation period, total HAAs detected in the blended water were 30% higher than predictions based on volumetric averages.

As with THMs, little HAA was produced from chloramination of tap water, desalinated water, or blended water (Figures 5.13 and 5.14). Because of free chlorine disinfection at the treatment plant, up to 10 μg of HAAs/L was detected in tap water at the beginning of the experiments. Blending with chloraminated desalinated water diluted the concentration of HAAs without any appreciable increase during the experiment.
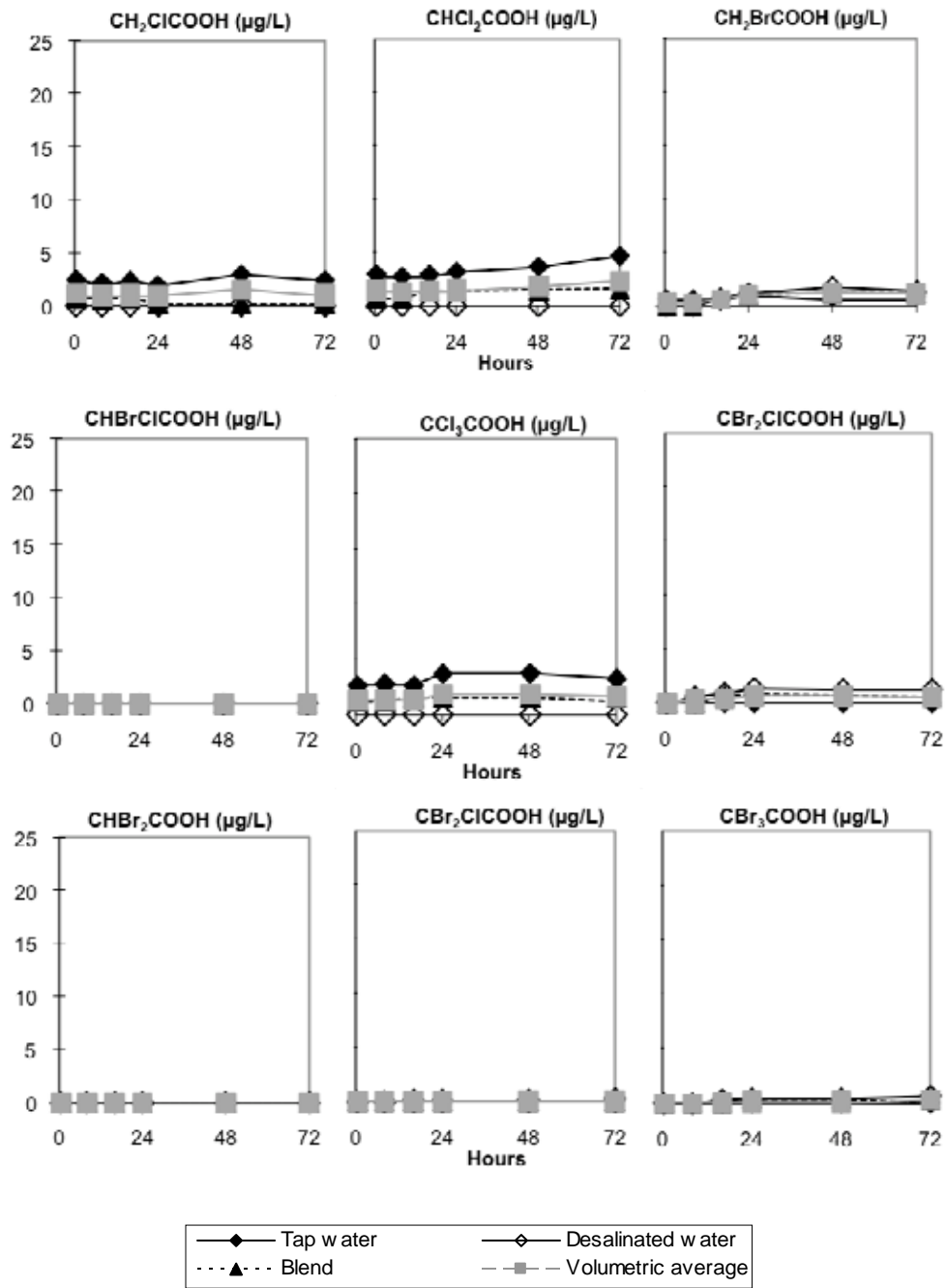
Figure 5.13. Individual HAAs (HAA9) during blending of chloraminated desalinated water and chloraminated tap water (1:1 [v/v]).
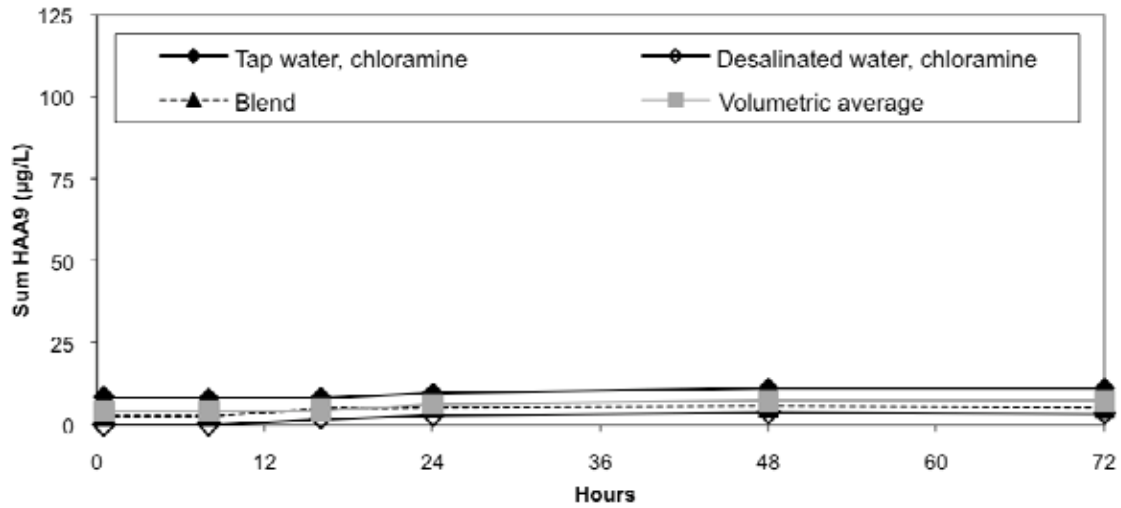
Figure 5.14. Sum of HAAs (HAA9) during blending of chloraminated desalinated water and chloraminated tap water (1:1 [v/v]).

5.4.3.3   HANs

Despite the modest increase in bromide concentrations upon blending, a shift in speciation of HANs was observed in the blending experiment with Colorado River water (Figure 5.15). The speciation of the di-HANs shifted from mainly dichloroacetonitrile (53% of total) in the Colorado River water to bromochloroacetonitrile (54%) in the blended water. Dibromoacetonitrile (22% of total) also accounted for a larger fraction of the HANs after blending. Prediction by volumetric average was comparable to dichloroacetonitrile concentrations observed in the blended water. For the brominated di-HANs, formation in blended water typically exceeds concentrations detected in Colorado River water and therefore is significantly above the concentrations predicted by volumetric average.
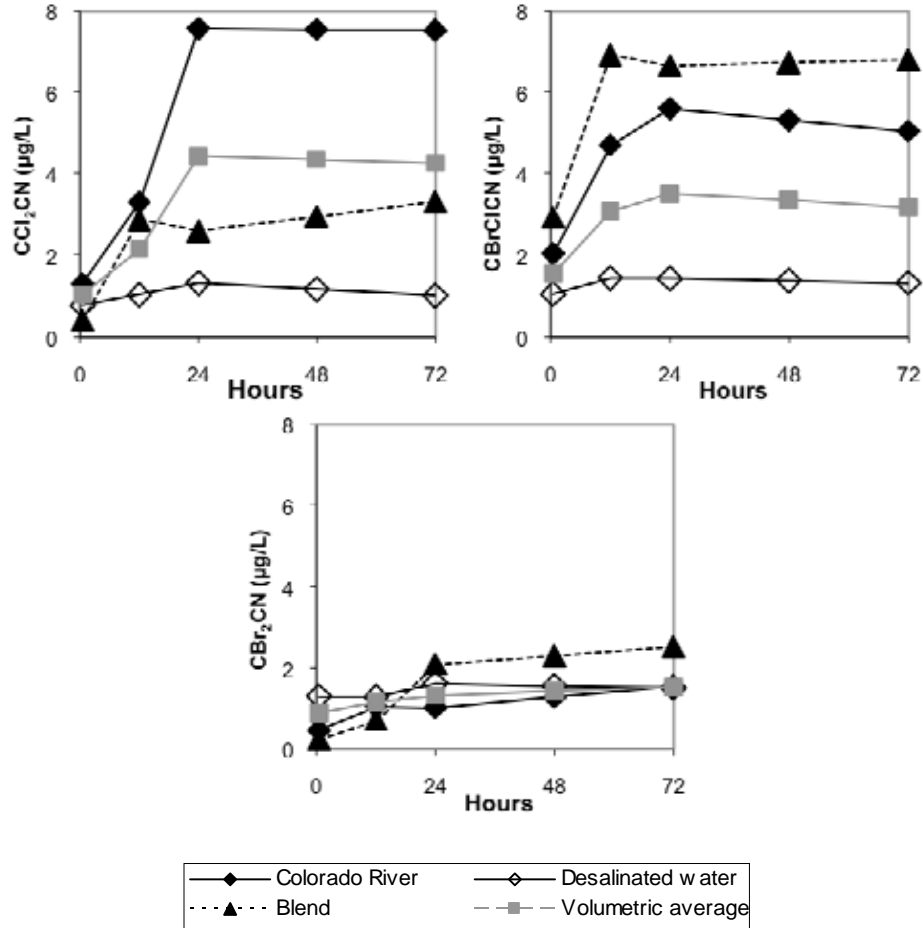
Figure 5.15. Dichloroacetonitrile, bromochloroacetonitrile, and dibromoacetonitrile during chlorination of RO permeate from the desalination pilot plant water blended (1:1 [v/v]) with raw Colorado River water.

The sum of di-HANs produced in the blending experiments with Colorado River water was relatively high (Figure 5.16). About 15 μg of total di-HANs/L was produced after 24 h in the chlorination of Colorado River water, which has both high concentrations of bromide and DOC. In the blended water, the level of total HANs was higher than the value predicted by the volumetric average on a mass-per-volume basis.

During the first 12 h of the experiment, concentrations of HANs in the blended water were comparable to those observed in the chlorinated untreated surface water. Di-HANs undergo hydrolysis, and as a result, the concentration measured in chlorinated water is a balance between formation by oxidation reactions and loss by hydrolysis. In the blended water samples, HAN levels decreased after the first 24 h because HAN precursors were depleted during contact with chlorine.
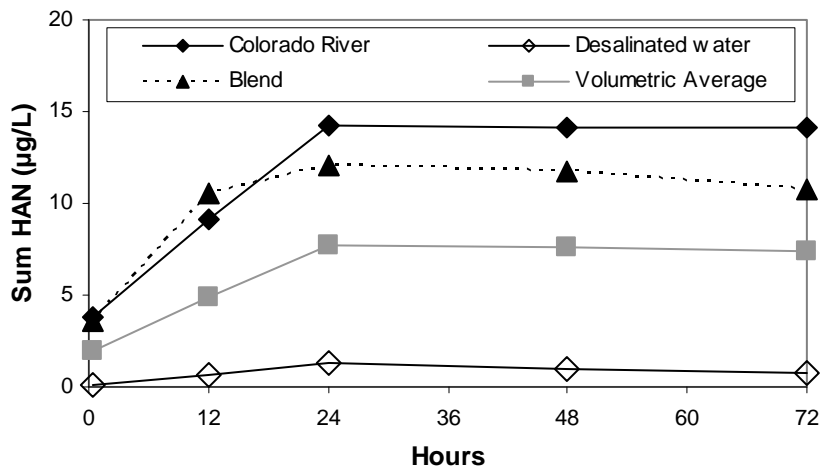
Figure 5.16. Sum of HANs during chlorination of RO permeate from the desalination pilot plant water blended (1:1 [v/v]) with raw Colorado River water.

A slightly more pronounced shift in HAN speciation was observed in the blend of San Pablo Reservoir and desalinated water (Figure 5.17). Whereas dichloroacetonitrile accounted for half of the HANs in the San Pablo Reservoir water, bromochloroacetonitrile (55% of total HANs) and dibromoacetonitrile (26% of total HANs) dominated the speciation in the blended water.
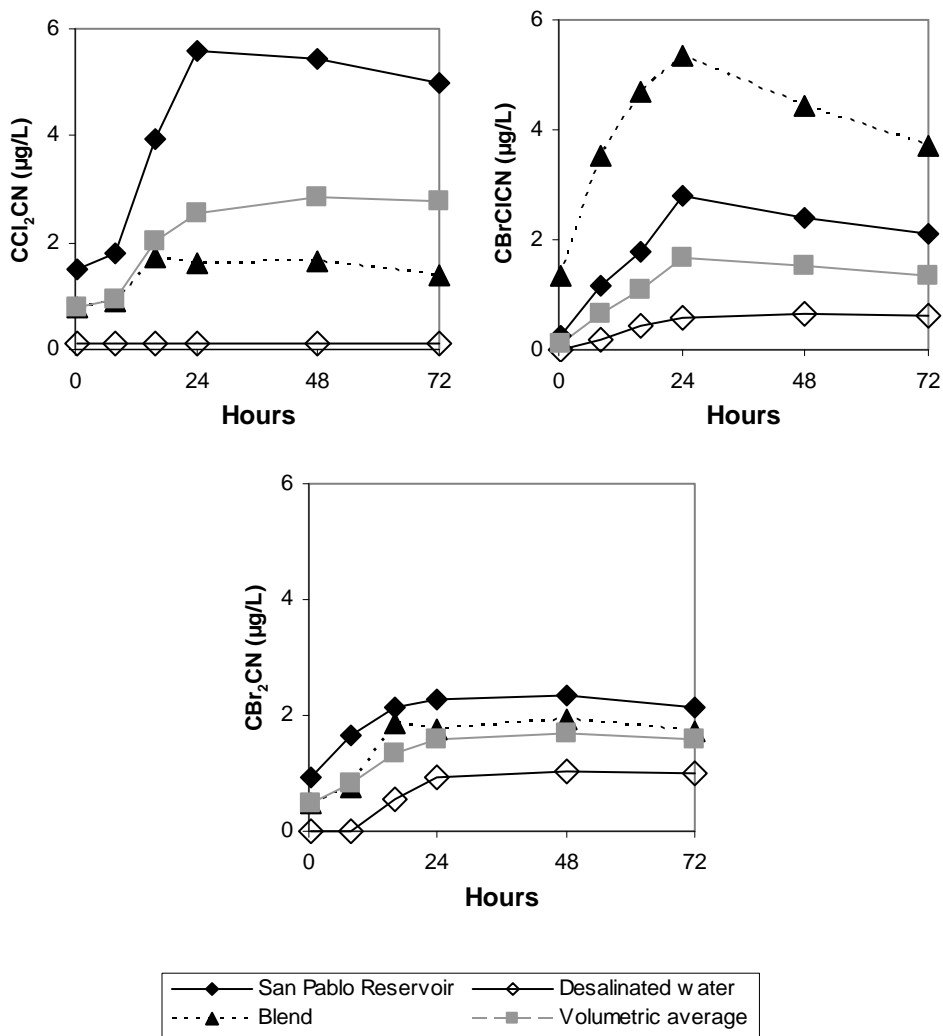
Figure 5.17. Sum of HANs, dichloroacetonitrile, bromochloroacetonitrile, and dibromoacetonitrile during chlorination of RO permeate from the desalination pilot plant water blended (1:1 [v/v]) with raw San Pablo Reservoir water.

In blending experiments with San Pablo Reservoir water, about 10 μg of total di-HANs/L were produced after 24 h (Figure 5.18). As discussed in the Colorado River samples, the concentrations of HANs measured during the first 24 h were approximately equal to the concentrations in the chlorinated raw water, after which time the concentrations steadily decreased because of hydrolysis. Again, the decrease was more prominent in the blended water, which presumably contained fewer HAN precursors at the start of the experiment. As found in the Colorado River experiments, the sum of di-HANs in the blended water was higher by about 40% than the concentrations predicted by a volumetric average.
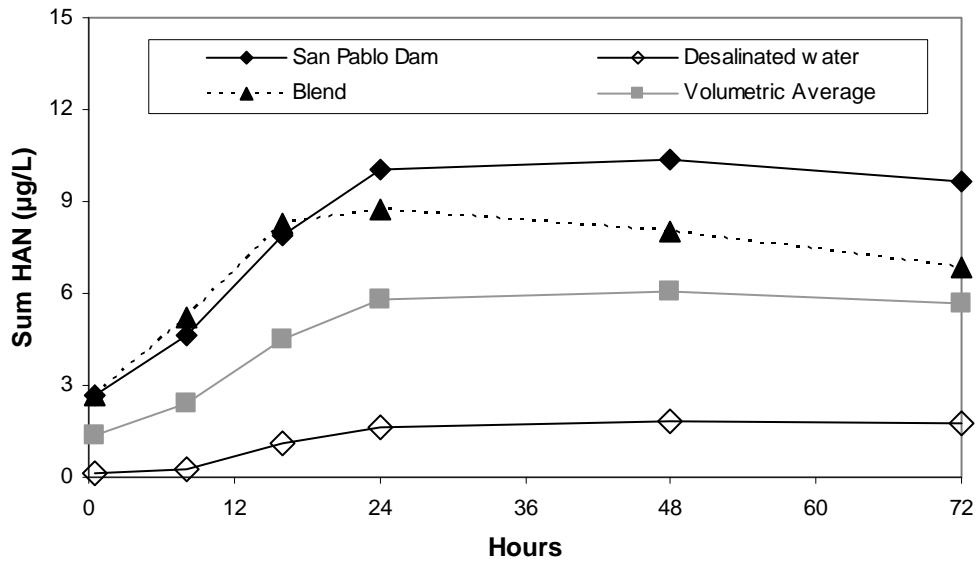
Figure 5.18. Sum of HANs, dichloroacetonitrile, bromochloroacetonitrile, and dibromoacetonitrile during chlorination of RO permeate from the desalination pilot plant water blended (1:1 [v/v]) with raw San Pablo Reservoir water.

In the experiments with chloraminated tap water, very low concentrations of HANs were detected in all sample types after 72 h (Figures 5.19 and 5.20). The individual compounds were never detected at concentrations higher than 1.1 µg/L.
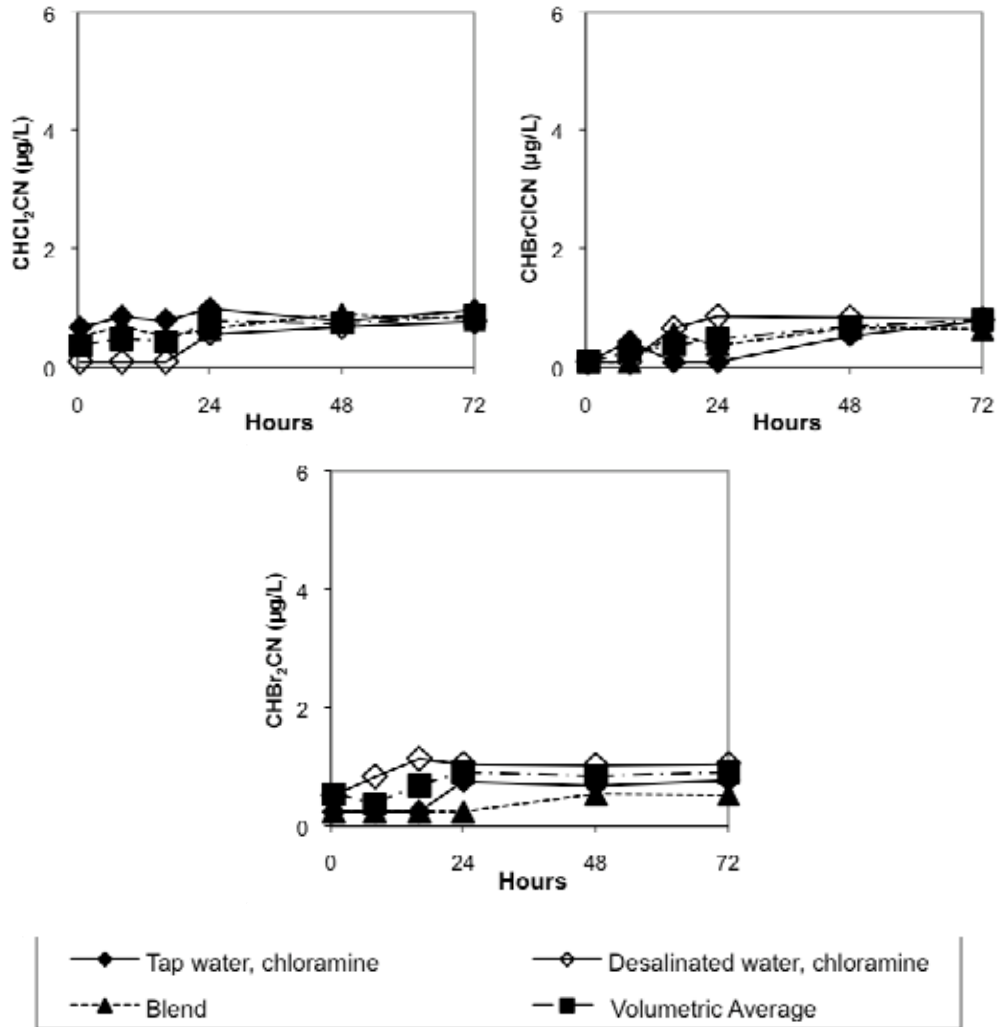
Figure 5.19. Dichloroacetonitrile, bromochloroacetonitrile, and dibromoacetonitrile during blending of chloraminated desalinated water and chloraminated tap water (1:1 [v/v]).
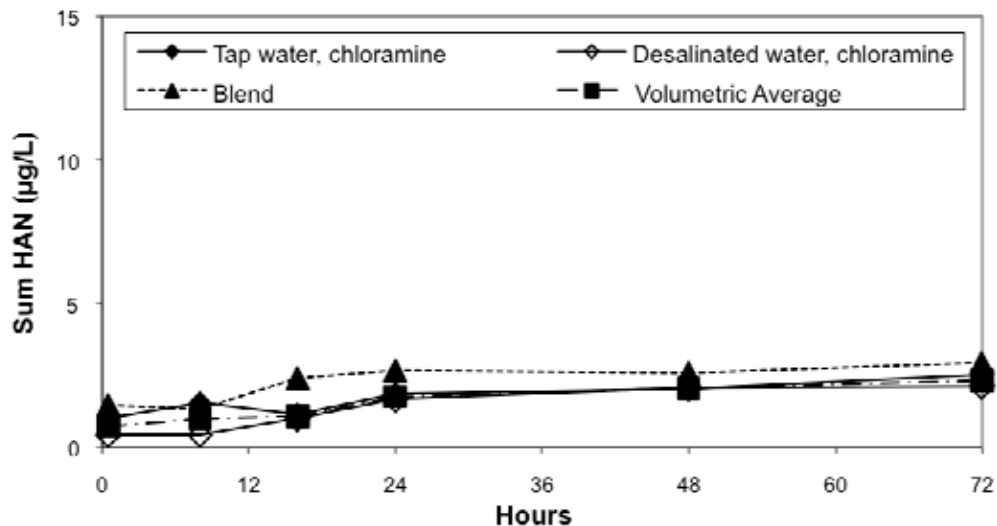
Figure 5.20. Sum of HANs, dichloroacetonitrile, and bromochloroacetonitrile during blending of chloraminated desalinated water and chloraminated tap water (1:1 [v/v]). Dibromoacetonitrile was not detected in any sample.

5.5   DISCUSSION

5.5.1   Disinfection Byproduct Formation Compared on Molar Basis

Comparing the prediction of disinfection byproduct formation on a mass-per-volume basis is relevant to regulatory compliance. However, it is more useful to evaluate the yield of disinfection byproducts on a molar basis to determine how bromide addition from desalinated seawater affects disinfection byproduct formation.

For THMs, the molar yield measured in the blended water was 90% of the predicted value for blended Colorado River water and 132% of the predicted value for San Pablo Reservoir water. Because of the relatively high concentration of bromide in the untreated water sample, the Colorado River experiments showed less of an effect from bromide addition. For the San Pablo Reservoir experiments, the larger increase in bromide after blending with desalinated water contributes to an increase in THM production due to HOBr being more reactive than HOCl.

For HAAs, the bromide addition did not appear to increase the yield of HAAs produced after blending. The molar yield for all HAAs (HAA9) measured in the blended water was 96% of the volumetric average for Colorado River water and 106% for San Pablo Reservoir water. For the regulated HAAs (HAA5), which are mostly chlorine substituted, the molar yield measured in the blended water was 116% of the volumetric average for Colorado River water and 75% of the volumetric average for San Pablo Reservoir water.

For HANs, bromide addition increased the formation of disinfection byproducts on a molar basis. For these compounds, loss by hydrolysis in the blended waters was usually faster than the formation after the first 24 h of the experiments. For incubation periods of 24 h or less, the molar yields for HANs in the blended water were approximately 75% higher than the

prediction based on a volumetric average for both Colorado River water and San Pablo Reservoir water. After 24 h, the molar yields were around only 30% higher than the volumetric average for Colorado River water and 15% higher than the volumetric average for San Pablo Reservoir water. Degradation of the HANs in the blended San Pablo Reservoir water may have been faster because of the lower initial concentrations of HAN precursors.

5.5.2 Comparison with Previous Research

The results of these blending experiments were consistent with a previous laboratory study involving the addition of bromide (2 to 20 μM) to water prior to chlorination. In that study, the formation of THMs was reportedly enhanced by the addition of bromide even when expressed on a molar basis (Hua et al., 2006). However, the previous research indicated that bromide addition changed the speciation of HAAs but did not increase their formation appreciably on a molar basis. Similar findings were observed here for THMs and HAAs in blended water. Thus, the increase in disinfection byproduct formation upon blending of surface water with desalinated water may be accounted for entirely by the presence of elevated concentrations of bromide. Blending with surface water that has undergone treatments for organic precursor removal will yield lower overall byproduct formation.

Although the effect of bromide addition on the molar yield of HANs has not been reported in previous studies, formation of relatively high concentrations of HANs has been reported after chlorination of bromide-rich water. In a study of chlorination at Lake Kinneret (Br$^-$ ~ 2000 μg/L), the sum of HAN after chlorination was 12 μg/L (Heller-Grossman et al., 1999). This value is comparable to the results of our chlorination of raw waters (14 μg/L for Colorado River water and 10 μg/L for San Pablo Reservoir water). The sum of HANs measured after chlorination of the raw and blended water in this study was higher than the median (3 μg/L) and maximum (14 μg/L) reported values in a recent survey of water treatment plants (Krasner et al., 2006).

Because of the low total-dissolved-solid removal goal (200 mg/L) employed at the desalination pilot plant, bromide concentrations in the desalination permeate used for this blending study were low in comparison to typical values reported from other desalination plants (Agus et al., 2009). Blending with desalinated water that has higher concentrations of bromide could produce more pronounced increases in disinfection byproduct formation and changes in speciation.

5.5.3 Comparison with Regulatory Standards and Health Guidelines

The blending experiments with raw water represent the worst-case scenario for a blending study because we did not remove DOC prior to chlorination as would occur in a drinking water treatment plant. DOC concentrations in Colorado River (7.6 mg/L) and San Pablo Reservoir (4.7 mg/L) are typical of raw water sources. Despite the effect of bromide on disinfection byproduct formation, blending with desalinated water, which has very low OC concentrations, will decrease the formation of disinfection byproducts by diluting the precursors. A comparison of disinfection byproduct concentrations in raw water and blended water (Table 5.3) illustrated the impact of blending.

Table 5.3. Comparison of Observed Maximum Concentration (µg/L) of Disinfection Byproducts and Relevant Standards and Guidelines

		Observed Maximum			
		Colorado River		San Pablo Reservoir	
Disinfection Byproduct	Guideline	Raw Water	Blend	Raw Water	Blend
THMs	80	**228**	**114**	**90**	**83**
HAAs					
HAA5	60	58	36	**71**	36
HAA9	—	138	69	93	67
Dichloroacetonitrile	4	**7.6**	2.6	**5.6**	1.7
Dibromoacetonitrile	20	1.5	2.3	2.4	1.9

[a]Boldfaced values exceed guideline level.

For Colorado River water, maximum THM production was cut in half after blending whereas the maximum THM formation in San Pablo Reservoir water decreased by only about 10% upon blending. The absence of a strong dilution effect in the San Pablo Reservoir water is attributable both to the enhanced production of THMs by HOBr and to the increase in production of higher-molecular-weight brominated THMs.

Relative to applicable guidelines listed in Table 5.3, the THMs were the class of compounds driving the need to control disinfection byproducts in chlorination of these two raw water samples. In experiments with both surface water samples, maximum sum concentrations of THMs in chlorinated raw water and blended water exceed the drinking water MCL. Additional measures to meet THM standards—including removal of organic precursors in drinking water treatment—are likely to simultaneously meet standards for HAAs and health guidelines for HANs. For example, if DOC is removed during water treatment or if chloramines are used as a residual, as illustrated by the blending experiments with tap water, none of the disinfection byproducts exceeds the guidelines and standards. It should be noted, however, that elevated concentrations of bromide in blended tap water decreased the stability of the chloramines and would pose challenges to the maintenance of residual in the distribution system.

With respect to HAN formation, a significant reduction of overall byproduct concentration due to dilution of HAN precursors is observed upon blending. Lowering concentrations of HAN precursors by blending only modestly decreases the concentration of HANs in the first 24 h. However, because of loss by hydrolysis, the lowered initial precursor concentration resulted in concentrations of HANs much lower than the guideline levels at the end of the 72-h incubation period. Production of dichloroacetonitrile, which has a lower health effect guideline level, was also decreased after blending. However, limited toxicity data on bromochloroacetonitrile—which was dominant in blended water—are available to support a belief in an overall decrease in health risks upon blending.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

The use of chlorine in seawater desalination plants and in their associated water distribution systems provides numerous benefits, such as the control of biofouling on membranes, longer run times in medium filters, and the inactivation of pathogens. However, when chlorine is used for pretreatment of seawater or for the disinfection of freshwater, a suite of disinfection byproducts is formed. As a result of concerns associated with chlorine use, alternative approaches for pretreatment of seawater and the use of free chlorine in water distribution systems are becoming more popular. Despite concerns about disinfection byproducts, chlorine is likely to remain attractive for operators of desalination plants because it provides a reliable and cost-effective means of achieving treatment objectives and because engineers have considerable experience with its use. To make informed decisions about the use of chlorine, the designers and operators of desalination plants need to understand the potential risks that chlorine disinfection byproducts pose to water consumers and aquatic organisms. Research presented in the previous chapters has provided insight into some of the risks associated with the use of chlorine in seawater desalination plants. In the following paragraphs, we discuss the areas of concern associated with chlorine use for the design and operation of seawater desalination plants as well as steps that can be taken to minimize potential risks.

Under conditions typically employed in pretreatment systems, several common disinfection byproducts are produced at concentrations near the thresholds for toxicity in aquatic organisms. For example, monobromoacetic acid, one of the most prominent HAAs produced during seawater pretreatment, causes adverse effects on certain algae at concentrations slightly higher than those produced during seawater pretreatment. Our review of the scientific literature, as well as of data collected as part of this research project, suggests that while the concentrations of chlorine disinfection byproducts in RO retentate may sometimes exceed the threshold for impacts to aquatic organisms, the concentrations are unlikely to exceed the effect threshold by more than a factor of 2. Because outfalls are usually designed to dilute the briny discharge to salinities close to that of seawater within a short distance and because the chlorine disinfection byproducts are not known to bioaccumulate, it is likely that the concentrations of chlorine disinfection byproducts will decrease below levels of concern within a short distance of the concentrate outfall. To obtain a better understanding of the risks to aquatic organisms associated with chlorine disinfection byproducts discharged by desalination plants, concentrations of THMs and HAAs should be monitored in concentrate from desalination plants. After accounting for dilution near the plant outfall, one should compare these data with toxicity data for compounds to which marine organisms are sensitive. Aquatic toxicity data are unavailable for some of the other common disinfection byproducts. Collection of additional data on these compounds would be useful in assessing potential risks associated with the discharge of desalination concentrate.

Chlorine disinfection byproducts formed during seawater pretreatment are not entirely removed from the product water during RO treatment. However, concentrations of the disinfection byproducts rarely exceed the standards or guidelines for protection of human health prior to RO. After one accounts for the nearly complete removal of the compounds during RO, the concentrations of most of the chlorine disinfection byproducts in the RO permeate are likely to be a small fraction of the standards and guidelines. An exception to this

generalization may occur at some locations for the bromine-containing HANs (namely, dibromoacetonitrile and bromochloroacetonitrile), which are neutral, low-molecular-weight compounds that are only partially removed during seawater RO (for example, about 40% of the dibromoacetonitrile formed during pretreatment passes through RO membranes). Most of the data on seawater chlorination show HAN concentrations that are considerably lower than those stipulated by the USEPA's guidelines after chlorination. After one considers the partial removal of the compounds during RO, the concentrations of HANs in desalinated water from most locations should be much lower than the guideline concentrations. However, chlorination of seawater samples from Singapore and from a wintertime sample collected in Carlsbad, CA, produced concentrations of dibromoacetonitrile that approached the drinking water guidelines. Further monitoring and additional research are needed to obtain a better understanding of the formation of HANs at other locations as well as the factors controlling HAN formation during seawater pretreatment.

Desalinated seawater is usually disinfected prior to delivery to water distributions systems, and a disinfectant residual is often added to protect water quality in distribution systems. Because desalinated water contains relatively high concentrations of bromide and because ozonation of bromide-rich waters can lead to formation of the disinfection byproduct bromate, ozone is generally not considered an appropriate disinfectant for desalinated waters. The use of chloramines, either as a primary disinfectant or as a residual, also poses problems in the presence of elevated bromide concentrations due to the formation of bromamines, which are less stable than chloramines. As a result, free chlorine, chlorine dioxide, and UV light are the main alternatives for primary disinfection of desalinated water. Free chlorine and chlorine dioxide are the main alternatives for a disinfectant residual in desalinated water systems. As a result of the relatively low concentrations of organic disinfection byproduct precursors in RO product waters, application of free chlorine to desalinated water produces concentrations of disinfection byproducts that are considerably lower than the ones foreseen in existing drinking water standards and guidelines and free chlorine can be used with few worries about exceeding disinfection byproduct standards or guidelines.

In some situations, desalinated water may be blended with water from other sources prior to chlorination. For example, a utility might want to blend desalinated water with surface water that produces elevated concentrations of disinfection byproducts upon chlorination in order to create blended water that meets disinfection byproduct standards and guidelines. For the THMs and HAAs, blending of organic-matter-rich surface water with desalinated water prior to chlorination reduces the total concentrations of THMs and HAAs relative to those formed in unblended surface water. However, the presence of elevated bromide concentrations in the desalinated water shifts the distribution of disinfection byproducts from chlorinated compounds to brominated compounds. Because HOBr is more reactive than HOCl and the molecular weights of the brominated compounds are higher than those of chlorinated compounds, the total THM and total HAA concentrations, when expressed on a mass-per-volume basis, are often higher than what would be predicted simply by taking a weighted average of the concentrations of the different classes of compounds in the chlorinated surface water and chlorinated desalinated water. Thus, blending may not provide the expected benefits of dilution if regulatory compliance is based on concentrations expressed on a mass-per-volume basis. Typically, surface water that has been treated to remove organic precursors will be used for blending and will produce lower overall concentrations of disinfection byproducts than shown in the blending experiments involving raw water supplies.

In most situations, blending of desalinated water with surface waters is a viable means of lowering the total THM and total HAA concentrations. For the HANs, the higher reactivity of

HOBr than that of HOCl can result in a shift in the halogen substitution distribution. The higher bromide from desalinated water also resulted in a higher formation yield of HANs on a molar basis than would be expected from a weighted average. In other words, blending of desalinated water with surface water may yield a reduction in the concentration of dichloroacetonitrile accompanied by increases in the concentrations of bromochloroacetonitrile and dibromoacetonitrile. Based on their neutrality and low molecular weight, a portion of HANs produced during pretreatment with chlorine can pass through the desalination membrane. Because of this potential for incomplete removal, HAN formation in blended water should be considered prior to adoption of blending as a strategy for meeting health guidelines for HANs.

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APPENDIX A

DISINFECTION BYPRODUCT DATA

Table A3.1. Seawater Chlorination Results: THMs [Figure 3.1]

Sample	Concn and Disinfectant	Experiment Date	Concn (µg/L)			
			$CHCl_3$	$CHBrCl_2$	$CHBr_2Cl$	$CHBr_3$
Carlsbad summer	0.5 mg/L Cl_2	8/2/2007	<1.1	<1.1	1.2	4.7
Carlsbad winter	0.5 mg/L Cl_2	3/20/2008	<1.1	<1.1	2.2	17
Moss Landing	0.5 mg/L Cl_2	11/6/2007	<1.1	<1.1	<1.1	8.0
SF Bay	0.5 mg/L Cl_2	2/15/2008	<1.1	<1.1	1.2	6.5
Singapore 1	0.5 mg/L Cl_2	3/20/2008	<1.1	<1.1	<1.1	2.1
Singapore 2	0.5 mg/L Cl_2	7/15/2008	<1.1	<1.1	<1.1	8.5
Panama City	0.5 mg/L Cl_2	3/20/2008	<1.1	<1.1	<1.1	49
Carlsbad summer	2.0 mg/L Cl_2	8/2/2007	<1.1	<1.1	1.2	4.7
Carlsbad winter	2.0 mg/L Cl_2	3/20/2008	1.6	3.8	6.0	40
Moss Landing	2.0 mg/L Cl_2	11/6/2007	<1.1	<1.1	<1.1	14
SF Bay	2.0 mg/L Cl_2	2/15/2008	<1.1	<1.1	1.4	8.2
Singapore 1	2.0 mg/L Cl_2	3/20/2008	<1.1	<1.1	<1.1	13
Singapore 2	2.0 mg/L Cl_2	7/15/2008	<1.1	<1.1	1.6	14
Panama City	2.0 mg/L Cl_2	3/20/2008	<1.1	<1.1	1.1	119

Table A3.2. Seawater Chlorination Results: HAAs [Figure 3.2]

Sample	Concn and Disinfectant	Experiment Date	Concn (µg/L)		
			$CH_2ClCOOH$	$CHCl_2COOH$	$CH_2BrCOOH$
Carlsbad summer	0.5 mg/L Cl_2	8/2/2007	0.3	1.6	9.5
Carlsbad winter	0.5 mg/L Cl_2	3/20/2008	0.6	<0.5	2.2
Moss Landing	0.5 mg/L Cl_2	11/6/2007	0.8	1.8	18.2
SF Bay	0.5 mg/L Cl_2	2/15/2008	0.9	<0.5	6.7
Singapore 1	0.5 mg/L Cl_2	3/20/2008	0.8	1.6	<0.2
Panama City	0.5 mg/L Cl_2	3/20/2008	<0.2	1.5	12
Carlsbad summer	2.0 mg/L Cl_2	8/2/2007	1.7	3.4	30
Carlsbad winter	2.0 mg/L Cl_2	3/20/2008	1.8	1.4	5.5
Moss Landing	2.0 mg/L Cl_2	11/6/2007	2.1	5.0	35
SF Bay	2.0 mg/L Cl_2	2/15/2008	2.4	0.7	24
Singapore 1	2.0 mg/L Cl_2	3/20/2008	2.4	5.1	1.3
Panama City	2.0 mg/L Cl_2	3/20/2008	0.7	4.5	41

Table A3.2. Seawater Chlorination Results: HAAs [Figure 3.2]

Sample	Concn and Disinfectant	Experiment Date	Concn (μg/L)		
			CCl_3COOH	$CHBrClCOOH$	$CBrCl_2COOH$
Carlsbad summer	0.5 mg/L Cl_2	8/2/2007	<0.5	<0.2	<0.7
Carlsbad winter	0.5 mg/L Cl_2	3/20/2008	3.2	1.9	2.0
Moss Landing	0.5 mg/L Cl_2	11/6/2007	2.4	1.0	1.3
SF Bay	0.5 mg/L Cl_2	2/15/2008	0.6	<0.2	<0.7
Singapore 1	0.5 mg/L Cl_2	3/20/2008	2.3	<0.2	<0.7
Panama City	0.5 mg/L Cl_2	3/20/2008	2.1	<0.2	1.5
Carlsbad summer	2.0 mg/L Cl_2	8/2/2007	<0.5	2.6	0.9
Carlsbad winter	2.0 mg/L Cl_2	3/20/2008	9.4	6.8	5.7
Moss Landing	2.0 mg/L Cl_2	11/6/2007	6.8	2.5	3.9
SF Bay	2.0 mg/L Cl_2	2/15/2008	1.3	2.6	2.1
Singapore 1	2.0 mg/L Cl_2	3/20/2008	6.1	<0.2	1.5
Panama City	2.0 mg/L Cl_2	3/20/2008	6.9	<0.2	4.0

Table A3.2. Seawater Chlorination Results: HAAs [Figure 3.2]

Sample	Concn and Disinfectant	Experiment Date	Concn (μg/L)		
			$CHBr_2COOH$	$CBr_2ClCOOH$	CBr_3COOH
Carlsbad summer	0.5 mg/L Cl_2	8/2/2007	<0.7	<0.2	<0.4
Carlsbad winter	0.5 mg/L Cl_2	3/20/2008	<0.7	<0.2	0.5
Moss Landing	0.5 mg/L Cl_2	11/6/2007	<0.7	<0.2	<0.4
SF Bay	0.5 mg/L Cl_2	2/15/2008	1.4	0.5	1.1
Singapore 1	0.5 mg/L Cl_2	3/20/2008	<0.7	<0.2	2.1
Panama City	0.5 mg/L Cl_2	3/20/2008	<0.7	<0.2	<0.4
Carlsbad summer	2.0 mg/L Cl_2	8/2/2007	1.7	<0.2	0.9
Carlsbad winter	2.0 mg/L Cl_2	3/20/2008	0.9	0.6	3.8
Moss Landing	2.0 mg/L Cl_2	11/6/2007	<0.7	<0.2	<0.4
SF Bay	2.0 mg/L Cl_2	2/15/2008	2.8	1.2	4.1
Singapore 1	2.0 mg/L Cl_2	3/20/2008	0.9	<0.2	6.1
Panama City	2.0 mg/L Cl_2	3/20/2008	<0.7	<0.2	2.3

Table A3.3. Seawater Chlorination Results: Halophenols [Figure 3.3]

Sample	Concn and Disinfectant	Experiment Date	Concn (μg/L)		
			2-Bromophenol	**2,6-Dibromophenol**	**2,4,6-Tribromophenol**
Carlsbad summer	0.5 mg/L Cl$_2$	8/2/2007	<0.045	<0.086	0.427
Carlsbad winter	0.5 mg/L Cl$_2$	3/20/2008	<0.045	<0.086	0.733
Moss Landing	0.5 mg/L Cl$_2$	11/6/2007	<0.045	0.160	0.547
SF Bay	0.5 mg/L Cl$_2$	2/15/2008	<0.045	0.435	0.945
Singapore 1	0.5 mg/L Cl$_2$	3/20/2008	<0.045	0.102	0.205
Panama City	0.5 mg/L Cl$_2$	3/20/2008	0.061	0.120	0.727
Carlsbad summer	2.0 mg/L Cl$_2$	8/2/2007	<0.045	0.092	0.116
Carlsbad winter	2.0 mg/L Cl$_2$	3/20/2008	<0.045	<0.086	0.628
Moss Landing	2.0 mg/L Cl$_2$	11/6/2007	0.052	0.119	0.208
SF Bay	2.0 mg/L Cl$_2$	2/15/2008	<0.045	<0.086	0.138
Singapore 1	2.0 mg/L Cl$_2$	3/20/2008	<0.045	<0.086	0.122
Panama City	2.0 mg/L Cl$_2$	3/20/2008	<0.045	0.089	<0.11

Table A3.4. Seawater Chlorination Results: HANs [Figure 3.4]

Sample	Concn and Disinfectant	Experiment Date	Concn (μg/L)		
			CHCl$_2$CN	**CHBrClCN**	**CHBr$_2$CN**
Carlsbad summer	0.5 mg/L Cl$_2$	8/2/2007	<0.2	<0.2	<0.5
Carlsbad winter	0.5 mg/L Cl$_2$	3/20/2008	<0.2	<0.2	0.9
Moss Landing	0.5 mg/L Cl$_2$	11/6/2007	<0.2	<0.2	<0.5
SF Bay	0.5 mg/L Cl$_2$	2/15/2008	<0.2	<0.2	<0.5
Singapore 1	0.5 mg/L Cl$_2$	3/20/2008	<0.2	<0.2	2.4
Singapore 2	0.5 mg/L Cl$_2$	7/15/2008	<0.2	<0.2	2.7
Panama City	0.5 mg/L Cl$_2$	3/20/2008	<0.2	<0.2	<0.5
Carlsbad summer	2.0 mg/L Cl$_2$	8/2/2007	<0.2	<0.2	1.6
Carlsbad winter	2.0 mg/L Cl$_2$	3/20/2008	<0.2	11	4.7
Moss Landing	2.0 mg/L Cl$_2$	11/6/2007	<0.2	<0.2	2.8
SF Bay	2.0 mg/L Cl$_2$	2/15/2008	<0.2	<0.2	1.6
Singapore 1	2.0 mg/L Cl$_2$	3/20/2008	<0.2	3.3	20
Singapore 2	2.0 mg/L Cl$_2$	7/15/2008	<0.2	1.2	8.9
Panama City	2.0 mg/L Cl$_2$	3/20/2008	<0.2	<0.2	<0.5

Table A4.1. Pilot Plant Sampling Results: THMs [Figures 4.3–4.6]

Sample	Round	Concn and Disinfectant	Experiment Date	Concn (µg/L)			
				CHCl$_3$	CHBrCl$_2$	CHBr$_2$Cl	CHBr$_3$
Intake	2	0.5 mg of Cl$_2$/L	10/5/2007	<1.1	<1.1	<1.1	<1.1
Intake	2	2.0 mg of Cl$_2$/L	10/5/2007	<1.1	<1.1	<1.1	<1.1
Intake	3	0.5 mg of Cl$_2$/L	10/12/2007	<1.1	<1.1	<1.1	<1.1
Intake	3	2.0 mg of Cl$_2$/L	10/12/2007	<1.1	<1.1	<1.1	<1.1
Intake	4	0.5 mg of Cl$_2$/L	10/17/2007	<1.1	<1.1	<1.1	<1.1
Intake	4	2.0 mg of Cl$_2$/L	10/17/2007	<1.1	<1.1	<1.1	<1.1
Intake	5	0.5 mg of Cl$_2$/L	10/30/2007	<1.1	<1.1	<1.1	<1.1
Intake	5	2.0 mg of Cl$_2$/L	10/30/2007	<1.1	<1.1	<1.1	<1.1
Intake	6	0.5 mg of Cl$_2$/L	2/12/2008	45	7.9	1.9	<1.1
Intake	6	2.0 mg of Cl$_2$/L	2/12/2008	36	<1.1	<1.1	<1.1
Intake	7	0.5 mg of Cl$_2$/L	2/19/2008	<1.1	<1.1	<1.1	1.2
Intake	7	2.0 mg of Cl$_2$/L	2/19/2008	<1.1	<1.1	<1.1	<1.1
Intake	8	0.5 mg of Cl$_2$/L	3/28/2008	<1.1	1.9	<1.1	1.4
Intake	8	2.0 mg of Cl$_2$/L	3/28/2008	<1.1	<1.1	<1.1	<1.1
Intake	9	0.5 mg of Cl$_2$/L	4/29/2008	<1.1	<1.1	<1.1	<1.1
Intake	9	2.0 mg of Cl$_2$/L	4/29/2008	<1.1	<1.1	<1.1	<1.1
Feed	2	0.5 mg of Cl$_2$/L	10/5/2007	<1.1	<1.1	<1.1	<1.1
Feed	2	2.0 mg of Cl$_2$/L	10/5/2007	<1.1	<1.1	<1.1	4.8
Feed	3	0.5 mg of Cl$_2$/L	10/12/2007	<1.1	<1.1	<1.1	2.2
Feed	3	2.0 mg of Cl$_2$/L	10/12/2007	<1.1	<1.1	<1.1	13
Feed	4	0.5 mg of Cl$_2$/L	10/17/2007	<1.1	<1.1	<1.1	1.2
Feed	4	2.0 mg of Cl$_2$/L	10/17/2007	<1.1	<1.1	<1.1	7.7
Feed	5	0.5 mg of Cl$_2$/L	10/30/2007	<1.1	<1.1	<1.1	1.5
Feed	5	2.0 mg of Cl$_2$/L	10/30/2007	<1.1	<1.1	<1.1	7.9
Feed	6	0.5 mg of Cl$_2$/L	2/12/2008	14	2.6	4.8	3.7
Feed	6	2.0 mg of Cl$_2$/L	2/12/2008	34	6.5	9.0	15
Feed	7	0.5 mg of Cl$_2$/L	2/19/2008	3.8	<1.1	4.0	<1.1
Feed	7	2.0 mg of Cl$_2$/L	2/19/2008	4.7	<1.1	2.7	5.0
Feed	8	0.5 mg of Cl$_2$/L	3/28/2008	<1.1	1.5	14	2.4
Feed	8	2.0 mg of Cl$_2$/L	3/28/2008	26	5.0	16	8.8
Feed	9	0.5 mg of Cl$_2$/L	4/29/2008	<1.1	1.7	1.8	25
Feed	9	2.0 mg of Cl$_2$/L	4/29/2008	<1.1	3.7	2.4	67

Table A4.1. Pilot Plant Sampling Results: THMs [Figures 4.3–4.6]

Sample	Round	Concn and Disinfectant	Experiment Date	Concn (µg/L) CHCl$_3$	CHBrCl$_2$	CHBr$_2$Cl	CHBr$_3$
Concentrate	2	0.5 mg of Cl$_2$/L	10/5/2007	<1.1	<1.1	<1.1	1.2
Concentrate	2	2.0 mg of Cl$_2$/L	10/5/2007	<1.1	<1.1	<1.1	7.8
Concentrate	3	0.5 mg of Cl$_2$/L	10/12/2007	<1.1	<1.1	<1.1	5.7
Concentrate	3	2.0 mg of Cl$_2$/L	10/12/2007	<1.1	<1.1	<1.1	18
Concentrate	4	0.5 mg of Cl$_2$/L	10/17/2007	1.2	<1.1	<1.1	2.6
Concentrate	4	2.0 mg of Cl$_2$/L	10/17/2007	<1.1	<1.1	<1.1	10
Concentrate	5	0.5 mg of Cl$_2$/L	10/30/2007	<1.1	<1.1	<1.1	3.3
Concentrate	5	2.0 mg of Cl$_2$/L	10/30/2007	<1.1	<1.1	<1.1	14
Concentrate	6	0.5 mg of Cl$_2$/L	2/12/2008	26	4.8	3.7	6.6
Concentrate	6	2.0 mg of Cl$_2$/L	2/12/2008	44	14	8.0	24
Concentrate	7	0.5 mg of Cl$_2$/L	2/19/2008	7.6	<1.1	6.3	1.2
Concentrate	7	2.0 mg of Cl$_2$/L	2/19/2008	<1.1	<1.1	5.2	7.9
Concentrate	8	0.5 mg of Cl$_2$/L	3/28/2008	2.0	1.7	2.7	4.8
Concentrate	8	2.0 mg of Cl$_2$/L	3/28/2008	40	8.2	9.4	13
Concentrate	9	0.5 mg of Cl$_2$/L	4/29/2008	<1.1	1.7	<1.1	46
Concentrate	9	2.0 mg of Cl$_2$/L	4/29/2008	<1.1	<1.1	2.8	65
Permeate	2	0.5 mg of Cl$_2$/L	10/5/2007	<1.1	<1.1	<1.1	<1.1
Permeate	2	2.0 mg of Cl$_2$/L	10/5/2007	<1.1	<1.1	<1.1	<1.1
Permeate	3	0.5 mg of Cl$_2$/L	10/12/2007	<1.1	<1.1	<1.1	<1.1
Permeate	3	2.0 mg of Cl$_2$/L	10/12/2007	<1.1	<1.1	<1.1	<1.1
Permeate	4	0.5 mg of Cl$_2$/L	10/17/2007	<1.1	<1.1	<1.1	<1.1
Permeate	4	2.0 mg of Cl$_2$/L	10/17/2007	<1.1	<1.1	<1.1	<1.1
Permeate	5	0.5 mg of Cl$_2$/L	10/30/2007	<1.1	<1.1	<1.1	<1.1
Permeate	5	2.0 mg of Cl$_2$/L	10/30/2007	<1.1	<1.1	<1.1	<1.1
Permeate	6	0.5 mg of Cl$_2$/L	2/12/2008	13	<1.1	4.1	<1.1
Permeate	6	2.0 mg of Cl$_2$/L	2/12/2008	13	<1.1	1.7	<1.1
Permeate	7	0.5 mg of Cl$_2$/L	2/19/2008	<1.1	<1.1	2.2	<1.1
Permeate	7	2.0 mg of Cl$_2$/L	2/19/2008	<1.1	<1.1	<1.1	<1.1
Permeate	8	0.5 mg of Cl$_2$/L	3/28/2008	<1.1	<1.1	7.9	<1.1
Permeate	8	2.0 mg of Cl$_2$/L	3/28/2008	<1.1	<1.1	3.2	<1.1
Permeate	9	0.5 mg of Cl$_2$/L	4/29/2008	<1.1	<1.1	<1.1	3.5
Permeate	9	2.0 mg of Cl$_2$/L	4/29/2008	<1.1	<1.1	<1.1	2.5

Table A4.2. Pilot Plant Sampling Results: HAAs [Figures 4.7–4.15]

Sample	Round	Concn and Disinfectant	Experiment Date	Concn (µg/L)		
				MCAA	DCAA	MBAA
Intake	2	0.5 mg of Cl₂/L	10/5/2007	1.6	2.3	0.9
Intake	2	2.0 mg of Cl₂/L	10/5/2007	1.3	6.1	0.2
Intake	3	0.5 mg of Cl₂/L	10/12/2007	<0.2	3.0	0.7
Intake	3	2.0 mg of Cl₂/L	10/12/2007	<0.2	2.1	0.6
Intake	4	0.5 mg of Cl₂/L	10/17/2007	0.6	3.0	1.6
Intake	4	2.0 mg of Cl₂/L	10/17/2007	0.7	3.0	0.9
Intake	5	0.5 mg of Cl₂/L	10/30/2007	<0.2	1.9	0.5
Intake	5	2.0 mg of Cl₂/L	10/30/2007	<0.2	2.5	0.6
Intake	6	0.5 mg of Cl₂/L	2/12/2008	<0.2	<0.5	3.0
Intake	6	2.0 mg of Cl₂/L	2/12/2008	<0.2	0.8	2.9
Intake	7	0.5 mg of Cl₂/L	2/19/2008	<0.2	<0.5	1.3
Intake	7	2.0 mg of Cl₂/L	2/19/2008	<0.2	<0.5	0.8
Intake	8	0.5 mg of Cl₂/L	3/28/2008	<0.2	1.3	3.9
Intake	8	2.0 mg of Cl₂/L	3/28/2008	<0.2	1.0	3.3
Intake	9	0.5 mg of Cl₂/L	4/29/2008	<0.2	<0.5	<0.2
Intake	9	2.0 mg of Cl₂/L	4/29/2008	<0.2	<0.5	<0.2
Feed	2	0.5 mg of Cl₂/L	10/5/2007	1.3	3.3	0.8
Feed	2	2.0 mg of Cl₂/L	10/5/2007	1.8	3.6	4.6
Feed	3	0.5 mg of Cl₂/L	10/12/2007	<0.2	1.6	1.3
Feed	3	2.0 mg of Cl₂/L	10/12/2007	<0.2	0.7	5.4
Feed	4	0.5 mg of Cl₂/L	10/17/2007	0.9	1.5	0.9
Feed	4	2.0 mg of Cl₂/L	10/17/2007	1.3	3.4	7.3
Feed	5	0.5 mg of Cl₂/L	10/30/2007	<0.2	2.2	1.3
Feed	5	2.0 mg of Cl₂/L	10/30/2007	<0.2	2.9	5.5
Feed	6	0.5 mg of Cl₂/L	2/12/2008	<0.2	1.3	2.8
Feed	6	2.0 mg of Cl₂/L	2/12/2008	<0.2	1.0	5.1
Feed	7	0.5 mg of Cl₂/L	2/19/2008	2.8	0.6	1.7
Feed	7	2.0 mg of Cl₂/L	2/19/2008	3.4	1.8	4.2
Feed	8	0.5 mg of Cl₂/L	3/28/2008	<0.2	2.7	3.6
Feed	8	2.0 mg of Cl₂/L	3/28/2008	0.6	0.7	13
Feed	9	0.5 mg of Cl₂/L	4/29/2008	1.9	0.7	0.5
Feed	9	2.0 mg of Cl₂/L	4/29/2008	<0.2	1.8	2.1

Table A4.2. Pilot Plant Sampling Results: HAAs [Figures 4.7–4.15]

Sample	Round	Concn and Disinfectant	Experiment Date	Concn (µg/L) MCAA	DCAA	MBAA
Concentrate	2	0.5 mg of Cl$_2$/L	10/5/2007	1.7	4.2	1.7
Concentrate	2	2.0 mg of Cl$_2$/L	10/5/2007	3.6	1.5	12
Concentrate	3	0.5 mg of Cl$_2$/L	10/12/2007	<0.2	2.7	2.6
Concentrate	3	2.0 mg of Cl$_2$/L	10/12/2007	<0.2	1.5	14
Concentrate	4	0.5 mg of Cl$_2$/L	10/17/2007	1.0	2.3	1.6
Concentrate	4	2.0 mg of Cl$_2$/L	10/17/2007	1.1	1.0	12
Concentrate	5	0.5 mg of Cl$_2$/L	10/30/2007	<0.2	3.7	2.5
Concentrate	5	2.0 mg of Cl$_2$/L	10/30/2007	<0.2	2.5	10
Concentrate	6	0.5 mg of Cl$_2$/L	2/12/2008	<0.2	2.2	3.8
Concentrate	6	2.0 mg of Cl$_2$/L	2/12/2008	<0.2	3.4	9.1
Concentrate	7	0.5 mg of Cl$_2$/L	2/19/2008	3.4	2.6	3.2
Concentrate	7	2.0 mg of Cl$_2$/L	2/19/2008	3.5	3.7	5.0
Concentrate	8	0.5 mg of Cl$_2$/L	3/28/2008	<0.2	3.7	6.7
Concentrate	8	2.0 mg of Cl$_2$/L	3/28/2008	1.2	4.0	3.1
Concentrate	9	0.5 mg of Cl$_2$/L	4/29/2008	0.8	<0.5	0.5
Concentrate	9	2.0 mg of Cl$_2$/L	4/29/2008	0.6	2.0	4.4
Permeate	2	0.5 mg of Cl$_2$/L	10/5/2007	1.2	1.4	<0.2
Permeate	2	2.0 mg of Cl$_2$/L	10/5/2007	0.9	7.8	<0.2
Permeate	3	0.5 mg of Cl$_2$/L	10/12/2007	<0.2	1.0	<0.2
Permeate	3	2.0 mg of Cl$_2$/L	10/12/2007	<0.2	2.0	<0.2
Permeate	4	0.5 mg of Cl$_2$/L	10/17/2007	0.6	2.0	<0.2
Permeate	4	2.0 mg of Cl$_2$/L	10/17/2007	0.5	4.0	<0.2
Permeate	5	0.5 mg of Cl$_2$/L	10/30/2007	<0.2	1.2	<0.2
Permeate	5	2.0 mg of Cl$_2$/L	10/30/2007	<0.2	2.9	<0.2
Permeate	6	0.5 mg of Cl$_2$/L	2/12/2008	<0.2	1.7	<0.2
Permeate	6	2.0 mg of Cl$_2$/L	2/12/2008	<0.2	0.5	0.4
Permeate	7	0.5 mg of Cl$_2$/L	2/19/2008	<0.2	<0.5	<0.2
Permeate	7	2.0 mg of Cl$_2$/L	2/19/2008	<0.2	<0.5	<0.2
Permeate	8	0.5 mg of Cl$_2$/L	3/28/2008	<0.2	3.0	<0.2
Permeate	8	2.0 mg of Cl$_2$/L	3/28/2008	<0.2	<0.5	0.6
Permeate	9	0.5 mg of Cl$_2$/L	4/29/2008	<0.2	<0.5	0.3
Permeate	9	2.0 mg of Cl$_2$/L	4/29/2008	<0.2	<0.5	0.2

Table A4.2. Pilot Plant Sampling Results: HAAs [Figures 4.7–4.15]

Sample	Round	Concn and Disinfectant	Experiment Date	Concn (μg/L)		
				TCAA	BCAA	BDCAA
Intake	2	0.5 mg of Cl$_2$/L	10/5/2007	<0.5	<0.4	<0.7
Intake	2	2.0 mg of Cl$_2$/L	10/5/2007	<0.5	<0.4	<0.7
Intake	3	0.5 mg of Cl$_2$/L	10/12/2007	12	<0.4	1.1
Intake	3	2.0 mg of Cl$_2$/L	10/12/2007	3.1	<0.4	0.7
Intake	4	0.5 mg of Cl$_2$/L	10/17/2007	3.4	<0.4	<0.7
Intake	4	2.0 mg of Cl$_2$/L	10/17/2007	3.9	<0.4	<0.7
Intake	5	0.5 mg of Cl$_2$/L	10/30/2007	7.3	<0.4	<0.7
Intake	5	2.0 mg of Cl$_2$/L	10/30/2007	3.9	<0.4	<0.7
Intake	6	0.5 mg of Cl$_2$/L	2/12/2008	7.9	1.3	0.8
Intake	6	2.0 mg of Cl$_2$/L	2/12/2008	5.4	0.8	0.8
Intake	7	0.5 mg of Cl$_2$/L	2/19/2008	<0.5	<0.4	<0.7
Intake	7	2.0 mg of Cl$_2$/L	2/19/2008	<0.5	<0.4	<0.7
Intake	8	0.5 mg of Cl$_2$/L	3/28/2008	8.3	1.2	0.8
Intake	8	2.0 mg of Cl$_2$/L	3/28/2008	6.3	0.7	0.8
Intake	9	0.5 mg of Cl$_2$/L	4/29/2008	<0.5	<0.4	<0.7
Intake	9	2.0 mg of Cl$_2$/L	4/29/2008	<0.5	<0.4	<0.7
Feed	2	0.5 mg of Cl$_2$/L	10/5/2007	<0.5	<0.4	<0.7
Feed	2	2.0 mg of Cl$_2$/L	10/5/2007	<0.5	<0.4	1.9
Feed	3	0.5 mg of Cl$_2$/L	10/12/2007	8.6	0.8	<0.7
Feed	3	2.0 mg of Cl$_2$/L	10/12/2007	4.7	<0.4	<0.7
Feed	4	0.5 mg of Cl$_2$/L	10/17/2007	2.1	<0.4	<0.7
Feed	4	2.0 mg of Cl$_2$/L	10/17/2007	4.2	<0.4	<0.7
Feed	5	0.5 mg of Cl$_2$/L	10/30/2007	4.9	<0.4	<0.7
Feed	5	2.0 mg of Cl$_2$/L	10/30/2007	3.5	<0.4	0.9
Feed	6	0.5 mg of Cl$_2$/L	2/12/2008	2.9	1.6	<0.7
Feed	6	2.0 mg of Cl$_2$/L	2/12/2008	2.9	1.4	2.0
Feed	7	0.5 mg of Cl$_2$/L	2/19/2008	1.9	1.8	<0.7
Feed	7	2.0 mg of Cl$_2$/L	2/19/2008	2.8	<0.4	0.8
Feed	8	0.5 mg of Cl$_2$/L	3/28/2008	5.8	0.6	<0.7
Feed	8	2.0 mg of Cl$_2$/L	3/28/2008	7.4	1.1	0.8
Feed	9	0.5 mg of Cl$_2$/L	4/29/2008	7.1	8.7	6.0
Feed	9	2.0 mg of Cl$_2$/L	4/29/2008	2.1	1.3	1.1

Table A4.2. Pilot Plant Sampling Results: HAAs [Figures 4.7–4.15]

Sample	Round	Concn and Disinfectant	Experiment Date	Concn (μg/L) TCAA	BCAA	BDCAA
Concentrate	2	0.5 mg of Cl$_2$/L	10/5/2007	<0.5	<0.4	1.0
Concentrate	2	2.0 mg of Cl$_2$/L	10/5/2007	<0.5	0.6	3.8
Concentrate	3	0.5 mg of Cl$_2$/L	10/12/2007	19	3.6	3.8
Concentrate	3	2.0 mg of Cl$_2$/L	10/12/2007	9.5	1.3	3.0
Concentrate	4	0.5 mg of Cl$_2$/L	10/17/2007	3.5	<0.4	0.7
Concentrate	4	2.0 mg of Cl$_2$/L	10/17/2007	4.9	0.7	3.8
Concentrate	5	0.5 mg of Cl$_2$/L	10/30/2007	4.1	1.3	2.0
Concentrate	5	2.0 mg of Cl$_2$/L	10/30/2007	5.4	0.9	2.6
Concentrate	6	0.5 mg of Cl$_2$/L	2/12/2008	3.3	1.7	2.0
Concentrate	6	2.0 mg of Cl$_2$/L	2/12/2008	5.4	0.8	0.9
Concentrate	7	0.5 mg of Cl$_2$/L	2/19/2008	2.4	<0.4	0.8
Concentrate	7	2.0 mg of Cl$_2$/L	2/19/2008	3.8	0.6	2.0
Concentrate	8	0.5 mg of Cl$_2$/L	3/28/2008	1.7	2.5	2.9
Concentrate	8	2.0 mg of Cl$_2$/L	3/28/2008	1.0	2.1	2.4
Concentrate	9	0.5 mg of Cl$_2$/L	4/29/2008	8.4	8.6	5.3
Concentrate	9	2.0 mg of Cl$_2$/L	4/29/2008	4.6	3.2	2.0
Permeate	2	0.5 mg of Cl$_2$/L	10/5/2007	<0.5	<0.4	<0.7
Permeate	2	2.0 mg of Cl$_2$/L	10/5/2007	<0.5	<0.4	<0.7
Permeate	3	0.5 mg of Cl$_2$/L	10/12/2007	<0.5	<0.4	<0.7
Permeate	3	2.0 mg of Cl$_2$/L	10/12/2007	<0.5	<0.4	<0.7
Permeate	4	0.5 mg of Cl$_2$/L	10/17/2007	<0.5	<0.4	<0.7
Permeate	4	2.0 mg of Cl$_2$/L	10/17/2007	<0.5	<0.4	<0.7
Permeate	5	0.5 mg of Cl$_2$/L	10/30/2007	<0.5	<0.4	<0.7
Permeate	5	2.0 mg of Cl$_2$/L	10/30/2007	<0.5	<0.4	<0.7
Permeate	6	0.5 mg of Cl$_2$/L	2/12/2008	<0.5	<0.4	<0.7
Permeate	6	2.0 mg of Cl$_2$/L	2/12/2008	<0.5	<0.4	<0.7
Permeate	7	0.5 mg of Cl$_2$/L	2/19/2008	<0.5	<0.4	<0.7
Permeate	7	2.0 mg of Cl$_2$/L	2/19/2008	<0.5	<0.4	<0.7
Permeate	8	0.5 mg of Cl$_2$/L	3/28/2008	<0.5	<0.4	<0.7
Permeate	8	2.0 mg of Cl$_2$/L	3/28/2008	<0.5	<0.4	<0.7
Permeate	9	0.5 mg of Cl$_2$/L	4/29/2008	<0.5	<0.4	<0.7
Permeate	9	2.0 mg of Cl$_2$/L	4/29/2008	<0.5	<0.4	<0.7

Table A4.2. Pilot Plant Sampling Results: HAAs [Figures 4.7–4.15]

Sample	Round	Concn and Disinfectant	Experiment Date	Concn (µg/L) DBAA	DBCAA	TBAA
Intake	2	0.5 mg of Cl$_2$/L	10/5/2007	<0.6	<0.2	<0.4
Intake	2	2.0 mg of Cl$_2$/L	10/5/2007	<0.6	<0.2	1.1
Intake	3	0.5 mg of Cl$_2$/L	10/12/2007	0.7	<0.2	0.7
Intake	3	2.0 mg of Cl$_2$/L	10/12/2007	<0.6	<0.2	4.2
Intake	4	0.5 mg of Cl$_2$/L	10/17/2007	1.3	<0.2	<0.4
Intake	4	2.0 mg of Cl$_2$/L	10/17/2007	<0.6	<0.2	2.6
Intake	5	0.5 mg of Cl$_2$/L	10/30/2007	0.7	<0.2	0.6
Intake	5	2.0 mg of Cl$_2$/L	10/30/2007	<0.6	<0.2	2.4
Intake	6	0.5 mg of Cl$_2$/L	2/12/2008	0.9	<0.2	<0.4
Intake	6	2.0 mg of Cl$_2$/L	2/12/2008	0.7	<0.2	3.5
Intake	7	0.5 mg of Cl$_2$/L	2/19/2008	<0.6	<0.2	<0.4
Intake	7	2.0 mg of Cl$_2$/L	2/19/2008	<0.6	<0.2	3.4
Intake	8	0.5 mg of Cl$_2$/L	3/28/2008	<0.6	<0.2	<0.4
Intake	8	2.0 mg of Cl$_2$/L	3/28/2008	<0.6	<0.2	4.1
Intake	9	0.5 mg of Cl$_2$/L	4/29/2008	<0.6	<0.2	0.8
Intake	9	2.0 mg of Cl$_2$/L	4/29/2008	<0.6	<0.2	0.8
Feed	2	0.5 mg of Cl$_2$/L	10/5/2007	<0.6	<0.2	<0.4
Feed	2	2.0 mg of Cl$_2$/L	10/5/2007	<0.6	<0.2	0.5
Feed	3	0.5 mg of Cl$_2$/L	10/12/2007	1.2	<0.2	<0.4
Feed	3	2.0 mg of Cl$_2$/L	10/12/2007	2.1	<0.2	1.3
Feed	4	0.5 mg of Cl$_2$/L	10/17/2007	<0.6	<0.2	<0.4
Feed	4	2.0 mg of Cl$_2$/L	10/17/2007	3.3	<0.2	1.0
Feed	5	0.5 mg of Cl$_2$/L	10/30/2007	1.0	<0.2	<0.4
Feed	5	2.0 mg of Cl$_2$/L	10/30/2007	0.8	<0.2	1.2
Feed	6	0.5 mg of Cl$_2$/L	2/12/2008	1.4	1.3	0.5
Feed	6	2.0 mg of Cl$_2$/L	2/12/2008	2.1	0.6	3.6
Feed	7	0.5 mg of Cl$_2$/L	2/19/2008	1.9	1.8	<0.4
Feed	7	2.0 mg of Cl$_2$/L	2/19/2008	3.7	0.7	2.8
Feed	8	0.5 mg of Cl$_2$/L	3/28/2008	<0.6	<0.2	<0.4
Feed	8	2.0 mg of Cl$_2$/L	3/28/2008	<0.6	<0.2	4.0
Feed	9	0.5 mg of Cl$_2$/L	4/29/2008	1.3	0.4	0.8
Feed	9	2.0 mg of Cl$_2$/L	4/29/2008	<0.6	<0.2	0.6

Table A4.2. Pilot Plant Sampling Results: HAAs [Figures 4.7–4.15]

Sample	Round	Concn and Disinfectant	Experiment Date	Concn (μg/L)		
				DBAA	DBCAA	TBAA
Concentrate	2	0.5 mg of Cl$_2$/L	10/5/2007	<0.6	<0.2	<0.4
Concentrate	2	2.0 mg of Cl$_2$/L	10/5/2007	<0.6	0.3	<0.4
Concentrate	3	0.5 mg of Cl$_2$/L	10/12/2007	2.3	<0.2	<0.4
Concentrate	3	2.0 mg of Cl$_2$/L	10/12/2007	4.7	0.4	<0.4
Concentrate	4	0.5 mg of Cl$_2$/L	10/17/2007	<0.6	<0.2	<0.4
Concentrate	4	2.0 mg of Cl$_2$/L	10/17/2007	4.6	0.4	<0.4
Concentrate	5	0.5 mg of Cl$_2$/L	10/30/2007	1.5	<0.2	<0.4
Concentrate	5	2.0 mg of Cl$_2$/L	10/30/2007	1.3	0.3	<0.4
Concentrate	6	0.5 mg of Cl$_2$/L	2/12/2008	1.9	<0.2	<0.4
Concentrate	6	2.0 mg of Cl$_2$/L	2/12/2008	2.7	0.2	<0.4
Concentrate	7	0.5 mg of Cl$_2$/L	2/19/2008	2.3	<0.2	<0.4
Concentrate	7	2.0 mg of Cl$_2$/L	2/19/2008	4.0	1.9	<0.4
Concentrate	8	0.5 mg of Cl$_2$/L	3/28/2008	0.9	<0.2	<0.4
Concentrate	8	2.0 mg of Cl$_2$/L	3/28/2008	<0.6	<0.2	<0.4
Concentrate	9	0.5 mg of Cl$_2$/L	4/29/2008	1.1	<0.2	<0.4
Concentrate	9	2.0 mg of Cl$_2$/L	4/29/2008	1.0	<0.2	<0.4
Permeate	2	0.5 mg of Cl$_2$/L	10/5/2007	<0.6	<0.2	<0.4
Permeate	2	2.0 mg of Cl$_2$/L	10/5/2007	<0.6	<0.2	<0.4
Permeate	3	0.5 mg of Cl$_2$/L	10/12/2007	<0.6	<0.2	<0.4
Permeate	3	2.0 mg of Cl$_2$/L	10/12/2007	<0.6	<0.2	<0.4
Permeate	4	0.5 mg of Cl$_2$/L	10/17/2007	<0.6	<0.2	<0.4
Permeate	4	2.0 mg of Cl$_2$/L	10/17/2007	<0.6	<0.2	<0.4
Permeate	5	0.5 mg of Cl$_2$/L	10/30/2007	<0.6	<0.2	<0.4
Permeate	5	2.0 mg of Cl$_2$/L	10/30/2007	<0.6	<0.2	<0.4
Permeate	6	0.5 mg of Cl$_2$/L	2/12/2008	<0.6	<0.2	<0.4
Permeate	6	2.0 mg of Cl$_2$/L	2/12/2008	<0.6	<0.2	<0.4
Permeate	7	0.5 mg of Cl$_2$/L	2/19/2008	<0.6	<0.2	<0.4
Permeate	7	2.0 mg of Cl$_2$/L	2/19/2008	<0.6	<0.2	<0.4
Permeate	8	0.5 mg of Cl$_2$/L	3/28/2008	<0.6	<0.2	<0.4
Permeate	8	2.0 mg of Cl$_2$/L	3/28/2008	<0.6	<0.2	<0.4
Permeate	9	0.5 mg of Cl$_2$/L	4/29/2008	<0.6	<0.2	<0.4
Permeate	9	2.0 mg of Cl$_2$/L	4/29/2008	<0.6	<0.2	<0.4

Table A4.3. Pilot Plant Sampling Results: Halophenols [Figures 4.16–4.18]

Sample	Round	Concn and Disinfectant	Experiment Date	Concn (μg/L) 2-Bromophenol	2,6-Dibromophenol	2,4,6-Tribromophenol
Intake	2	0.5 mg of Cl$_2$/L	10/5/2007	<0.045	<0.086	0.177
Intake	2	2.0 mg of Cl$_2$/L	10/5/2007	<0.045	0.183	<0.110
Intake	3	0.5 mg of Cl$_2$/L	10/12/2007	<0.045	<0.086	<0.110
Intake	3	2.0 mg of Cl$_2$/L	10/12/2007	<0.045	0.093	0.242
Intake	4	0.5 mg of Cl$_2$/L	10/17/2007	<0.045	<0.086	<0.110
Intake	4	2.0 mg of Cl$_2$/L	10/17/2007	<0.045	<0.086	<0.110
Intake	5	0.5 mg of Cl$_2$/L	10/30/2007	<0.045	<0.086	<0.110
Intake	5	2.0 mg of Cl$_2$/L	10/30/2007	<0.045	<0.086	0.230
Intake	6	0.5 mg of Cl$_2$/L	2/12/2008	0.064	<0.086	<0.110
Intake	6	2.0 mg of Cl$_2$/L	2/12/2008	<0.045	<0.086	0.121
Intake	7	0.5 mg of Cl$_2$/L	2/19/2008	<0.045	<0.086	<0.110
Intake	7	2.0 mg of Cl$_2$/L	2/19/2008	<0.045	<0.086	0.146
Intake	8	0.5 mg of Cl$_2$/L	3/28/2008	<0.045	<0.086	<0.110
Intake	8	2.0 mg of Cl$_2$/L	3/28/2008	<0.045	<0.086	<0.110
Intake	9	0.5 mg of Cl$_2$/L	4/29/2008	0.047	0.101	0.223
Intake	9	2.0 mg of Cl$_2$/L	4/29/2008	0.063	0.155	0.133
Feed	2	0.5 mg of Cl$_2$/L	10/5/2007	<0.045	0.155	0.692
Feed	2	2.0 mg of Cl$_2$/L	10/5/2007	<0.045	0.367	0.129
Feed	3	0.5 mg of Cl$_2$/L	10/12/2007	<0.045	<0.086	0.251
Feed	3	2.0 mg of Cl$_2$/L	10/12/2007	<0.045	<0.086	0.125
Feed	4	0.5 mg of Cl$_2$/L	10/17/2007	<0.045	<0.086	<0.110
Feed	4	2.0 mg of Cl$_2$/L	10/17/2007	<0.045	<0.086	0.144
Feed	5	0.5 mg of Cl$_2$/L	10/30/2007	<0.045	0.273	0.228
Feed	5	2.0 mg of Cl$_2$/L	10/30/2007	<0.045	<0.086	0.286
Feed	6	0.5 mg of Cl$_2$/L	2/12/2008	0.080	0.332	0.399
Feed	6	2.0 mg of Cl$_2$/L	2/12/2008	0.049	0.186	0.663
Feed	7	0.5 mg of Cl$_2$/L	2/19/2008	<0.045	<0.086	0.376
Feed	7	2.0 mg of Cl$_2$/L	2/19/2008	<0.045	<0.086	0.184
Feed	8	0.5 mg of Cl$_2$/L	3/28/2008	<0.045	0.094	0.380
Feed	8	2.0 mg of Cl$_2$/L	3/28/2008	<0.045	0.243	0.126
Feed	9	0.5 mg of Cl$_2$/L	4/29/2008	0.057	<0.086	0.496
Feed	9	2.0 mg of Cl$_2$/L	4/29/2008	<0.045	0.497	0.217

Table A4.3. Pilot Plant Sampling Results: Halophenols [Figures 4.16–4.18]

				Concn (µg/L)		
Sample	Round	Concn and Disinfectant	Experiment Date	2-Bromophenol	2,6-Dibromophenol	2,4,6-Tribromophenol
Concentrate	2	0.5 mg of Cl$_2$/L	10/5/2007	0.054	0.216	0.747
Concentrate	2	2.0 mg of Cl$_2$/L	10/5/2007	0.054	0.542	0.298
Concentrate	3	0.5 mg of Cl$_2$/L	10/12/2007	<0.045	<0.086	0.320
Concentrate	3	2.0 mg of Cl$_2$/L	10/12/2007	<0.045	<0.086	0.231
Concentrate	4	0.5 mg of Cl$_2$/L	10/17/2007	<0.045	<0.086	<0.110
Concentrate	4	2.0 mg of Cl$_2$/L	10/17/2007	<0.045	<0.086	0.111
Concentrate	5	0.5 mg of Cl$_2$/L	10/30/2007	0.266	0.764	0.502
Concentrate	5	2.0 mg of Cl$_2$/L	10/30/2007	<0.045	0.170	0.567
Concentrate	6	0.5 mg of Cl$_2$/L	2/12/2008	0.076	0.256	0.802
Concentrate	6	2.0 mg of Cl$_2$/L	2/12/2008	0.086	0.716	0.467
Concentrate	7	0.5 mg of Cl$_2$/L	2/19/2008	0.055	0.196	0.542
Concentrate	7	2.0 mg of Cl$_2$/L	2/19/2008	0.054	0.444	0.293
Concentrate	8	0.5 mg of Cl$_2$/L	3/28/2008	0.089	0.155	0.559
Concentrate	8	2.0 mg of Cl$_2$/L	3/28/2008	0.052	0.387	0.235
Concentrate	9	0.5 mg of Cl$_2$/L	4/29/2008	0.083	0.132	0.791
Concentrate	9	2.0 mg of Cl$_2$/L	4/29/2008	0.047	0.729	0.319
Permeate	2	0.5 mg of Cl$_2$/L	10/5/2007	<0.045	<0.086	<0.110
Permeate	2	2.0 mg of Cl$_2$/L	10/5/2007	<0.045	<0.086	<0.110
Permeate	3	0.5 mg of Cl$_2$/L	10/12/2007	<0.045	<0.086	<0.110
Permeate	3	2.0 mg of Cl$_2$/L	10/12/2007	<0.045	<0.086	<0.110
Permeate	4	0.5 mg of Cl$_2$/L	10/17/2007	<0.045	<0.086	<0.110
Permeate	4	2.0 mg of Cl$_2$/L	10/17/2007	<0.045	<0.086	<0.110
Permeate	5	0.5 mg of Cl$_2$/L	10/30/2007	<0.045	<0.086	<0.110
Permeate	5	2.0 mg of Cl$_2$/L	10/30/2007	<0.045	<0.086	<0.110
Permeate	6	0.5 mg of Cl$_2$/L	2/12/2008	<0.045	<0.086	<0.110
Permeate	6	2.0 mg of Cl$_2$/L	2/12/2008	<0.045	<0.086	<0.110
Permeate	7	0.5 mg of Cl$_2$/L	2/19/2008	<0.045	<0.086	<0.110
Permeate	7	2.0 mg of Cl$_2$/L	2/19/2008	<0.045	<0.086	<0.110
Permeate	8	0.5 mg of Cl$_2$/L	3/28/2008	<0.045	<0.086	<0.110
Permeate	8	2.0 mg of Cl$_2$/L	3/28/2008	<0.045	<0.086	<0.110
Permeate	9	0.5 mg of Cl$_2$/L	4/29/2008	<0.045	<0.086	<0.110
Permeate	9	2.0 mg of Cl$_2$/L	4/29/2008	<0.045	<0.086	<0.110

Table A4.4. Pilot Plant Sampling Results: HANs [Figures 4.19–4.20]

Sample	Round	Concn and Disinfectant	Experiment Date	Concn (µg/L) CHCl$_2$CN	CHBrClCN	CHBr$_2$CN
Intake	2	0.5 mg of Cl$_2$/L	10/5/2007	<0.2	<0.2	<0.49
Intake	2	2.0 mg of Cl$_2$/L	10/5/2007	<0.2	0.24	<0.49
Intake	3	0.5 mg of Cl$_2$/L	10/12/2007	<0.2	<0.2	<0.49
Intake	3	2.0 mg of Cl$_2$/L	10/12/2007	<0.2	<0.2	<0.49
Intake	4	0.5 mg of Cl$_2$/L	10/17/2007	<0.2	0.22	<0.49
Intake	4	2.0 mg of Cl$_2$/L	10/17/2007	<0.2	0.21	<0.49
Intake	5	0.5 mg of Cl$_2$/L	10/30/2007	<0.2	0.24	<0.49
Intake	5	2.0 mg of Cl$_2$/L	10/30/2007	<0.2	0.24	<0.49
Intake	6	0.5 mg of Cl$_2$/L	2/12/2008	<0.2	<0.2	0.55
Intake	6	2.0 mg of Cl$_2$/L	2/12/2008	<0.2	5.1	0.59
Intake	7	0.5 mg of Cl$_2$/L	2/19/2008	<0.2	<0.2	7.6
Intake	7	2.0 mg of Cl$_2$/L	2/19/2008	<0.2	0.25	<0.49
Intake	8	0.5 mg of Cl$_2$/L	3/28/2008	<0.2	0.21	<0.49
Intake	8	2.0 mg of Cl$_2$/L	3/28/2008	<0.2	<0.2	<0.49
Intake	9	0.5 mg of Cl$_2$/L	4/29/2008	<0.2	<0.2	<0.49
Intake	9	2.0 mg of Cl$_2$/L	4/29/2008	<0.2	<0.2	<0.49
Feed	2	0.5 mg of Cl$_2$/L	10/5/2007	<0.2	<0.2	<0.49
Feed	2	2.0 mg of Cl$_2$/L	10/5/2007	<0.2	<0.2	3.4
Feed	3	0.5 mg of Cl$_2$/L	10/12/2007	<0.2	<0.2	<0.49
Feed	3	2.0 mg of Cl$_2$/L	10/12/2007	<0.2	<0.2	<0.49
Feed	4	0.5 mg of Cl$_2$/L	10/17/2007	<0.2	0.21	<0.49
Feed	4	2.0 mg of Cl$_2$/L	10/17/2007	<0.2	<0.2	0.59
Feed	5	0.5 mg of Cl$_2$/L	10/30/2007	<0.2	<0.2	<0.49
Feed	5	2.0 mg of Cl$_2$/L	10/30/2007	<0.2	0.22	<0.49
Feed	6	0.5 mg of Cl$_2$/L	2/12/2008	<0.2	0.65	<0.49
Feed	6	2.0 mg of Cl$_2$/L	2/12/2008	<0.2	0.25	<0.49
Feed	7	0.5 mg of Cl$_2$/L	2/19/2008	<0.2	1.9	0.63
Feed	7	2.0 mg of Cl$_2$/L	2/19/2008	<0.2	0.21	<0.49
Feed	8	0.5 mg of Cl$_2$/L	3/28/2008	<0.2	0.35	<0.49
Feed	8	2.0 mg of Cl$_2$/L	3/28/2008	<0.2	<0.2	2.9
Feed	9	0.5 mg of Cl$_2$/L	4/29/2008	<0.2	2.2	1.1
Feed	9	2.0 mg of Cl$_2$/L	4/29/2008	<0.2	2.1	<0.49

Table A4.4. Pilot Plant Sampling Results: HANs [Figures 4.19–4.20]

Sample	Round	Concn and Disinfectant	Experiment Date	Concn (µg/L)		
				CHCl$_2$CN	CHBrClCN	CHBr$_2$CN
Concentrate	2	0.5 mg of Cl$_2$/L	10/5/2007	<0.2	0.22	1.0
Concentrate	2	2.0 mg of Cl$_2$/L	10/5/2007	<0.2	0.23	3.4
Concentrate	3	0.5 mg of Cl$_2$/L	10/12/2007	<0.2	<0.2	<0.49
Concentrate	3	2.0 mg of Cl$_2$/L	10/12/2007	<0.2	0.26	<0.49
Concentrate	4	0.5 mg of Cl$_2$/L	10/17/2007	<0.2	0.21	0.49
Concentrate	4	2.0 mg of Cl$_2$/L	10/17/2007	<0.2	<0.2	0.99
Concentrate	5	0.5 mg of Cl$_2$/L	10/30/2007	<0.2	0.21	<0.49
Concentrate	5	2.0 mg of Cl$_2$/L	10/30/2007	<0.2	<0.2	1.7
Concentrate	6	0.5 mg of Cl$_2$/L	2/12/2008	<0.2	1.2	<0.49
Concentrate	6	2.0 mg of Cl$_2$/L	2/12/2008	<0.2	0.22	<0.49
Concentrate	7	0.5 mg of Cl$_2$/L	2/19/2008	<0.2	3.3	1.2
Concentrate	7	2.0 mg of Cl$_2$/L	2/19/2008	<0.2	0.20	<0.49
Concentrate	8	0.5 mg of Cl$_2$/L	3/28/2008	<0.2	0.47	<0.49
Concentrate	8	2.0 mg of Cl$_2$/L	3/28/2008	<0.2	0.22	4.7
Concentrate	9	0.5 mg of Cl$_2$/L	4/29/2008	<0.2	3.3	2.0
Concentrate	9	2.0 mg of Cl$_2$/L	4/29/2008	<0.2	2.5	<0.49
Permeate	2	0.5 mg of Cl$_2$/L	10/5/2007	<0.2	0.26	<0.49
Permeate	2	2.0 mg of Cl$_2$/L	10/5/2007	<0.2	0.25	<0.49
Permeate	3	0.5 mg of Cl$_2$/L	10/12/2007	<0.2	0.23	<0.49
Permeate	3	2.0 mg of Cl$_2$/L	10/12/2007	<0.2	0.22	<0.49
Permeate	4	0.5 mg of Cl$_2$/L	10/17/2007	<0.2	<0.2	0.58
Permeate	4	2.0 mg of Cl$_2$/L	10/17/2007	<0.2	0.26	<0.49
Permeate	5	0.5 mg of Cl$_2$/L	10/30/2007	<0.2	0.25	0.60
Permeate	5	2.0 mg of Cl$_2$/L	10/30/2007	<0.2	0.23	0.68
Permeate	6	0.5 mg of Cl$_2$/L	2/12/2008	<0.2	0.28	<0.49
Permeate	6	2.0 mg of Cl$_2$/L	2/12/2008	<0.2	<0.2	0.64
Permeate	7	0.5 mg of Cl$_2$/L	2/19/2008	<0.2	<0.2	0.50
Permeate	7	2.0 mg of Cl$_2$/L	2/19/2008	<0.2	0.24	0.93
Permeate	8	0.5 mg of Cl$_2$/L	3/28/2008	<0.2	<0.2	<0.49
Permeate	8	2.0 mg of Cl$_2$/L	3/28/2008	<0.2	<0.2	<0.49
Permeate	9	0.5 mg of Cl$_2$/L	4/29/2008	<0.2	0.23	<0.49
Permeate	9	2.0 mg of Cl$_2$/L	4/29/2008	<0.2	0.27	<0.49

Table A5.1. Blending Experiment Results: THMs [Figures 5.3–5.6]

Sample	Time (h)	Concn and Disinfectant	Experiment Date	Concn (μg/L)			
				CHCl$_3$	CHBrCl$_2$	CHBr$_2$Cl	CHBr$_3$
Blend of chlorinated raw Colorado River water with chlorinated desalinated water							
Colorado River	0	4 mg of Cl$_2$/L	3/20/2008	<1.1	<1.1	<1.1	<1.1
Colorado River	0.5	4 mg of Cl$_2$/L	3/20/2008	10	32	75	<1.1
Colorado River	12	4 mg of Cl$_2$/L	3/20/2008	74	41	100	<1.1
Colorado River	24	4 mg of Cl$_2$/L	3/20/2008	80	19	106	<1.1
Colorado River	48	4 mg of Cl$_2$/L	3/20/2008	87	16	114	<1.1
Colorado River	72	4 mg of Cl$_2$/L	3/20/2008	93	12	123	<1.1
Blend	0	4 mg of Cl$_2$/L	3/20/2008	<1.1	<1.1	<1.1	<1.1
Blend	0.5	4 mg of Cl2/L	3/20/2008	1.5	9.4	20	5.8
Blend	12	4 mg of Cl$_2$/L	3/20/2008	1.5	19	45	13
Blend	24	4 mg of Cl$_2$/L	3/20/2008	4.5	31	49	15
Blend	48	4 mg of Cl$_2$/L	3/20/2008	3.9	38	48	17
Blend	72	4 mg of Cl$_2$/L	3/20/2008	3.2	45	47	20
Desalinated water	0	4 mg of Cl$_2$/L	3/20/2008	<1.1	<1.1	<1.1	<1.1
Desalinated water	0.5	4 mg of Cl$_2$/L	3/20/2008	<1.1	<1.1	<1.1	<1.1
Desalinated water	12	4 mg of Cl$_2$/L	3/20/2008	<1.1	<1.1	<1.1	1.8
Desalinated water	24	4 mg of Cl$_2$/L	3/20/2008	<1.1	<1.1	<1.1	1.8
Desalinated water	48	4 mg of Cl$_2$/L	3/20/2008	<1.1	<1.1	<1.1	2.6
Desalinated water	72	4 mg of Cl$_2$/L	3/20/2008	<1.1	<1.1	<1.1	3.4
Blend of chlorinated raw San Pablo Reservoir water with chlorinated desalinated water							
San Pablo	0	4 mg of Cl$_2$/L	6/18/2008	<1.1	<1.1	<1.1	<1.1
San Pablo	0.5	4 mg of Cl$_2$/L	6/18/2008	18	5.4	<1.1	1.6
San Pablo	8	4 mg of Cl$_2$/L	6/18/2008	42	10	<1.1	1.6
San Pablo	16	4 mg of Cl$_2$/L	6/18/2008	46	13	<1.1	1.8
San Pablo	24	4 mg of Cl$_2$/L	6/18/2008	65	15	<1.1	2.3
San Pablo	48	4 mg of Cl$_2$/L	6/18/2008	61	16	<1.1	1.9
San Pablo	72	4 mg of Cl$_2$/L	6/18/2008	69	18	<1.1	3.0
Blend	0	4 mg of Cl$_2$/L	6/18/2008	<1.1	<1.1	<1.1	<1.1
Blend	0.5	4 mg of Cl$_2$/L	6/18/2008	2.1	11	<1.1	1.0
Blend	8	4 mg of Cl$_2$/L	6/18/2008	2.6	25	<1.1	2.9
Blend	16	4 mg of Cl$_2$/L	6/18/2008	3.0	33	<1.1	5.2
Blend	24	4 mg of Cl$_2$/L	6/18/2008	3.6	43	0.9	9.8
Blend	48	4 mg of Cl$_2$/L	6/18/2008	3.6	57	1.7	13.0
Blend	72	4 mg of Cl$_2$/L	6/18/2008	3.1	63	2.4	15.2
Desalinated water	0	4 mg of Cl$_2$/L	6/18/2008	<1.1	<1.1	<1.1	<1.1
Desalinated water	0.5	4 mg of Cl$_2$/L	6/18/2008	<1.1	<1.1	<1.1	1.2
Desalinated water	8	4 mg of Cl$_2$/L	6/18/2008	1.4	<1.1	<1.1	1.2
Desalinated water	16	4 mg of Cl$_2$/L	6/18/2008	1.8	<1.1	<1.1	1.3
Desalinated water	24	4 mg of Cl$_2$/L	6/18/2008	2.4	<1.1	<1.1	1.9
Desalinated water	48	4 mg of Cl$_2$/L	6/18/2008	2.8	<1.1	<1.1	2.0

| Desalinated water | 72 | 4 mg of Cl$_2$/L | 6/18/2008 | 2.9 | <1.1 | <1.1 | 2.0 |

Table A5.1. Blending Experiment Results: THMs [Figures 5.7–5.8]

| | Time | Concn and | Experiment | Concn (µg/L) | | | |
Sample	(h)	Disinfectant	Date	CHCl$_3$	CHBrCl$_2$	CHBr$_2$Cl	CHBr$_3$
Blend of chloraminated tap water with chloraminated desalinated water							
EBMUD	0	2.5 mg/L NH$_2$Cl	6/24/2008	<1.1	<1.1	<1.1	<1.1
EBMUD	0.5	2.5 mg/L NH$_2$Cl	6/24/2008	5.6	3.6	1.8	3.2
EBMUD	8	2.5 mg/L NH$_2$Cl	6/24/2008	8.6	3.5	2.1	2.9
EBMUD	16	2.5 mg/L NH$_2$Cl	6/24/2008	5.8	4.2	2.6	3.0
EBMUD	24	2.5 mg/L NH$_2$Cl	6/24/2008	6.4	2.9	2.3	3.8
EBMUD	48	2.5 mg/L NH$_2$Cl	6/24/2008	6.6	2.9	3.0	3.6
EBMUD	72	2.5 mg/L NH$_2$Cl	6/24/2008	6.8	2.4	2.8	3.9
Blend	0	2.5 mg/L NH$_2$Cl	6/24/2008	<1.1	<1.1	<1.1	<1.1
Blend	0.5	2.5 mg/L NH$_2$Cl	6/24/2008	2.2	<1.1	<1.1	1.6
Blend	8	2.5 mg/L NH$_2$Cl	6/24/2008	3.7	<1.1	<1.1	2.4
Blend	16	2.5 mg/L NH$_2$Cl	6/24/2008	3.3	1.3	<1.1	3.7
Blend	24	2.5 mg/L NH$_2$Cl	6/24/2008	2.4	<1.1	<1.1	2.9
Blend	48	2.5 mg/L NH$_2$Cl	6/24/2008	3.9	1.9	1.5	3.5
Blend	72	2.5 mg/L NH$_2$Cl	6/24/2008	3.8	1.5	<1.1	3.2
Desalinated water	0	2.5 mg/L NH$_2$Cl	6/24/2008	<1.1	<1.1	<1.1	<1.1
Desalinated water	0.5	2.5 mg/L NH$_2$Cl	6/24/2008	<1.1	<1.1	<1.1	1.4
Desalinated water	8	2.5 mg/L NH$_2$Cl	6/24/2008	<1.1	1.3	<1.1	1.5
Desalinated water	16	2.5 mg/L NH$_2$Cl	6/24/2008	<1.1	1.3	<1.1	1.8
Desalinated water	24	2.5 mg/L NH$_2$Cl	6/24/2008	<1.1	1.5	1.3	1.1
Desalinated water	48	2.5 mg/L NH$_2$Cl	6/24/2008	<1.1	1.4	1.2	1.3
Desalinated water	72	2.5 mg/L NH$_2$Cl	6/24/2008	<1.1	<1.1	<1.1	1.2

Table A5.1. Blending Experiment Results: THMs [Appendix B, Figure B2]

Sample	Time (h)	Concn and Disinfectant	Experiment Date	Concn (µg/L)			
				CHCl$_3$	CHBrCl$_2$	CHBr$_2$Cl	CHBr$_3$
Blend of chloraminated tap water with chlorinated desalinated water							
EBMUD	0	2.5 mg/L NH$_2$Cl	6/11/2008	<1.1	<1.1	<1.1	<1.1
EBMUD	0.5	2.5 mg/L NH$_2$Cl	6/11/2008	10	4.2	2.4	3.4
EBMUD	8	2.5 mg/L NH$_2$Cl	6/11/2008	8.8	4.0	2.5	2.8
EBMUD	16	2.5 mg/L NH$_2$Cl	6/11/2008	8.5	5.2	3.6	2.6
EBMUD	24	2.5 mg/L NH$_2$Cl	6/11/2008	8.5	4.0	2.9	4.0
EBMUD	48	2.5 mg/L NH$_2$Cl	6/11/2008	7.6	5.1	3.0	3.4
EBMUD	72	2.5 mg/L NH$_2$Cl	6/11/2008	9.1	6.0	3.6	3.6
Blend	0	Mix NH$_2$Cl/Cl$_2$	6/11/2008	<1.1	<1.1	<1.1	<1.1
Blend	0.5	Mix NH$_2$Cl/Cl$_2$	6/11/2008	<1.1	2.2	1.9	6.1
Blend	8	Mix NH$_2$Cl/Cl$_2$	6/11/2008	<1.1	2.0	1.8	5.6
Blend	16	Mix NH$_2$Cl/Cl$_2$	6/11/2008	<1.1	2.9	2.6	6.4
Blend	24	Mix NH$_2$Cl/Cl$_2$	6/11/2008	<1.1	2.3	2.1	8.1
Blend	48	Mix NH$_2$Cl/Cl$_2$	6/11/2008	<1.1	4.6	4.0	7.7
Blend	72	Mix NH$_2$Cl/Cl$_2$	6/11/2008	1.5	3.5	4.5	5.6
Desalinated water	0	2.5 mg/L NH$_2$Cl	6/11/2008	<1.1	<1.1	<1.1	<1.1
Desalinated water	0.5	2.5 mg/L NH$_2$Cl	6/11/2008	<1.1	<1.1	<1.1	9
Desalinated water	8	2.5 mg/L NH$_2$Cl	6/11/2008	<1.1	<1.1	<1.1	8
Desalinated water	16	2.5 mg/L NH$_2$Cl	6/11/2008	<1.1	<1.1	<1.1	11
Desalinated water	24	2.5 mg/L NH$_2$Cl	6/11/2008	<1.1	1.2	<1.1	11
Desalinated water	48	2.5 mg/L NH$_2$Cl	6/11/2008	<1.1	1.4	<1.1	11
Desalinated water	72	2.5 mg/L NH$_2$Cl	6/11/2008	<1.1	1.3	<1.1	7.4

Table A5.2. Blending Experiment Results: HAAs [Figures 5.9–5.12]

Sample	Time (h)	Concn and Disinfectant	Experiment Date	Concn (µg/L) MCAA	DCAA	MBAA
Blend of chlorinated raw Colorado River water with chlorinated desalinated water						
Colorado River	0	4 mg of Cl$_2$/L	3/20/2008	<0.2	<0.5	<0.2
Colorado River	0.5	4 mg of Cl$_2$/L	3/20/2008	1.5	14	1.1
Colorado River	12	4 mg of Cl$_2$/L	3/20/2008	2.4	17	3.3
Colorado River	24	4 mg of Cl$_2$/L	3/20/2008	1.9	13	12
Colorado River	48	4 mg of Cl$_2$/L	3/20/2008	2.2	13	7.9
Colorado River	72	4 mg of Cl$_2$/L	3/20/2008	2.4	13	3.6
Blend	0	4 mg of Cl$_2$/L	3/20/2008	<0.2	<0.5	<0.2
Blend	0.5	4 mg of Cl$_2$/L	3/20/2008	0.8	0.9	5.5
Blend	12	4 mg of Cl$_2$/L	3/20/2008	0.8	1.4	10
Blend	24	4 mg of Cl$_2$/L	3/20/2008	0.3	5.5	10
Blend	48	4 mg of Cl$_2$/L	3/20/2008	0.3	5.8	6.8
Blend	72	4 mg of Cl$_2$/L	3/20/2008	0.2	6.1	7.1
Desalinated water	0	4 mg of Cl$_2$/L	3/20/2008	<0.2	<0.5	<0.2
Desalinated water	0.5	4 mg of Cl$_2$/L	3/20/2008	<0.2	<0.5	<0.2
Desalinated water	12	4 mg of Cl$_2$/L	3/20/2008	<0.2	<0.5	0.4
Desalinated water	24	4 mg of Cl$_2$/L	3/20/2008	<0.2	<0.5	0.6
Desalinated water	48	4 mg of Cl$_2$/L	3/20/2008	<0.2	<0.5	0.5
Desalinated water	72	4 mg of Cl$_2$/L	3/20/2008	<0.2	<0.5	0.3
Blend of chlorinated raw San Pablo Reservoir water with chlorinated desalinated water						
San Pablo	0	4 mg of Cl$_2$/L	6/18/2008	<0.2	<0.5	<0.2
San Pablo	0.5	4 mg of Cl$_2$/L	6/18/2008	0.7	6.3	1.5
San Pablo	8	4 mg of Cl$_2$/L	6/18/2008	7.9	9.4	1.1
San Pablo	16	4 mg of Cl$_2$/L	6/18/2008	12	12	1.5
San Pablo	24	4 mg of Cl$_2$/L	6/18/2008	12	15	2.0
San Pablo	48	4 mg of Cl$_2$/L	6/18/2008	15	22	1.7
San Pablo	72	4 mg of Cl$_2$/L	6/18/2008	15	19	1.9
Blend	0	4 mg of Cl$_2$/L	6/18/2008	<0.2	<0.5	<0.2
Blend	0.5	4 mg of Cl$_2$/L	6/18/2008	2.0	0.8	7.6
Blend	8	4 mg of Cl$_2$/L	6/18/2008	4.0	1.5	12
Blend	16	4 mg of Cl$_2$/L	6/18/2008	4.8	2.0	13
Blend	24	4 mg of Cl$_2$/L	6/18/2008	4.7	2.0	11
Blend	48	4 mg of Cl$_2$/L	6/18/2008	0.8	2.2	9.5
Blend	72	4 mg of Cl$_2$/L	6/18/2008	1.1	2.9	7.5
Desalinated water	0	4 mg of Cl$_2$/L	6/18/2008	<0.2	<0.5	<0.2
Desalinated water	0.5	4 mg of Cl$_2$/L	6/18/2008	<0.2	<0.5	1.1
Desalinated water	8	4 mg of Cl$_2$/L	6/18/2008	<0.2	<0.5	2.8
Desalinated water	16	4 mg of Cl$_2$/L	6/18/2008	0.2	<0.5	4.3
Desalinated water	24	4 mg of Cl$_2$/L	6/18/2008	0.7	<0.5	3.2
Desalinated water	48	4 mg of Cl$_2$/L	6/18/2008	0.6	<0.5	3.0
Desalinated water	72	4 mg of Cl$_2$/L	6/18/2008	0.3	<0.5	2.0

Table A5.2. Blending Experiment Results: HAAs [Figures 5.13–5.14]

Sample	Time (h)	Concn and Disinfectant	Experiment Date	Concn (µg/L) MCAA	DCAA	MBAA
Blend of chloraminated tap water with chloraminated desalinated water						
EBMUD	0	2.5 mg/L NH₂Cl	6/24/2008	2.5	3.0	0.6
EBMUD	0.5	2.5 mg/L NH₂Cl	6/24/2008	2.5	3.0	0.6
EBMUD	8	2.5 mg/L NH₂Cl	6/24/2008	2.2	2.7	0.6
EBMUD	16	2.5 mg/L NH₂Cl	6/24/2008	2.4	2.9	0.6
EBMUD	24	2.5 mg/L NH₂Cl	6/24/2008	1.9	3.2	1.0
EBMUD	48	2.5 mg/L NH₂Cl	6/24/2008	3.0	3.7	0.8
EBMUD	72	2.5 mg/L NH₂Cl	6/24/2008	2.4	4.7	0.9
Blend	0	2.5 mg/L NH₂Cl	6/24/2008	0.8	0.7	<0.2
Blend	0.5	2.5 mg/L NH₂Cl	6/24/2008	0.8	0.7	<0.2
Blend	8	2.5 mg/L NH₂Cl	6/24/2008	0.7	0.9	<0.2
Blend	16	2.5 mg/L NH₂Cl	6/24/2008	0.8	1.4	0.7
Blend	24	2.5 mg/L NH₂Cl	6/24/2008	0.3	1.4	1.0
Blend	48	2.5 mg/L NH₂Cl	6/24/2008	0.4	1.5	1.2
Blend	72	2.5 mg/L NH₂Cl	6/24/2008	0.2	1.6	1.2
Desalinated water	0	2.5 mg/L NH₂Cl	6/24/2008	<0.2	<0.5	<0.2
Desalinated water	0.5	2.5 mg/L NH₂Cl	6/24/2008	<0.2	<0.5	<0.2
Desalinated water	8	2.5 mg/L NH₂Cl	6/24/2008	<0.2	<0.5	<0.2
Desalinated water	16	2.5 mg/L NH₂Cl	6/24/2008	<0.2	<0.5	0.7
Desalinated water	24	2.5 mg/L NH₂Cl	6/24/2008	<0.2	<0.5	1.2
Desalinated water	48	2.5 mg/L NH₂Cl	6/24/2008	<0.2	<0.5	1.7
Desalinated water	72	2.5 mg/L NH₂Cl	6/24/2008	<0.2	<0.5	1.4

Table A5.2. Blending Experiment Results: HAAs [Appendix B, Figure B3]

Sample	Time (h)	Concn and Disinfectant	Experiment Date	Concn (µg/L)		
				MCAA	DCAA	MBAA
Blend of chloraminated tap water with chlorinated desalinated water						
EBMUD	0	2.5 mg/L NH$_2$Cl	6/11/2008	2.6	3.0	<0.2
EBMUD	0.5	2.5 mg/L NH$_2$Cl	6/11/2008	2.6	3.0	0.8
EBMUD	8	2.5 mg/L NH$_2$Cl	6/11/2008	2.6	3.1	0.6
EBMUD	16	2.5 mg/L NH$_2$Cl	6/11/2008	2.7	3.2	0.8
EBMUD	24	2.5 mg/L NH$_2$Cl	6/11/2008	3.1	3.6	0.9
EBMUD	48	2.5 mg/L NH$_2$Cl	6/11/2008	3.7	4.7	1.2
EBMUD	72	2.5 mg/L NH$_2$Cl	6/11/2008	3.1	4.5	0.9
Blend	0	Mix NH$_2$Cl/Cl$_2$	6/11/2008	<0.2	<0.5	<0.2
Blend	0.5	Mix NH$_2$Cl/Cl$_2$	6/11/2008	0.3	1.8	<0.2
Blend	8	Mix NH$_2$Cl/Cl$_2$	6/11/2008	1.1	1.3	1.4
Blend	16	Mix NH$_2$Cl/Cl$_2$	6/11/2008	1.3	2.1	1.3
Blend	24	Mix NH$_2$Cl/Cl$_2$	6/11/2008	2.0	2.3	1.3
Blend	48	Mix NH$_2$Cl/Cl$_2$	6/11/2008	2.0	2.5	<0.2
Blend	72	Mix NH$_2$Cl/Cl$_2$	6/11/2008	2.0	3.1	0.4
Desalinated water	0	2.5 mg/L NH$_2$Cl	6/11/2008	<0.2	<0.5	<0.2
Desalinated water	0.5	2.5 mg/L NH$_2$Cl	6/11/2008	<0.2	<0.5	<0.2
Desalinated water	8	2.5 mg/L NH$_2$Cl	6/11/2008	<0.2	<0.5	1.4
Desalinated water	16	2.5 mg/L NH$_2$Cl	6/11/2008	<0.2	<0.5	2.6
Desalinated water	24	2.5 mg/L NH$_2$Cl	6/11/2008	<0.2	<0.5	2.2
Desalinated water	48	2.5 mg/L NH$_2$Cl	6/11/2008	<0.2	<0.5	1.5
Desalinated water	72	2.5 mg/L NH$_2$Cl	6/11/2008	<0.2	<0.5	1.7

Table A5.2. Blending Experiment Results: HAAs [Figures 5.9–5.12]

Sample	Time (h)	Concn and Disinfectant	Experiment Date	Concn (µg/L)		
				TCAA	BCAA	BDCAA
Blend of chlorinated raw Colorado River water with chlorinated desalinated water						
Colorado River	0	4 mg of Cl$_2$/L	3/20/2008	<0.5	<0.2	<0.7
Colorado River	0.5	4 mg of Cl$_2$/L	3/20/2008	4.5	4.1	0.8
Colorado River	12	4 mg of Cl$_2$/L	3/20/2008	10	9.5	5.0
Colorado River	24	4 mg of Cl$_2$/L	3/20/2008	17	19	11
Colorado River	48	4 mg of Cl$_2$/L	3/20/2008	20	18	15
Colorado River	72	4 mg of Cl$_2$/L	3/20/2008	22	16	20
Blend	0	4 mg of Cl$_2$/L	3/20/2008	<0.5	<0.2	<0.7
Blend	0.5	4 mg of Cl$_2$/L	3/20/2008	5.3	1.6	1.8
Blend	12	4 mg of Cl$_2$/L	3/20/2008	8.5	2.5	3.2
Blend	24	4 mg of Cl$_2$/L	3/20/2008	13	3.3	4.0
Blend	48	4 mg of Cl$_2$/L	3/20/2008	16	3.5	4.2
Blend	72	4 mg of Cl$_2$/L	3/20/2008	19	3.7	4.4
Desalinated water	0	4 mg of Cl$_2$/L	3/20/2008	<0.5	<0.2	<0.7
Desalinated water	0.5	4 mg of Cl$_2$/L	3/20/2008	<0.5	0.5	<0.7
Desalinated water	12	4 mg of Cl$_2$/L	3/20/2008	<0.5	0.7	1.7
Desalinated water	24	4 mg of Cl$_2$/L	3/20/2008	<0.5	1.7	3.7
Desalinated water	48	4 mg of Cl$_2$/L	3/20/2008	<0.5	1.5	4.2
Desalinated water	72	4 mg of Cl$_2$/L	3/20/2008	<0.5	1.3	4.6
Blend of chlorinated raw San Pablo Reservoir water with chlorinated desalinated water						
San Pablo	0	4 mg of Cl$_2$/L	6/18/2008	<0.5	<0.2	<0.7
San Pablo	0.5	4 mg of Cl$_2$/L	6/18/2008	<0.5	3.4	3.3
San Pablo	8	4 mg of Cl$_2$/L	6/18/2008	8.0	12	5.1
San Pablo	16	4 mg of Cl$_2$/L	6/18/2008	8.9	17	12
San Pablo	24	4 mg of Cl$_2$/L	6/18/2008	12	20	14
San Pablo	48	4 mg of Cl$_2$/L	6/18/2008	14	21	15
San Pablo	72	4 mg of Cl$_2$/L	6/18/2008	15	20	17
Blend	0	4 mg of Cl$_2$/L	6/18/2008	<0.5	<0.2	<0.7
Blend	0.5	4 mg of Cl$_2$/L	6/18/2008	0.6	1.0	1.7
Blend	8	4 mg of Cl$_2$/L	6/18/2008	6.4	1.9	3.7
Blend	16	4 mg of Cl$_2$/L	6/18/2008	7.2	2.5	5.1
Blend	24	4 mg of Cl$_2$/L	6/18/2008	10	2.7	7.3
Blend	48	4 mg of Cl$_2$/L	6/18/2008	19	3.5	13
Blend	72	4 mg of Cl$_2$/L	6/18/2008	21	3.6	15
Desalinated water	0	4 mg of Cl$_2$/L	6/18/2008	<0.5	<0.2	<0.7
Desalinated water	0.5	4 mg of Cl$_2$/L	6/18/2008	<0.5	<0.2	<0.7
Desalinated water	8	4 mg of Cl$_2$/L	6/18/2008	<0.5	<0.2	1.6
Desalinated water	16	4 mg of Cl$_2$/L	6/18/2008	<0.5	1.2	2.6
Desalinated water	24	4 mg of Cl$_2$/L	6/18/2008	0.6	2.5	6.2
Desalinated water	48	4 mg of Cl$_2$/L	6/18/2008	<0.5	2.3	5.0
Desalinated water	72	4 mg of Cl$_2$/L	6/18/2008	<0.5	1.6	5.7

Table A5.2. Blending Experiment Results: HAAs [Figures 5.13–5.14]

Sample	Time (h)	Concn and Disinfectant	Experiment Date	Concn (µg/L)		
				TCAA	BCAA	BDCAA
Blend of chloraminated tap water with chloraminated desalinated water						
EBMUD	0	2.5 mg/L NH$_2$Cl	6/24/2008	<0.5	2.7	<0.7
EBMUD	0.5	2.5 mg/L NH$_2$Cl	6/24/2008	<0.5	2.7	<0.7
EBMUD	8	2.5 mg/L NH$_2$Cl	6/24/2008	<0.5	2.9	<0.7
EBMUD	16	2.5 mg/L NH$_2$Cl	6/24/2008	<0.5	2.7	<0.7
EBMUD	24	2.5 mg/L NH$_2$Cl	6/24/2008	<0.5	3.8	<0.7
EBMUD	48	2.5 mg/L NH$_2$Cl	6/24/2008	<0.5	3.8	<0.7
EBMUD	72	2.5 mg/L NH$_2$Cl	6/24/2008	<0.5	3.3	<0.7
Blend	0	2.5 mg/L NH$_2$Cl	6/24/2008	<0.5	1.2	<0.7
Blend	0.5	2.5 mg/L NH$_2$Cl	6/24/2008	<0.5	1.2	<0.7
Blend	8	2.5 mg/L NH$_2$Cl	6/24/2008	<0.5	1.5	<0.7
Blend	16	2.5 mg/L NH$_2$Cl	6/24/2008	<0.5	1.6	0.7
Blend	24	2.5 mg/L NH$_2$Cl	6/24/2008	<0.5	1.6	0.8
Blend	48	2.5 mg/L NH$_2$Cl	6/24/2008	<0.5	1.5	0.8
Blend	72	2.5 mg/L NH$_2$Cl	6/24/2008	<0.5	1.5	<0.7
Desalinated water	0	2.5 mg/L NH$_2$Cl	6/24/2008	<0.5	<0.2	<0.7
Desalinated water	0.5	2.5 mg/L NH$_2$Cl	6/24/2008	<0.5	<0.2	<0.7
Desalinated water	8	2.5 mg/L NH$_2$Cl	6/24/2008	<0.5	<0.2	<0.7
Desalinated water	16	2.5 mg/L NH$_2$Cl	6/24/2008	<0.5	<0.2	0.9
Desalinated water	24	2.5 mg/L NH$_2$Cl	6/24/2008	<0.5	<0.2	1.4
Desalinated water	48	2.5 mg/L NH$_2$Cl	6/24/2008	<0.5	<0.2	1.3
Desalinated water	72	2.5 mg/L NH$_2$Cl	6/24/2008	<0.5	<0.2	1.2

Table A5.2. Blending Experiment Results: HAAs [Appendix B, Figure B3]

Sample	Time (h)	Concn and Disinfectant	Experiment Date	Concn (µg/L)		
				TCAA	BCAA	BDCAA
Blend of chloraminated tap water with chlorinated desalinated water						
EBMUD	0	2.5 mg/L NH$_2$Cl	6/11/2008	<0.5	3.0	<0.7
EBMUD	0.5	2.5 mg/L NH$_2$Cl	6/11/2008	<0.5	3.1	<0.7
EBMUD	8	2.5 mg/L NH$_2$Cl	6/11/2008	<0.5	4.0	<0.7
EBMUD	16	2.5 mg/L NH$_2$Cl	6/11/2008	<0.5	3.9	<0.7
EBMUD	24	2.5 mg/L NH$_2$Cl	6/11/2008	<0.5	4.8	<0.7
EBMUD	48	2.5 mg/L NH$_2$Cl	6/11/2008	<0.5	4.8	<0.7
EBMUD	72	2.5 mg/L NH$_2$Cl	6/11/2008	<0.5	4.7	<0.7
Blend	0	Mix NH$_2$Cl/Cl$_2$	6/11/2008	<0.5	<0.2	<0.7
Blend	0.5	Mix NH$_2$Cl/Cl$_2$	6/11/2008	<0.5	1.4	<0.7
Blend	8	Mix NH$_2$Cl/Cl$_2$	6/11/2008	<0.5	2.0	<0.7
Blend	16	Mix NH$_2$Cl/Cl$_2$	6/11/2008	<0.5	2.3	<0.7
Blend	24	Mix NH$_2$Cl/Cl$_2$	6/11/2008	<0.5	3.1	<0.7
Blend	48	Mix NH$_2$Cl/Cl$_2$	6/11/2008	0.6	3.2	<0.7
Blend	72	Mix NH$_2$Cl/Cl$_2$	6/11/2008	0.5	2.4	0.9
Desalinated water	0	2.5 mg/L NH$_2$Cl	6/11/2008	<0.5	<0.2	<0.7
Desalinated water	0.5	2.5 mg/L NH$_2$Cl	6/11/2008	<0.5	<0.2	<0.7
Desalinated water	8	2.5 mg/L NH$_2$Cl	6/11/2008	1.4	<0.2	1.5
Desalinated water	16	2.5 mg/L NH$_2$Cl	6/11/2008	2.1	1.2	2.9
Desalinated water	24	2.5 mg/L NH$_2$Cl	6/11/2008	1.7	1.6	2.6
Desalinated water	48	2.5 mg/L NH$_2$Cl	6/11/2008	2.1	2.2	3.0
Desalinated water	72	2.5 mg/L NH$_2$Cl	6/11/2008	2.5	1.9	2.7

Table A5.2. Blending Experiment Results: HAAs [Figures 5.9–5.12]

Sample	Time (h)	Disinfectant	Experiment Date	Concn (µg/L) DBAA	DBCAA	TBAA
Blend of chlorinated raw Colorado River water with chlorinated desalinated water						
Colorado River	0	4 mg of Cl$_2$/L	3/20/2008	<0.7	<0.2	<0.4
Colorado River	0.5	4 mg of Cl$_2$/L	3/20/2008	<0.7	<0.2	1.0
Colorado River	12	4 mg of Cl$_2$/L	3/20/2008	4.1	5.6	2.7
Colorado River	24	4 mg of Cl$_2$/L	3/20/2008	21	11	8.9
Colorado River	48	4 mg of Cl$_2$/L	3/20/2008	24	24	8.1
Colorado River	72	4 mg of Cl$_2$/L	3/20/2008	24	30	7.4
Blend	0	4 mg of Cl$_2$/L	3/20/2008	<0.7	<0.2	<0.4
Blend	0.5	4 mg of Cl$_2$/L	3/20/2008	2.1	<0.2	4.3
Blend	12	4 mg of Cl$_2$/L	3/20/2008	4.0	<0.2	8.9
Blend	24	4 mg of Cl$_2$/L	3/20/2008	8.5	1.2	15
Blend	48	4 mg of Cl$_2$/L	3/20/2008	9.8	2.5	14
Blend	72	4 mg of Cl$_2$/L	3/20/2008	11	3.8	14
Desalinated water	0	4 mg of Cl$_2$/L	3/20/2008	<0.7	<0.2	<0.4
Desalinated water	0.5	4 mg of Cl$_2$/L	3/20/2008	<0.7	<0.2	<0.4
Desalinated water	12	4 mg of Cl$_2$/L	3/20/2008	<0.7	<0.2	<0.4
Desalinated water	24	4 mg of Cl$_2$/L	3/20/2008	<0.7	<0.2	0.5
Desalinated water	48	4 mg of Cl$_2$/L	3/20/2008	<0.7	0.2	0.6
Desalinated water	72	4 mg of Cl$_2$/L	3/20/2008	<0.7	0.3	0.7
Blend of chlorinated raw San Pablo Reservoir water with chlorinated desalinated water						
San Pablo	0	4 mg of Cl$_2$/L	6/18/2008	<0.7	<0.2	<0.4
San Pablo	0.5	4 mg of Cl$_2$/L	6/18/2008	<0.7	1.3	<0.4
San Pablo	8	4 mg of Cl$_2$/L	6/18/2008	<0.7	0.7	0.5
San Pablo	16	4 mg of Cl$_2$/L	6/18/2008	1.3	0.8	0.8
San Pablo	24	4 mg of Cl$_2$/L	6/18/2008	1.7	1.1	1.0
San Pablo	48	4 mg of Cl$_2$/L	6/18/2008	1.8	1.7	1.0
San Pablo	72	4 mg of Cl$_2$/L	6/18/2008	1.8	1.7	1.0
Blend	0	4 mg of Cl$_2$/L	6/18/2008	<0.7	<0.2	<0.4
Blend	0.5	4 mg of Cl$_2$/L	6/18/2008	0.9	0.6	1.4
Blend	8	4 mg of Cl$_2$/L	6/18/2008	1.6	1.1	2.2
Blend	16	4 mg of Cl2/L	6/18/2008	3.7	1.4	3.5
Blend	24	4 mg of Cl$_2$/L	6/18/2008	4.9	2.6	4.3
Blend	48	4 mg of Cl$_2$/L	6/18/2008	6.2	3.4	5.0
Blend	72	4 mg of Cl$_2$/L	6/18/2008	6.7	3.3	5.6
Desalinated water	0	4 mg of Cl$_2$/L	6/18/2008	<0.7	<0.2	<0.4
Desalinated water	0.5	4 mg of Cl$_2$/L	6/18/2008	<0.7	<0.2	<0.4
Desalinated water	8	4 mg of Cl$_2$/L	6/18/2008	<0.7	<0.2	<0.4
Desalinated water	16	4 mg of Cl$_2$/L	6/18/2008	<0.7	<0.2	<0.4
Desalinated water	24	4 mg of Cl$_2$/L	6/18/2008	<0.7	<0.2	0.5
Desalinated water	48	4 mg of Cl$_2$/L	6/18/2008	<0.7	<0.2	0.5
Desalinated water	72	4 mg of Cl$_2$/L	6/18/2008	0.8	0.3	0.9

Table A5.2. Blending Experiment Results: HAAs [Figures 5.13–5.14]

Sample	Time (h)	Concn and Disinfectant	Experiment Date	Concn (μg/L)		
				DBAA	DBCAA	TBAA
Blend of chloraminated tap water with chloraminated desalinated water						
EBMUD	0	2.5 mg/L NH$_2$Cl	6/24/2008	<0.7	<0.2	<0.4
EBMUD	0.5	2.5 mg/L NH$_2$Cl	6/24/2008	<0.7	<0.2	<0.4
EBMUD	8	2.5 mg/L NH$_2$Cl	6/24/2008	<0.7	<0.2	<0.4
EBMUD	16	2.5 mg/L NH$_2$Cl	6/24/2008	<0.7	<0.2	<0.4
EBMUD	24	2.5 mg/L NH$_2$Cl	6/24/2008	<0.7	<0.2	<0.4
EBMUD	48	2.5 mg/L NH$_2$Cl	6/24/2008	<0.7	<0.2	<0.4
EBMUD	72	2.5 mg/L NH$_2$Cl	6/24/2008	<0.7	<0.2	<0.4
Blend	0	2.5 mg/L NH$_2$Cl	6/24/2008	<0.7	<0.2	<0.4
Blend	0.5	2.5 mg/L NH$_2$Cl	6/24/2008	<0.7	<0.2	<0.4
Blend	8	2.5 mg/L NH$_2$Cl	6/24/2008	<0.7	<0.2	<0.4
Blend	16	2.5 mg/L NH$_2$Cl	6/24/2008	<0.7	<0.2	<0.4
Blend	24	2.5 mg/L NH$_2$Cl	6/24/2008	<0.7	<0.2	0.4
Blend	48	2.5 mg/L NH$_2$Cl	6/24/2008	<0.7	<0.2	0.4
Blend	72	2.5 mg/L NH$_2$Cl	6/24/2008	<0.7	<0.2	0.3
Desalinated water	0	2.5 mg/L NH$_2$Cl	6/24/2008	<0.7	<0.2	<0.4
Desalinated water	0.5	2.5 mg/L NH$_2$Cl	6/24/2008	<0.7	<0.2	<0.4
Desalinated water	8	2.5 mg/L NH$_2$Cl	6/24/2008	<0.7	<0.2	<0.4
Desalinated water	16	2.5 mg/L NH$_2$Cl	6/24/2008	<0.7	<0.2	<0.4
Desalinated water	24	2.5 mg/L NH$_2$Cl	6/24/2008	<0.7	<0.2	0.4
Desalinated water	48	2.5 mg/L NH$_2$Cl	6/24/2008	<0.7	0.2	0.4
Desalinated water	72	2.5 mg/L NH$_2$Cl	6/24/2008	<0.7	0.3	0.7

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Table A5.2. Blending Experiment Results: HAAs [Appendix B, Figure B3]

Sample	Time (h)	Concn and Disinfectant	Experiment Date	Concn (μg/L)		
				DBAA	DBCAA	TBAA
Blend of chloraminated tap water with chlorinated desalinated water						
EBMUD	0	2.5 mg/L NH$_2$Cl	6/11/2008	<0.7	<0.2	<0.4
EBMUD	0.5	2.5 mg/L NH$_2$Cl	6/11/2008	<0.7	<0.2	<0.4
EBMUD	8	2.5 mg/L NH$_2$Cl	6/11/2008	<0.7	<0.2	<0.4
EBMUD	16	2.5 mg/L NH$_2$Cl	6/11/2008	<0.7	<0.2	<0.4
EBMUD	24	2.5 mg/L NH$_2$Cl	6/11/2008	<0.7	<0.2	<0.4
EBMUD	48	2.5 mg/L NH$_2$Cl	6/11/2008	<0.7	<0.2	<0.4
EBMUD	72	2.5 mg/L NH$_2$Cl	6/11/2008	<0.7	<0.2	<0.4
Blend	0	Mix NH$_2$Cl/Cl$_2$	6/11/2008	<0.7	<0.2	<0.4
Blend	0.5	Mix NH$_2$Cl/Cl$_2$	6/11/2008	<0.7	<0.2	<0.4
Blend	8	Mix NH$_2$Cl/Cl$_2$	6/11/2008	<0.7	<0.2	<0.4
Blend	16	Mix NH$_2$Cl/Cl$_2$	6/11/2008	<0.7	<0.2	<0.4
Blend	24	Mix NH$_2$Cl/Cl$_2$	6/11/2008	<0.7	<0.2	<0.4
Blend	48	Mix NH$_2$Cl/Cl$_2$	6/11/2008	<0.7	<0.2	<0.4
Blend	72	Mix NH$_2$Cl/Cl$_2$	6/11/2008	<0.7	<0.2	<0.4
Desalinated water	0	2.5 mg/L NH$_2$Cl	6/11/2008	<0.7	<0.2	<0.4
Desalinated water	0.5	2.5 mg/L NH$_2$Cl	6/11/2008	<0.7	<0.2	<0.4
Desalinated water	8	2.5 mg/L NH$_2$Cl	6/11/2008	<0.7	<0.2	<0.4
Desalinated water	16	2.5 mg/L NH$_2$Cl	6/11/2008	<0.7	<0.2	<0.4
Desalinated water	24	2.5 mg/L NH$_2$Cl	6/11/2008	<0.7	<0.2	0.5
Desalinated water	48	2.5 mg/L NH$_2$Cl	6/11/2008	0.8	0.2	0.6
Desalinated water	72	2.5 mg/L NH$_2$Cl	6/11/2008	0.8	0.3	0.6

Table A5.3. Blending Experiment Results: HANs [Figures 5.15–5.18]

Sample	Time (h)	Concn and Disinfectant	Experiment Date	Concn (µg/L) CHCl$_2$CN	CHBrClCN	CHBr$_2$CN
Blend of chlorinated raw Colorado River water with chlorinated desalinated water						
Colorado River	0	4 mg of Cl$_2$/L	3/20/2008	<0.2	<0.2	<0.5
Colorado River	0.5	4 mg of Cl$_2$/L	3/20/2008	1.3	2.0	<0.5
Colorado River	12	4 mg of Cl$_2$/L	3/20/2008	3.3	4.7	1.0
Colorado River	24	4 mg of Cl$_2$/L	3/20/2008	7.6	5.6	1.0
Colorado River	48	4 mg of Cl$_2$/L	3/20/2008	7.6	5.3	1.3
Colorado River	72	4 mg of Cl$_2$/L	3/20/2008	7.5	5.1	1.5
Blend	0	4 mg of Cl$_2$/L	3/20/2008	<0.2	<0.2	<0.5
Blend	0.5	4 mg of Cl$_2$/L	3/20/2008	0.4	2.9	<0.5
Blend	12	4 mg of Cl$_2$/L	3/20/2008	2.9	6.9	0.7
Blend	24	4 mg of Cl$_2$/L	3/20/2008	3.3	6.7	2.1
Blend	48	4 mg of Cl$_2$/L	3/20/2008	3.0	6.2	2.5
Blend	72	4 mg of Cl$_2$/L	3/20/2008	2.6	5.8	2.3
Desalinated water	0	4 mg of Cl$_2$/L	3/20/2008	<0.2	<0.2	<0.5
Desalinated water	0.5	4 mg of Cl$_2$/L	3/20/2008	<0.2	<0.2	<0.5
Desalinated water	12	4 mg of Cl$_2$/L	3/20/2008	0.3	0.4	<0.5
Desalinated water	24	4 mg of Cl$_2$/L	3/20/2008	0.6	0.4	<0.5
Desalinated water	48	4 mg of Cl$_2$/L	3/20/2008	0.4	0.3	<0.5
Desalinated water	72	4 mg of Cl$_2$/L	3/20/2008	0.2	0.3	<0.5
Blend of chlorinated raw San Pablo Reservoir water with chlorinated desalinated water						
San Pablo	0	4 mg of Cl$_2$/L	6/18/2008	<0.2	<0.2	<0.5
San Pablo	0.5	4 mg of Cl$_2$/L	6/18/2008	1.5	0.2	0.9
San Pablo	8	4 mg of Cl$_2$/L	6/18/2008	1.8	1.2	1.7
San Pablo	16	4 mg of Cl$_2$/L	6/18/2008	3.9	1.8	2.2
San Pablo	24	4 mg of Cl$_2$/L	6/18/2008	5.6	2.8	2.3
San Pablo	48	4 mg of Cl$_2$/L	6/18/2008	5.4	2.4	2.4
San Pablo	72	4 mg of Cl$_2$/L	6/18/2008	5.0	2.1	2.1
Blend	0	4 mg of Cl$_2$/L	6/18/2008	<0.2	<0.2	<0.5
Blend	0.5	4 mg of Cl$_2$/L	6/18/2008	0.8	1.4	0.5
Blend	8	4 mg of Cl$_2$/L	6/18/2008	0.9	3.5	0.8
Blend	16	4 mg of Cl$_2$/L	6/18/2008	1.7	4.7	1.9
Blend	24	4 mg of Cl$_2$/L	6/18/2008	1.6	5.4	1.7
Blend	48	4 mg of Cl$_2$/L	6/18/2008	1.6	4.4	1.9
Blend	72	4 mg of Cl$_2$/L	6/18/2008	1.4	3.7	1.7
Desalinated water	0	4 mg of Cl$_2$/L	6/18/2008	<0.2	<0.2	<0.5
Desalinated water	0.5	4 mg of Cl$_2$/L	6/18/2008	<0.2	<0.2	<0.5
Desalinated water	8	4 mg of Cl$_2$/L	6/18/2008	<0.2	<0.2	<0.5
Desalinated water	16	4 mg of Cl$_2$/L	6/18/2008	<0.2	0.4	0.5
Desalinated water	24	4 mg of Cl$_2$/L	6/18/2008	<0.2	0.6	0.9
Desalinated water	48	4 mg of Cl$_2$/L	6/18/2008	<0.2	0.7	1.0

| Desalinated water | 72 | 4 mg of Cl$_2$/L | 6/18/2008 | <0.2 | 0.6 | 1.0 |

Table A5.3. Blending Experiment Results: HANs [Figures 5.19–5.20]

Sample	Time (h)	Concn and Disinfectant	Experiment Date	Concn (µg/L)		
				CHCl$_2$CN	CHBrClCN	CHBr$_2$CN
Blend of chloraminated tap water with chloraminated desalinated water						
EBMUD	0	2.5 mg/L NH$_2$Cl	6/24/2008	<0.2	<0.2	<0.5
EBMUD	0.5	2.5 mg/L NH$_2$Cl	6/24/2008	0.7	0.5	<0.5
EBMUD	8	2.5 mg/L NH$_2$Cl	6/24/2008	0.9	0.4	<0.5
EBMUD	16	2.5 mg/L NH$_2$Cl	6/24/2008	0.8	<0.2	<0.5
EBMUD	24	2.5 mg/L NH$_2$Cl	6/24/2008	1.0	<0.2	0.7
EBMUD	48	2.5 mg/L NH$_2$Cl	6/24/2008	0.8	0.5	0.7
EBMUD	72	2.5 mg/L NH$_2$Cl	6/24/2008	0.8	0.8	0.8
Blend	0	2.5 mg/L NH$_2$Cl	6/24/2008	<0.2	<0.2	<0.5
Blend	0.5	2.5 mg/L NH$_2$Cl	6/24/2008	<0.2	<0.2	<0.5
Blend	8	2.5 mg/L NH$_2$Cl	6/24/2008	0.5	<0.2	<0.5
Blend	16	2.5 mg/L NH$_2$Cl	6/24/2008	<0.2	0.5	<0.5
Blend	24	2.5 mg/L NH$_2$Cl	6/24/2008	0.6	0.4	<0.5
Blend	48	2.5 mg/L NH$_2$Cl	6/24/2008	0.9	0.6	0.5
Blend	72	2.5 mg/L NH$_2$Cl	6/24/2008	0.8	0.6	0.5
Desalinated water	0	2.5 mg/L NH$_2$Cl	6/24/2008	<0.2	<0.2	<0.5
Desalinated water	0.5	2.5 mg/L NH$_2$Cl	6/24/2008	<0.2	<0.2	<0.5
Desalinated water	8	2.5 mg/L NH$_2$Cl	6/24/2008	<0.2	<0.2	0.8
Desalinated water	16	2.5 mg/L NH$_2$Cl	6/24/2008	<0.2	0.6	1.1
Desalinated water	24	2.5 mg/L NH$_2$Cl	6/24/2008	0.5	0.8	1.0
Desalinated water	48	2.5 mg/L NH$_2$Cl	6/24/2008	0.7	0.8	1.0
Desalinated water	72	2.5 mg/L NH$_2$Cl	6/24/2008	0.7	0.8	1.0

Table A5.3. Blending Experiment Results: HANs [Appendix B, Figure B4]

Sample	Time (h)	Concn and Disinfectant	Experiment Date	Concn (μg/L)		
				$CHCl_2CN$	$CHBrClCN$	$CHBr_2CN$
Blend of chloraminated tap water with chlorinated desalinated water						
EBMUD	0	2.5 mg/L NH_2Cl	6/11/2008	<0.2	<0.2	<0.5
EBMUD	0.5	2.5 mg/L NH_2Cl	6/11/2008	0.5	0.7	<0.5
EBMUD	8	2.5 mg/L NH_2Cl	6/11/2008	0.4	0.7	<0.5
EBMUD	16	2.5 mg/L NH_2Cl	6/11/2008	0.5	0.8	0.3
EBMUD	24	2.5 mg/L NH_2Cl	6/11/2008	0.4	0.7	0.3
EBMUD	48	2.5 mg/L NH_2Cl	6/11/2008	0.5	0.6	0.3
EBMUD	72	2.5 mg/L NH_2Cl	6/11/2008	0.4	0.7	0.3
Blend	0	Mix NH_2Cl/Cl_2	6/11/2008	<0.2	<0.2	<0.5
Blend	0.5	Mix NH_2Cl/Cl_2	6/11/2008	<0.2	0.4	0.6
Blend	8	Mix NH_2Cl/Cl_2	6/11/2008	<0.2	0.8	0.7
Blend	16	Mix NH_2Cl/Cl_2	6/11/2008	<0.2	0.9	1.2
Blend	24	Mix NH_2Cl/Cl_2	6/11/2008	<0.2	0.9	1.3
Blend	48	Mix NH_2Cl/Cl_2	6/11/2008	<0.2	0.9	1.4
Blend	72	Mix NH_2Cl/Cl_2	6/11/2008	<0.2	1.0	1.2
Desalinated water	0	2.5 mg/L NH_2Cl	6/11/2008	<0.2	<0.2	<0.5
Desalinated water	0.5	2.5 mg/L NH_2Cl	6/11/2008	0.3	0.3	<0.5
Desalinated water	8	2.5 mg/L NH_2Cl	6/11/2008	0.3	0.5	<0.5
Desalinated water	16	2.5 mg/L NH_2Cl	6/11/2008	0.3	0.6	<0.5
Desalinated water	24	2.5 mg/L NH_2Cl	6/11/2008	0.2	0.5	<0.5
Desalinated water	48	2.5 mg/L NH_2Cl	6/11/2008	0.2	0.6	<0.5
Desalinated water	72	2.5 mg/L NH_2Cl	6/11/2008	0.2	0.6	<0.5

APPENDIX B

MIXED DISINFECTANT BLENDING EXPERIMENT

Desalinated water was chlorinated at an initial chlorine concentration that produces a total combined residual concentration similar to that of freshly collected chloraminated tap water (2.5 mg of Cl_2/L). A rapid decrease of free chlorine and total combined residuals was observed, presumably due to breakpoint chlorination (Figure B1). Because of the low concentration of free chlorine residual throughout most of this experiment, chlorine disinfection byproduct formation was not observed (Figures B2 to B4). Concentrations of disinfection byproducts observed in this blending experiment were roughly equal to those predicted by volumetric averaging.
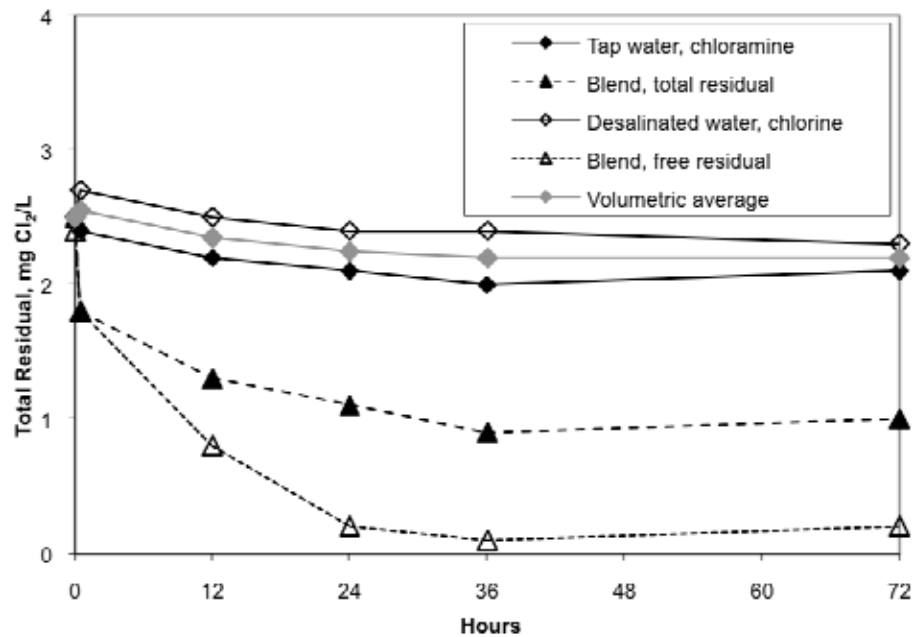
Figure B1. Chlorine residuals measured during blending of chlorinated RO permeate with chloraminated tap water (1:1 [v/v]). The volumetric average represents predictions made using data from the two unmixed sources.
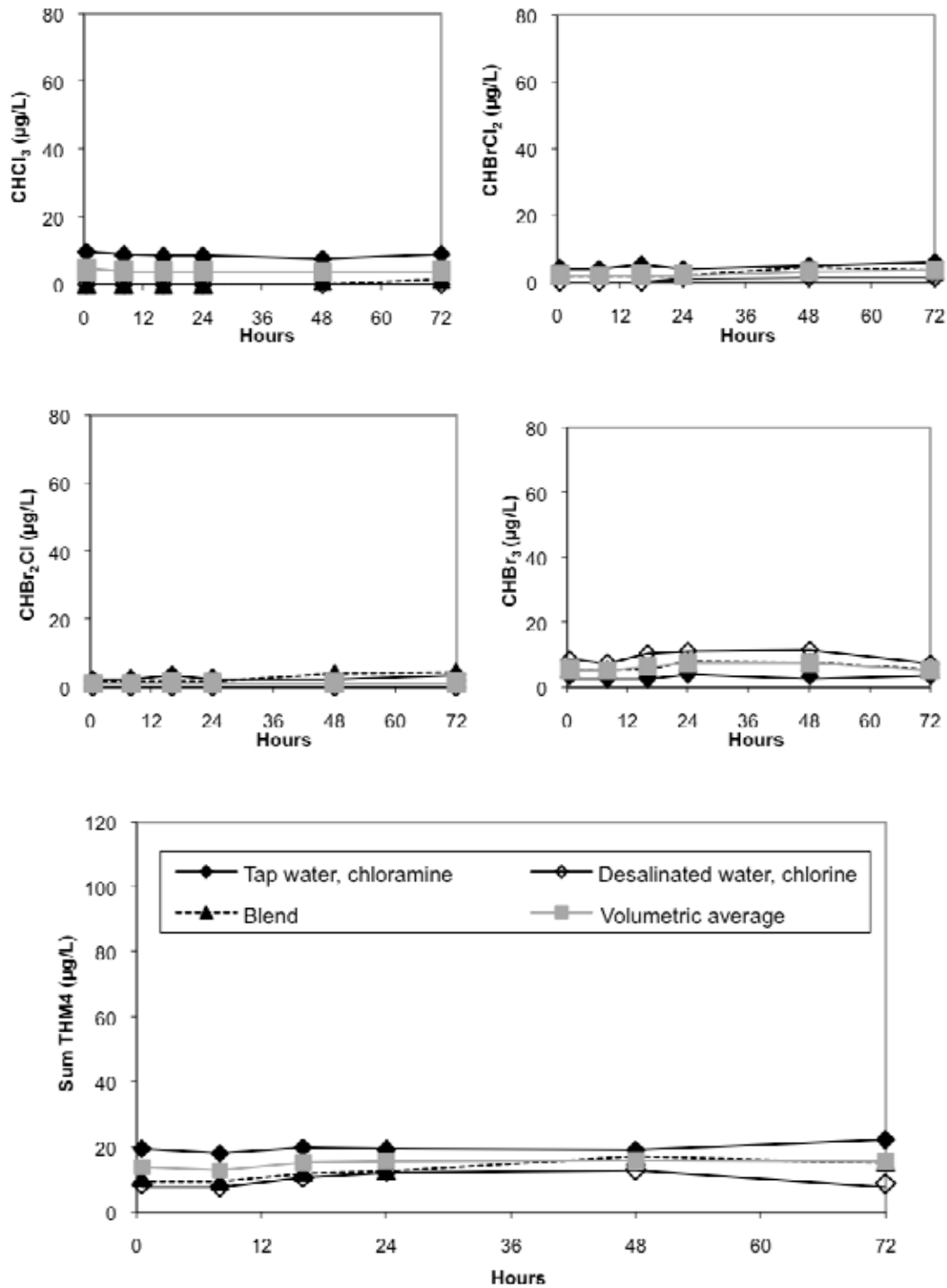
Figure B2. Sum of THMs, chloroform, bromodichloromethane, dibromochloromethane, and bromoform measured during blending of chlorinated desalinated water and chloraminated tap water (1:1 [v/v]).
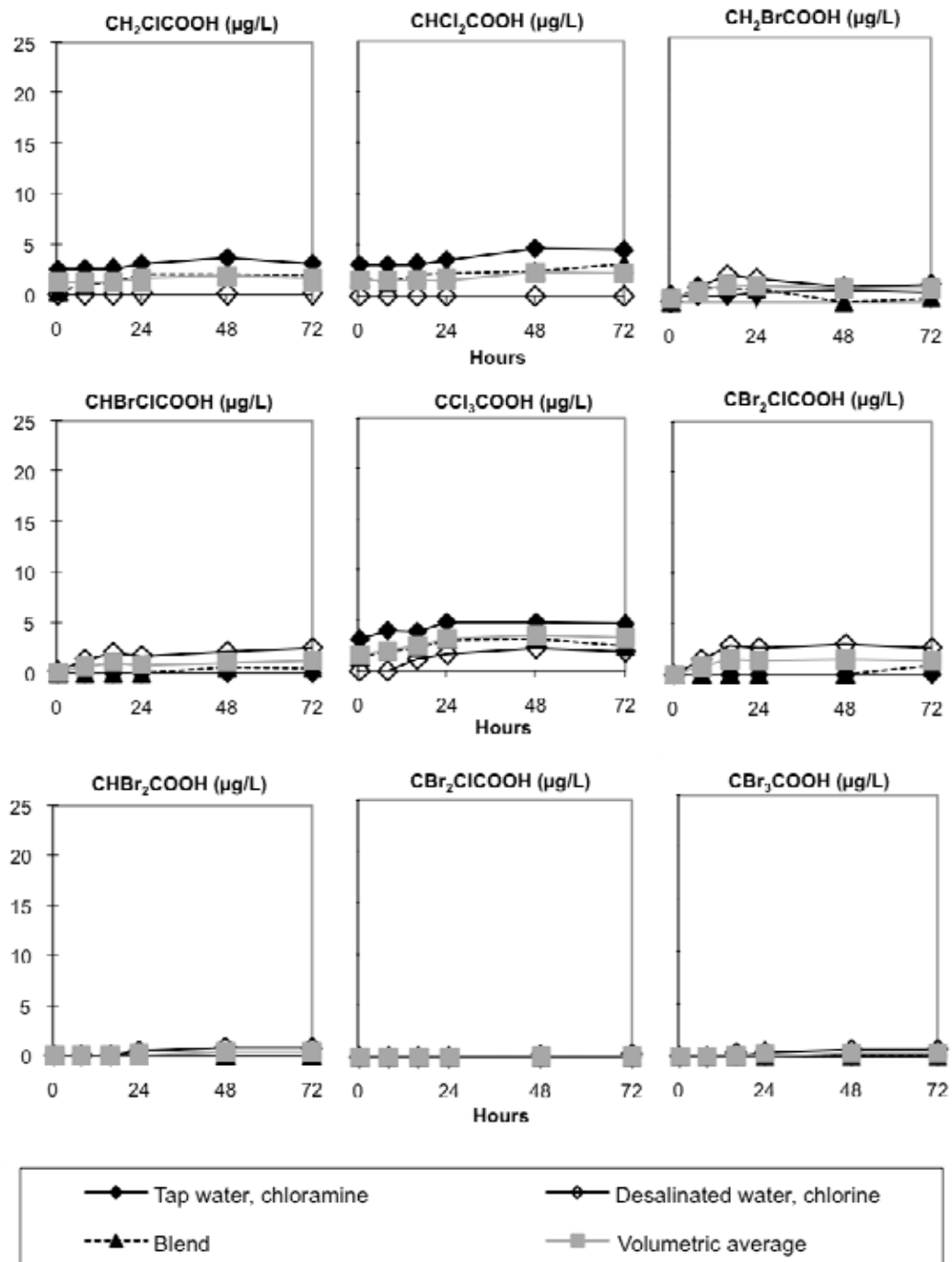
Figure B3a. Individual HAAs (HAA9) measured during blending of chlorinated desalinated water and chloraminated tap water (1:1 [v/v]).
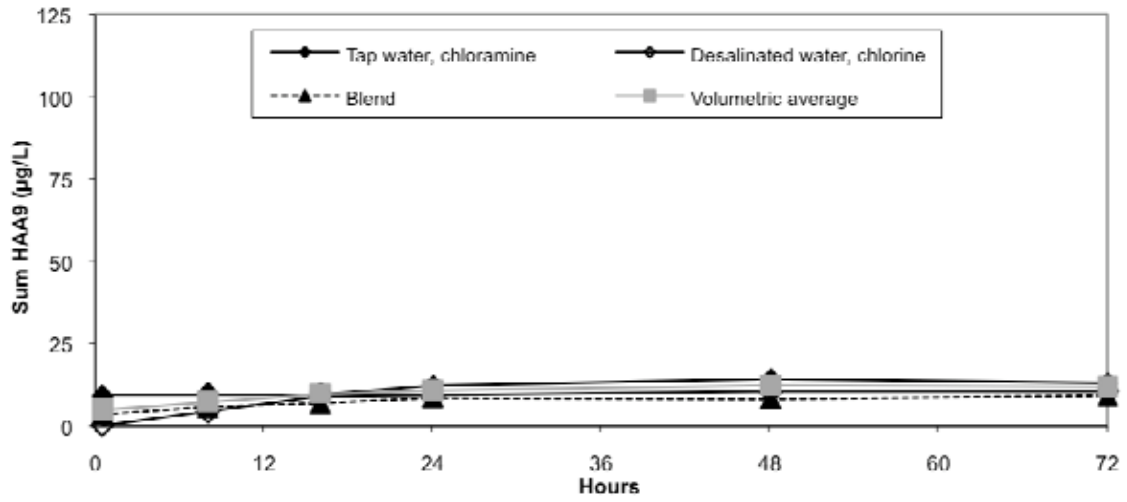
Figure B3b. Individual and sum of HAAs (HAA9) measured during blending of chlorinated desalinated water and chloraminated tap water (1:1 [v/v]).
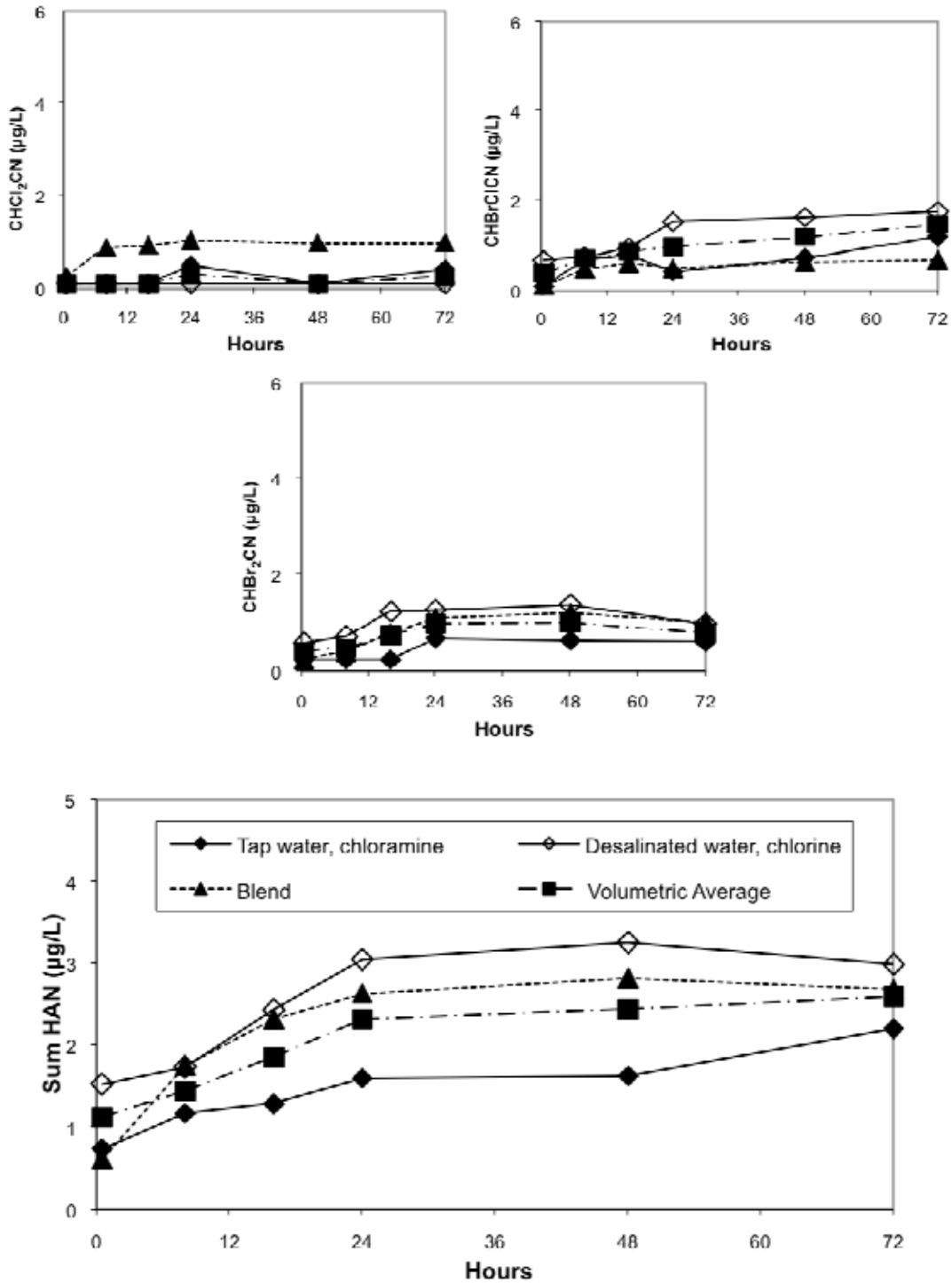
Figure B4. Sum of HANs, dichloroacetonitrile, bromochloroacetonitrile, and dibromoacetonitrile measured during blending of chlorinated desalinated water and chloraminated tap water (1:1 [v/v]).

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