TRIHALOMETHANE CONTROL BY AERATION

A Thesis in
Environmental Pollution Control
by
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ABSTRACT

Because of the potential public health risks from disinfection byproducts (DBPs) it is imperative that they are removed in drinking water. The purpose of this study is to demonstrate aeration as a method of the removal of DBPs from public drinking water. Trihalomethanes (THMs) are the most common DBPs and chloroform is the most dominant THM, especially in water low in bromide. DBPs are formed when disinfectants, such as chlorine, react with natural organic matter in water. Consecutive systems are experiencing high levels of THMs due to longer reaction times between chlorine and natural organic matter in their distribution systems.

To control trihalomethanes (THMs) in a consecutive system, Blacklick Valley Municipal Authority (BVMA), aeration was investigated through pilot testing, field testing, and mathematical modeling. Major conclusions from this study include:

- Laboratory studies indicating removals of THMs of up to 83% in six (6) hours of aeration in a 200-gallon (760 liter) tank in a batch mode. Water temperature and aeration time were also investigated to improve and optimize the efficiency of the aeration system.

- Field study with diffused aeration in a 70,000 gallon storage tank with a water flow of 70,000 gallons per day indicating THM removals of up to 50% over a 16 day aeration period.

- Mathematical modeling indicates that air flow, water volume, water flow and aeration time affect THM removal and can be optimized for better THM control.
The results of this study indicated that diffused aeration is an effective treatment technology for THM removal, especially in small and consecutive water systems. This study provides relevant information related to the design and operation of the aeration system.
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Chapter 1

Introduction and Study Approach

Because of the potential public health risks in drinking water from disinfection byproducts (DBPs) it is imperative that they are removed before ingested by the public. The purpose of this study is to demonstrate aeration as a DBP removal method. Trihalomethanes (THMs) are the most common DBPs and chloroform is the most dominant THM. DBPs are formed when disinfectants, such as chlorine, react with natural organic matter in water. Formation of DBPs depends primarily on the source water quality characteristics and on the location in the treatment process where disinfectants are added (Liang & Singer, 2003). The water quality characteristics that influence the formation of DBPs include: type and concentration of organic precursors, pH, temperature, and disinfectant. The disinfectant dose, point of addition, contact time, and residual concentration are integral to the formation of DBPs.

This project studied Blacklick Valley Municipal Authority (BVMA), located in western Pennsylvania. BVMA is a consecutive system that is experiencing high levels of THMs due to longer reaction times between chlorine and natural organic matter in its distribution system. BVMA obtains its water from the Nanty-Glo water treatment plant. Before the water from Nanty-Glo enters BVMA it flows through a storage tank. Once into BVMA, the water then flows through two more storage tanks before reaching the furthest point in its distribution system. Although the water quality from the Nanty-Glo water treatment plant is relatively low in THMs, the water that BVMA receives has been
experiencing levels of THMs above the United States Environmental Protection Agency’s (USEPA) maximum contamination limit (MCL) of 80 µg/L.

Parent systems, such as Nanty-Glo can effectively control THMs by utilizing technologies such as enhanced coagulation and alternative disinfectants. However, other than adding chlorine, most consecutive systems do not employ additional treatment processes.

Thus, the objective of this study is to evaluate aeration as a method to remove THMs from drinking water in storage tanks. To meet the study objective, the following study approach will be utilized:

- Complete a literature review of aeration;
- Characterize background water quality of Blacklick Valley Municipal Authority;
- Pilot lab testing of aeration for the removal of THMs and haloacetic acids (HAAs); and
- Test aeration for removal of THMs in a storage tank.
Chapter 2

Literature Review

2.1 DBP formation mechanisms

Disinfection Byproducts (DBPs) are formed when a disinfectant, such as chlorine, reacts with natural organic matter (NOM), (Singer, 1993):

\[ \text{HOCl} + \text{Br}^- + \text{NOM} \rightarrow \text{THMs and other halogenated DBPs} \]

NOM is the principal organic precursor with which halogens react to form byproducts. DBP formation is strongly dependant on NOM concentration (Roberts et al., 2002). Studies have shown that the physical and chemical properties of NOM influence DBP formation (Reckhow et al., 1990). For instance, increasing levels of NOM in chlorinated drinking water increases the formation of DBPs (Xie, 2004). Additionally, only chlorinated byproducts are formed if the bromide ion (Br^-) is not present. By contrast, in the presence of Br^-, the free chlorine (HOCl) reacts with the NOM to form mixed chloro-bromo byproducts.

The halogenated DBP groups discussed herein are HAAs and THMs. The regulated HAA group includes: monochloroacetic acid (MCAA), dichloroacetic acid (DCAA), trichloroacetic acid (TCAA), monobromoacetic acid (MBAA), and dibromoacetic acid (DBAA). The resulting THMs include: chloroform (CHCl_3),
bromodichloromethane (CHCl₂Br), dibromochloromethane (CHBr₂Cl), and bromoform (CHBr₃).

The environmental and treatment factors that influence DBP formation include: pH, contact time, temperature, season, type of NOM, chlorine dose and residual, and Br⁻ concentration. Results of some of the factors previously investigated are as follows:

1. Contact time increases THM formation. Said formation continues in the distribution system if a chlorine residual is present. HAA formation occurs quickly once the chlorine reacts with NOM and formation slows with increasing contact time. As the chlorine and DBP precursors are exhausted, hydrolysis reactions can reduce the concentration of DBPs. Since THMs are typical hydrolysis products and chlorination end products, the formation of THMs are generally increased by reaction time (Xie, 2004). Halogenated DBP formation increases with the activated aromatic content of NOM as shown by Reckhow et al. (1990);

2. THM has been shown to increase in the distribution system by 1.2-1.8 times that of the finished water (Toroz & Uyak, 2005). The largest variation of THM levels in the distribution system from the finished water occurs when temperatures exceed 24°C. Moreover, Rodriguez and Serodes (2001) state that increasing the temperature will also increase the THM formation. Additionally, an Ontario drinking water survey concluded that water temperature was perhaps the single most important factor influencing seasonal variation of TTHM concentrations (Stevens et al., 1989). Also, the effect of temperature on THM formation has been investigated for not only the distribution systems, but also in the home of the customer. Finally, the further formation of THMs when water is heated at home was studied by Li and Sun (2001). Samples were heated for 5 minutes and
observed for a 35 minute period. The samples revealed a significant increase in THM concentrations from 104 to 211 µg/L and 115 to 386 µg/L in water samples with an initial free chlorine residual concentration of 0.1 mg/L and 1.2 mg/L respectively. The initial heat increase above 80°C showed a rapid THM formation, indicating that temperature close to water boiling point was the favored condition for THM formation.

Li and Sun (2001) also studied THM volatilization. A sample with an initial THM concentration of 75 µg/L was heated in a temperature range of 85-90°C. To avoid any THM formation, ascorbic acid, a strong reducing agent, was added to the water samples prior to the heating process. The results revealed a decrease from 75 to 55 µg/L during the heating phase, and an additional decrease to 34 µg/L during the remainder of the 55-minute testing period. Higher THM concentrations were also investigated, which revealed better removal during the heating period from the initial concentration of 120 µg/L to 40 µg/L and further removal during the cooling period to 14 µg/L;

3. Some amount of chlorine residual is maintained in the distribution system to prevent organism re-growth in finished water. However, field data from studies indicating that THM levels will increase over time in the distribution system are inconsistent. In fact, Myerchin et al. (2006) showed that DBPs in finished water samples were similar in magnitude to the chlorine consumed over a period of time;

4. Illustrative of residence time, Chen & Weisel (1998) based a study on DBP concentrations in drinking water on the premise that the location with the maximum residence time in the distribution system will have the highest THM concentration. A distribution system in central New Jersey was monitored for a year at zero, one, two, and three-day residence time locations with a 0.5 mg/L of chlorine residual leaving the plant.
There were no storage tanks between the zero, one, and two-day residence time locations; but between the two-day and the three-day residence time locations there were several storage tanks at which no additional disinfectant was added. The results showed that THMs concentrations in the warm season were more than twice of those in the cold season. Chen & Weisel (1998) explained that seasonal differences in temperature account for the differences in chemical reaction rates. Thus, higher temperatures in the warm season accelerated the rate of THM production in the distribution BVMAs compared with the cold season. During both seasons, the free chlorine at the last sampling point was essentially depleted. The results indicate that the highest concentrations of THMs in the water distribution system were found at the farthest point from the treatment plant during the warm season. The higher temperatures and possibly differences in the organic matter present at the source during the warm season increased the production of THMs; and

5. HAAs are favored over THM formation under certain conditions (Speight & Singer, 2005). Because HAAs tend to form quicker than THMs, they are more likely to be formed in the treatment plant. But, HAA precursors are more likely to be removed by coagulation than THM precursors, thus leaving THM precursors in the finished water to form in the distribution system.
2.2 DBP regulations

To ensure the quality of drinking water the Environmental Protection Agency (EPA) started to monitor and limit exposure to DBPs with the Total Trihalomethane Rule (TTHMR) of 1979 by setting the maximum contamination level (MCL) for TTHM at 100, with no regulation on HAAs (Xie, 2004). The TTHMR applied to systems serving 10,000 people or more that added a disinfectant during the treatment process (Xie, 2004). Since then, there have been amendments to the TTHMR and other Rules enacted to improve the drinking water quality. For instance, the Stage 1 Disinfection and Disinfection Byproducts Rule (D/DBPR) of 1998 lowered the TTHM MCL to 80 µg/L and introduced the HAA MCL of 60 µg/L based on the Running Annual Average (RAA) of the distribution system. Also, Stage 1 applied to a wider range of systems that add a disinfectant, but did not include consecutive systems. Table 2-1 shows the maximum contamination level goals (MCLG) for Disinfectants and DBPs. Finally, Stage 1 established limits for disinfectants as well as reduced the level of organic precursor compounds in source water that may react with disinfectants to form DBPs (US EPA, 1999).
In 2006, the Stage 2 Disinfectants and Disinfectant Byproducts Rule was promulgated, revising Stage 1 D/DBPR. Stage 2’s purpose was to reduce potential cancer and reproductive and developmental health risks from DBPs in drinking water.

Importantly, Stage 2 includes systems omitted by Stage 1, such as community and non-transient non-community water systems that add and/or deliver water that is treated with a primary or residual disinfectant other than ultraviolet light. In addition, under Stage 2, each distribution system will conduct an Initial Distribution System Evaluation (IDSE), to identify locations with high DBP concentrations. The identified locations are then used to sample for compliance monitoring based on Locational Running Annual Average (LRAA) rather then the RAA introduced in Stage 1 (US EPA, 2006). Although

<table>
<thead>
<tr>
<th>Table 2-1: MCL for Disinfectant and Disinfectant Byproducts</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Disinfectant Residual</strong></td>
</tr>
<tr>
<td>Chlorine</td>
</tr>
<tr>
<td>Chloramine</td>
</tr>
<tr>
<td>Chlorine Dioxide</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Disinfectant Byproducts</strong></th>
<th><strong>MCLG (mg/L)</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Trihalomethanes (TTHM)</td>
<td>0.080</td>
</tr>
<tr>
<td>Haloacetic acids (five) (HAA5)</td>
<td>0.060</td>
</tr>
<tr>
<td>Chlorite</td>
<td>1.0</td>
</tr>
<tr>
<td>Bromate</td>
<td>0.010</td>
</tr>
</tbody>
</table>
the MCLs for TTHM and HAA5 do not change under Stage 2, the primary objective of the LRAA is to reduce exposure to high DBP levels.

2.2.1 Consecutive systems

A consecutive system is a public water system (PWS) that receives all of its water from one or more wholesale systems. A wholesale system is a PWS that treats source water to produce finished water and delivers some or all of the finished water to other PWSs. Finished water is introduced into the distribution system of a PWS intended for consumption without further treatment, except that which is necessary to maintain the water quality in the distribution system.

Because DBP concentration levels can increase in the distribution system, consecutive systems face challenges in providing water that meets regulatory standards for DBPs and other contaminants. The difficulty arises because consecutive distribution systems have no control over the water they are receiving from the wholesaler. US EPA (2006) studies reveal that contaminants including coliforms, and some DBPs which continue to react in the distribution system.

Because Stage 1 did not regulate consecutive systems, each state had flexibility in defining a system. Such flexibility allowed small systems to use wholesalers as an emergency water source, and thus to be considered a consecutive system. Because each state was permitted to define a system, regulations of DBP levels in consecutive systems varied from state to state. An US EPA example illustrates how some states without regulated DBP levels in consecutive systems deliver disinfected water, but do not add a
disinfectant (US EPA, 2006). Other states, such as Virginia and Pennsylvania, have set compliance DBP standards based on the combined distribution system that includes both the wholesaler and consecutive system. Therefore, to ensure that customers receive the same public health protection that is provided by wholesale distribution systems, Stage 2 includes consecutive systems, which means that they are required to meet the MCLs for TTHMs and HAA5s.

Finally, Stage 2 requires all systems, including consecutive systems, at sampling sites identified under the IDSE or existing Stage 2 monitoring locations use LRAAs to determine compliance with TTHM and HAA5 at MCLs of 80 µg/L and 60 µg/L respectively.

2.3 Technologies for DBP control in wholesale and consecutive systems

Recommended strategies for controlling halogenated DBP formation include: source control; precursor removal using enhanced coagulation; granular activated carbon adsorption, or membrane filtration; alternative oxidants and disinfectants such as combined chlorine (monochloramine); ozone; chlorine dioxide; permanganate; advanced oxidation process and UV light; and air stripping (Singer, 1993). It was stated by Singer (1993) that air stripping involves eliminating the volatile THM species after they are formed, but cannot be used to control other DBP’s that are nonvolatile and of public health concern.
Table 2-2 depicts the Best Available Technologies (BAT) for Disinfectants and Disinfectant Byproducts for each of the maximum disinfection residual level (MDRL) the EPA put into place for Stage 1.

In comparison, for Stage 2 DBPs the BAT for systems that treat source water are GAC10, GAC20, and nanofiltration. In addition, for consecutive systems serving at least 10,000 people the BAT is chloramination with management of hydraulic flow and storage to minimize residence time in the distribution system. For consecutive systems

<table>
<thead>
<tr>
<th>Disinfectant/DBP</th>
<th>BAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chlorine residual</td>
<td>Control of treatment processes to reduce disinfectant demand and control of disinfection treatment processes to reduce disinfectant levels</td>
</tr>
<tr>
<td>Chloramine residual</td>
<td>Control of treatment processes to reduce disinfectant demand and control of disinfection treatment processes to reduce disinfectant levels</td>
</tr>
<tr>
<td>Chlorine dioxide residual</td>
<td>Control of treatment processes to reduce disinfectant demand and control of disinfection treatment processes to reduce disinfectant levels</td>
</tr>
<tr>
<td>Total THMs</td>
<td>Enhanced coagulation or enhanced softening of GAC10* with chlorine as the primary and residual disinfectant</td>
</tr>
<tr>
<td>Total HAA5</td>
<td>Enhanced coagulation or enhanced softening of GAC10* with chlorine as the primary and residual disinfectant</td>
</tr>
<tr>
<td>Chlorite</td>
<td>Control of treatment processes to reduce disinfectant demand and control of disinfection treatment processes to reduce disinfectant levels</td>
</tr>
<tr>
<td>Bromate</td>
<td>Control of ozone treatment process to reduce production of bromate</td>
</tr>
</tbody>
</table>

*GAC10- granular activated carbon with an empty bed contact time of 10 minutes and a reactivation frequency for GAC of no more than 6 months (US EPA 1998)
serving fewer than 10,000 people the BAT is management of hydraulic flow and storage to minimize residence time in the distribution system without chloramination (US EPA, 2006).

It is important to maintain chlorine residual in the water supply and some consecutive systems add chlorine to the incoming water usually before it goes into a storage tank. A storage tank provides additional contact time for the formation of DBPs. Liang and Singer (2003) studied the water quality and treatment characteristics of five water utilities. Each of the five was evaluated under controlled chlorination conditions to determine their influence on the formation and distribution of HAA5 and THMs in drinking water. All samples were then chlorinated and pH adjusted to 6.0 or 8.0 for contact times of 1, 2, 4, 8, 24, and 72 hours. HAA and THM formation occurred rapidly during the first few hours, and then slowed as the concentration of NOM and chlorine decreased over time. Higher levels of HAA and THM formation were found in water samples with higher specific ultra-violet absorption (SUVA) values, which are used to evaluate water treatability. In addition, chlorination pH and Br/TOC or Br/Cl₂ ratios strongly influenced the distribution and speciation of HAAs and THMs. Formation of DBPs depends primarily on the source water quality characteristics, and on the location in the treatment process where disinfectants are added (Liang & Singer, 2003).

Rodriguez et al. (2004) studied a distribution system with a storage reservoir for DBP occurrence. The main objective was to study the occurrence of DBPs in drinking water with emphasis on seasonal and spatial evolution in a distribution system. Differences in the amount for different seasons were significant for both THMs and HAAs. The highest THMs were in the summer and fall, almost a fivefold increase from
the winter (Rodriguez et al., 2004). The differences in residence time in the distribution BVMA pre-, post-, and re-chlorination had considerable impact on the DBP formation. As the THMs increased with residence time, the HAAs decreased. The decrease in HAAs was attributed to microbiological degradation that was previously documented (Tung et al., 2006). The concentration of DBPs after the storage tank showed significant increases in both THMs and HAAs. The increases were due to the additional application of chlorine and the additional contact time for the chlorine with the NOM within the reservoir, and hydrolysis reaction of intermediate products.

2.3.1 Aeration

In 1977 the US EPA studied the cost ramifications of removing chloroform and other THMs from drinking water supplies. In the study the US EPA found that aeration was frequently practiced for the removal of hydrogen sulfide and other reduced materials, but experimental data showed that at typical air-to-water ratios used in water treatment (1:1) little removal of chloroform takes place (Clark et al. 1977). For a contact time of 20 minutes they used an air-to-water ratio of 30 ft$^3$ (0.85 m$^3$) to 1 ft$^3$ (0.03 m$^3$), and determined that utilizing aeration as a method of removing THMS from water was too expensive. Since then, air stripping’s efficacy has increased and the cost has made aeration a popular method for removing volatile organic compounds (VOCs) from contaminated groundwater (Narbaitz et al. 2002).

The efficiency of aeration for THM removal is principally dependent on the air-to-water ratio (Bilello & Singley, 1986). As the air-to-water ratio increases, so does the
THM removal efficiency. Generally, it is expected that removals will level off once an air-to-water ratio reaches equilibrium conditions (Bilello & Singely, 1986).

As the water depth increases, so does the removal efficiency because of the reduction in pressure on an air bubble. As the height of a water column above the bubble diminishes, the size of the bubble increases (Bilello & Singely, 1986).

Air stripping has almost universal applicability for the removal of VOCs from water (Kutzer et al., 1995). Air stripping or aeration can occur in many different forms and sizes depending on the water or wastewater being treated, and the amount of contaminants being stripped from the liquid. Aeration is generally most effective in removing low molecular weight organics, including THMs and many industrial solvents, in contrast to other common water treatment methods for the removal of chemical pollutants that are more effective for removing higher molecular weight impurities or organic matter (Albin & Holdren, 1985). Depending on the degree of removal required, the volatility of the compounds, the air-to-water ratio, the water flow rate, and the physical and chemical conditions that affect the rates of mass transfer, the required packing height in a countercurrent flow tower is a complex function usually determined by the method of transfer units (Kutzer et al., 1995).

Most stripping studies have been carried out in either packed tower or in batch-sparged aerators (Velazquez & Estevez, 1992). Velazquez and Estevez presented a study for stripping of THMs in a bubble-column aerator. The results show a rapid drop in concentration at the entrance of the column, a region in which concentration of THMs in water decreases, and a plateau region in which no further mass transfer occurs. The plateau is reached when equilibrium occurs between phases. A series of columns could
be used to achieve any level of removal, especially for less volatile THMs such as dibromochloromethane and bromoform, which might not be removed in one theoretical stage. The mass transfer rate determines how fast the plateau region is reached for each compound, but does not affect the final concentration. This is important when the contact time with air is not long enough for the concentration of the compound being removed to reach the plateau region. The mass transfer rates always increase as either phase velocity increases, meaning that the exit velocity will always decrease when gas velocity increases, enhancing mass transfer and lowering the equilibrium concentration.

Qaisi and Qasem (1996) reported excellent chloroform removal efficiencies using air stripping with either mechanical or diffused aeration. Bilello and Singley (1996) found that diffused aeration was less effective than packed column aeration for the reduction of THMs in water.

For most aeration applications, the equilibrium between air and water can be described by Henry’s Law (Hand et al. 1999). Henry’s Law constants for the compounds that are removed are important in the design of air stripping facilities (Nicholson et al. 1984). A compound in equilibrium between air and water during removal can be expressed by the following equation (Hand et al. 1999):

\[
H = \frac{A_{\text{air}}}{A_{\text{aq}}}
\]

Here \(H\) is equilibrium constant and \(A\) is activity of the compound in equilibrium either in air or water (\(aq\)). The most important parameter that affects the extent of removal is temperature (Ornektekin et al. 1996). Henry’s law can be used in systems where there is
a low volatile solute concentration in the liquid phase, low temperature, and low total pressure in vapor phase (Blatchley III et al. 1992).

2.4 Summary of Literature Review

Many studies focus on THM formation. Reckhow et al. (1990), Singer (1993), Liang and Singer (2003), and Xie (2004) looked at NOM and its effects on the formation of DBPs. Increased retention time and increased temperatures increase the formation potential for DBPs shown by Stevens et al. (1989), Chen and Weisel (1998), Li and Sun (2001), Rodriguez and Serodes (2001), Toroz and Uyak (2005), and Myerch et al. (2006). Aeration has been shown as a universal application for removal of VOCs by Kutzer et al., (1995) and also to be most effective in removing low molecular weight organics by Albin and Holdren (1985). Qaisi and Qasem (1996) found that packed column aeration was more effective than diffused aeration for the reduction of THMs in water.
Chapter 3
Methodology

3.1 Gas chromatography analysis

3.1.1 Chemicals

The standards for the pilot aeration studies were purchased from Aldrich Chemical Company, USA: CF, bromoform (BF), dibromochloromethane (BDCM), bromodichloromethane (BDCM), monochloroacetic acid (MCAA), monobromoacetic acid (MBAA), dichloroacetic acid (DCAA), dibromoacetic acid (DBAA), and trichloroacetic Acid (TCAA). Standard solutions were prepared by diluting aliquots of stock solutions in HPLC grade methanol from JT Baker, USA and stored in the dark for up to 3 months. The working standard was prepared by spiking known aliquots into 200 gallons (760 liters) of water in the storage tank. The samples were analyzed using granular ammonium chloride, methanol, and methyl tert-butyl ether (MtBE) from JT Baker, USA; pentane and sodium sulfate from EMD Inc., Germany; sulfuric acid from VWR International, USA; and 1,2-dibromopropane from Aldrich Chemical Company, USA.
3.1.2 Analytical methods

EPA method 551.1 was used to determine THMs by liquid-liquid microextraction and gas chromatography (GC) with electron capture detection (ECD). The THM samples were extracted with pentane containing an internal standard of 1,2-dibromopropane and sodium sulfate using EPA method 551.1.

The THMs are analyzed on an Agilent Technologies 6890N GC-ECD at 300 °C. The 1.0 μL of sample was injected by an Agilent 7683 Series autosampler and autoinjector with a splitless mode at a temperature of 150 °C. The sample then went through a DB-1 capillary column (30.0 m X 320 μm X 1 μm) at 30 °C for 22 minutes, increased by 10 °C/min to 145 °C and a post run time of 5 minutes at 200 °C using ultra high purity nitrogen gas (GT&S Inc., USA) at a flow of 1.4 mL/min. Gas saver was run at 20 mL/min for 2 minutes.

The HAA5 samples were analyzed using EPA method 552.3 by liquid-liquid microextraction, derivatization, and GC-ECD. The HAA5 samples were extracted using MtBE containing an internal standard of 1,2-dibromopropane, and sodium sulfate. The samples were then derivatized using sulfuric acid and methanol.

The HAA5s are analyzed on a Hewlet Packard (HP) 6890 Series GC-ECD at 300 °C. The 1.0 μL of sample was injected by an HP autosampler and a HP 6890 autoinjector with a splitless mode at a temperature of 200°C. The sample then went through a DB-1701 capillary column (30.0 m X 250 μm X 0.25 μm) at 35 °C for 10 minutes, increased by 5 °C/min to 75 °C for 16 minutes and a post run time of 3 minutes at 200 °C using
ultra high purity nitrogen gas (GT&S Inc., USA) at a flow of 1.0 mL/min. Gas saver was run at 20 mL/min for 2 minutes.

3.2 Pilot aeration studies

A 250-gallon cylinder cone tank was filled to the 200-gallon line with tap water from the Penn State Harrisburg Science and Technology Building. A TTHM and HAA5 standards were then spiked into the water. The tank was aerated for six (6) hours using air from an air hose and a 24 inch (61 cm) Flexline™ Membrane Tube fine bubble cylindrical diffuser (US Filter). The samples were collected every 30 minutes starting at time zero (0) in 40-mL glass vials with polytetrafluorethylene (PTFE) faced septa and preserved with granular ammonium chloride without any headspace. The samples were then stored in a refrigerator at 4°C for no more than 14 days. Every 30 minutes, chlorine residual was also measured using a Hach Spectrophotometer DR 2400. The samples were then analyzed using EPA method 551.1.

3.3 Field aeration study

A field study was conducted to look at the effects of aeration over a twenty-two day (22) day period a Twin Rocks Tank in BVMA, including sixteen (16) days with aeration. An Excelsior Blower package provided the air-flow into the tank at 63 ft³/min (1.7 m³/min) when the tank was at (270,000 liters) 70,000 gallons. FlexAir (7”) Fine bubble diffusers (4) and PermaCap5-Fine Bubble-3/4” NPT diffusers (16) were placed in
the bottom of the tank on PVC piping in an “X-shape”. Each arm of the “X-shape” had 1 FlexAir Fine bubble diffuser and 4 PermaCap5-Fine Bubble-3/4” NPT diffusers. Samples were collected by the operator at least once per day at four (4) different locations in BVMA’s distribution system: Inlet to the system, at Twin Rocks Tank, and at two (2) other locations after the Twin Rocks Tank. The other two (2) locations are at different retention times within the distribution system. The first location has a short retention time of approximately two (2) days. The second location is after Vintondale Tank and has a twelve (12) day retention time. The samples were collected in 40-mL glass vials with polytetrafluorethylene (PTFE) faced septa and preserved with granular ammonium chloride without any headspace. The samples were then shipped to Penn State Harrisburg and stored in a refrigerator at 4°C for no more than 14 days. Along with the THM samples, chlorine residual, pH, and temperature results were recorded with each sample.
4.1 Blacklick Valley Municipal Authority

BVMA is the consecutive system within the water distribution system participating in this aeration study. Notably, over the past few years water from the wholesaler’s (Nant-Y-Glo) storage tank has shown high levels of total trihalomethanes (TTHM). However, beyond Nant-Y-Glo’s storage tank water associated with BVMA has shown further increased levels of THMs. As the finished water is stored, DBPs are formed in a magnitude similar to that of the chlorine consumed over the storage period (Myerchin et al. 2006).

BVMA receives water from Nant-Y-Glo Water Treatment Plant. The Nant-Y-Glo water travels through its storage tank (Cardiff Tank, Location #1) before entering BVMA. The water from BVMA flows through Twin Rocks Tank (Location #3) and into Vintondale Tank (Location #4). Chlorine is added during the summer months via chlorine pump stations as the water flows into the Twin Rocks tank and the Vintondale tank. Nant-Y-Glo Water Treatment Plant utilizing surface water from Williams Run Reservoir pretreats the water with potassium permanganate and powdered activated carbon (PAC) combined with disinfection, coagulation, flocculation, dissolved air floatation and filtration before it is sent into the distribution system. As stated, the water
from Nant-Y-Glo has reported above MCL levels of TTHM. These inclined TTHM levels increase further with retention time in the BVMA distribution system.

In October 2006, monitoring of BVMA’s distribution system began at five (5) locations throughout the system beginning with the inlet to the BVMA ending at BVMA’s Waste Water Treatment Plant (Location #5), which is the maximum residence time in BVMA. The wholesaler’s system was also sampled monthly to compare to BVMA. The locations of the sampling points are identified on Figure 4-1 (Maps a la carte Inc.).
TTHM and HAA5 analysis were conducted each month on all samples as described in Chapter 3, Methodology. The results of the monitoring of BVMA from October 2006 – September 2007 are shown in Figure 4-2 (TTHM) and Figure 4-3 (HAA5). The Maximum Contamination Level (MCL) is shown at 80 µg/L.

Figure 4-2: TTHM results for BVMA.
The THMs in the BVMA are composed of chloroform and bromodichloromethane. Figure 4-4, shows the dominance of chloroform in the distribution BVMAs compared to bromodichloromethane in Figure 4-5.
Bromodichloromethane (DBCM) makes up the remainder of the THMs in the BVMA distribution system, Figure 4-5.

![Graph showing concentration of THMs from October 2006 to September 2007 for different locations in the BVMA system.](image)

**Figure 4-5**: Bromodichloromethane results for BVMA

The results from the TTHM monitoring indicate that the level of TTHM increase with the residence time in the distribution system. In April 2007, the water distribution lines were flushed between Locations #4, the Vintondale Tank, and Location #5, the end of the system. As a result, the concentration of the TTHM decreased significantly at Location #5 from above 100 µg/L in March to below 60 µg/L in April. Figure 4-6 illustrates that from October 2006 to March 2007, Location #5 has been above the MCL of 80 µg/L, and then decreased to below the MCL in April 2007 and remained below the MCL into June of 2007. The decrease in THM concentration was due to flushing the system due to low water use at Location #5. Location #5 did not exceed the MCL until July, when the rest of the distribution system was also above the MCL.
Furthermore, the results indicated that the concentration of the TTHM increased before entering BVMA, and continued to increase as the water was stored in Twin Rocks Tank and Vintondale Tank. The maximum, minimum, and average concentrations for all locations in BVMA, including a data from the Nant-Y-Glo water treatment plant are shown in Figure 4-7 and Figure 4-8.
Chlorine residual (Cl\textsubscript{2}) was recorded at the time of sampling starting in April 2007 to evaluate the residual through the summer months as shown in Figure 4-9. Chlorine residual MCL is shown at 0.2 mg/L.

Figure 4-7: THM maximum, minimum, and average concentrations for each sample location system from October 2006 – September 2007.

Figure 4-8: HAA5 maximum, minimum, and average concentrations for each sample location system from October 2006 – September 2007.
The chlorine residual depleted with increased residence time in the distribution system. Therefore, the chlorine is boosted during the warm weather months before the Twin Rocks Tank, Location #3, and the Vintondale Tank, Location #4.

The THM data from the BVMA distribution system shows a need for THM reduction before entering the distribution system. The THM concentration entering the system exceeds the MCL and continues to increase in the distribution system. A technique to remove or control the THMs would allow the BVMA to stay in compliance with the MCLs for TTHM. By reducing the THM concentration at beginning of the distribution system, the THMs should be in compliance throughout the distribution system. The Twin Rocks Tank would be a good location for THM removal or control due to its proximity to the beginning of the distribution BVMA the flow of the water through the tank before continuing on to the distribution system.
4.2 Laboratory studies

THMs are much more volatile than HAAs as shown by the Henry’s Law constants. THMs range from about 0.022 (2.19x10^-2 dimensionless) to about 0.17. The lowest Henry’s Law constant for the HAAs is monochloroacetic acid (MCAA) at 20°C, is 3.8x10^-7 dimensionless. During the laboratory testing, all of the HAAs tested exhibited no removal during six hours of aeration. Accordingly, the following discussion will focus on THMs. Table 4-1, provided with references, lists the Henry’s Law constants for nine THMs and HAAs at 25°C along with the boiling points and molecular weights. A Henry’s Law constant is calculated by dividing the vapor pressure of the compound by the water solubility of the compound.
At 20°C, the Henry’s Law constants of chloroform, bromodichloromethane, dibromochloroethane, and bromoform are 0.17, 0.0904, 0.048, and 0.022 respectively. Similar to trichloroethylene (TCE), which has a Henry’s Law constant of 0.82, THMs are volatile organic compounds. Packed aeration towers, which can achieve 90 to 99.99% removal, are commonly used for TCE removal in contaminated ground water. For THM removal, diffused aeration was studied because of the low removal percentage required to meet THM compliance.

<table>
<thead>
<tr>
<th></th>
<th>Molecular Weight</th>
<th>Boiling Point (°C)</th>
<th>Experimental Henry’s Law Constant (25°C)</th>
<th>Experimental Reference Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>CF</td>
<td>119.4</td>
<td>61.1</td>
<td>1.72 x 10^{-1}</td>
<td>Hand et al.</td>
</tr>
<tr>
<td>BDCM</td>
<td>163.8</td>
<td>90</td>
<td>9.04 x 10^{-2}</td>
<td>Warner et al.</td>
</tr>
<tr>
<td>DBCM</td>
<td>208.3</td>
<td>120</td>
<td>4.83 x 10^{-2}</td>
<td>Hand et al.</td>
</tr>
<tr>
<td>BF</td>
<td>252.7</td>
<td>149.1</td>
<td>2.19 x 10^{-2}</td>
<td>Munz &amp; Roberts</td>
</tr>
<tr>
<td>MCAA</td>
<td>94.5</td>
<td>189.3</td>
<td>3.78 x 10^{-7}</td>
<td>Bowden et al.</td>
</tr>
<tr>
<td>DCAA</td>
<td>128.9</td>
<td>194</td>
<td>3.43 x 10^{-7}</td>
<td>Bowden et al.</td>
</tr>
<tr>
<td>TCAA</td>
<td>163.4</td>
<td>196.5</td>
<td>5.53 x 10^{-7}</td>
<td>Bowden et al.</td>
</tr>
<tr>
<td>MBAA</td>
<td>139.0</td>
<td>208</td>
<td>2.67 x 10^{-7}</td>
<td>Bowden et al.</td>
</tr>
<tr>
<td>DBAA</td>
<td>217.9</td>
<td>233</td>
<td>1.81 x 10^{-7}</td>
<td>Bowden et al.</td>
</tr>
</tbody>
</table>
The effect of water temperature, air flow, and THM speciation on THM removal was investigated in a batch reactor. Initial pilot testing was done at an air flow of 0.14 m³/min (5 ft³/min) at 20°C. The effect of THM speciation on their removal is shown in Figure 4-10. With an initial concentration of 100 µg/L for each THM, water temperature of 20°C, and an air flow of 0.14 m³/min (5 ft³/min), a three hour aeration reduced the concentration of chloroform, bromodichloromethane, dibromochloromethane, and bromoform to 3, 7, 19, and 36 µg/L respectively. As THM species became more bromine substituted, their removal efficiency became lower. This trend is also seen in the Henry’s Law constants of THMs. The Henry’s Law constants for chloroform, bromodichloromethane, dibromochloromethane, and bromoform at 20°C are 0.13, 0.09, 0.04, and 0.02 respectively. In general, increasing the bromide level in water increases the level of brominated THMs. This indicates that a lower removal efficiency for TTHM is expected for water high in bromide.

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Figure 4-10: Aeration results using an air flow of 0.14 m³/min at 20°C.
Further pilot testing at different water temperatures showed that as the temperature increased, the removal also increased due to the effect of temperature on Henry’s Law constants for each of the THMs. An air flow of 0.03 m$^3$/min (1 ft$^3$/min) shows the effect of a temperature increase from 14°C to 21°C on chloroform, Figure 4-11.

![Figure 4-11: Effect of temperature on the removal of chloroform at 0.03 m$^3$/min.](image)

Additional pilot testing was conducted using 0.09 m$^3$/min (3 ft$^3$/min) to investigate the effect of air flow on the removal of THMs from water. The results from the 0.09 m$^3$/min (3 ft$^3$/min) indicate chloroform removals of 95% and 97%, Figure 4-12, and TTHM removals of 70% and 74%, Figure 4-13 for 18 °C and 21 °C, respectively. Figures 4-12 and 4-13 illustrate that as the temperature increases for each air flow, the chloroform and TTHM removal also increases over the same time period. The chloroform had a greater removal over the first two (2) hours at 22°C than at 18°C where the TTHM removal showed the same increase in removal for all six (6) hours.
The 0.14 m³/min (5 ft³/min) air flow indicated the most efficient of the air flows studied in the six (6) hours of aeration at 20-22°C for all the compounds. At the 0.14 m³/min (5 ft³/min), chloroform (Figure 4-14) is removed by 93% in two (2) hours, where the 0.03 m³/min (1 ft³/min) and 0.09 m³/min (3 ft³/min) air flows have removed 57% and
75%, respectively. The other THMs show the same increasing removal as the air-flow increases, Figure 4-15, Figure 4-16, and Figure 4-17.

Figure 4-14: Chloroform removal over different air flows at 20-22°C.

Figure 4-15: Bromodichloromethane removal over different air flows at 20-22°C.
Finally, the free residual chlorine was tested to determine the amount of chlorine that would be needed to maintain a chlorine residual to sustain the level of disinfectant required in the distribution BVMA after a tank is aerated. Chlorine was added to the water, mixed for five (5) minutes, and then aerated for one (1) minute to ensure adequate

Figure 4-16: Dibromochloromethane removal over different air flows at 20-22°C.

Figure 4-17: Bromoform removal over different air flows at 20-22°C.

Finally, the free residual chlorine was tested to determine the amount of chlorine that would be needed to maintain a chlorine residual to sustain the level of disinfectant required in the distribution BVMA after a tank is aerated. Chlorine was added to the water, mixed for five (5) minutes, and then aerated for one (1) minute to ensure adequate
mixing throughout the tank. Chlorine was tested at three (3) different chlorine residuals, 7.2, 2.1, and 0.5 mg/L Cl\textsubscript{2}, for each of the air flows, 0.03 (1 ft\textsuperscript{3}/min), 0.09 (3 ft\textsuperscript{3}/min), and 0.14 m\textsuperscript{3}/min (5 ft\textsuperscript{3}/min). The results indicate minimal removal of the chlorine residual from the water even at the highest air flow, 0.14 m\textsuperscript{3}/min (5 ft\textsuperscript{3}/min). Figure 4-18 shows the removal of chloroform and the chlorine residual over a 6 hour pilot aeration study at 0.03 m\textsuperscript{3}/min (1 ft\textsuperscript{3}/min).

![Figure 4-18: Chlorine residual removal by aeration at 0.03 m\textsuperscript{3}/min.](image_url)

Chlorine removal from water is more difficult to explain than the THMs. The unitless Henry’s Law constant for chlorine (0.104) is less than chloroform (0.172), but greater than the other THMs at 25°C (Figure 4-19) and has indicated that it is harder to remove than all the THMs.
As the chlorine is added into the water it hydrolyzes to form hypochlorous acid and hydrochloric acid Eq. 4.1:

\[ \text{Cl}_2 + \text{H}_2\text{O} \rightarrow \text{HOCl} + \text{HCl} \quad 4.1 \]

The hypochlorous acid is a weak acid and will then ionize in a reversible reaction for form hypochlorite Eq. 4.2, which has a much lower Henry’s Law constant, \(5.31 \times 10^{-18}\) (shown in Figure 4-19), than chlorine at 0.104.

\[ \text{HOCl} \rightleftharpoons \text{H}^+ + \text{OCl}^- \quad 4.2 \]

The 2 species exist in different quantities depending on the pH of the water they occupy. The dependence of the HOCl to the OCl\(^-\) on pH is shown in Figure 4-20 (Feng et al., 2007). The water in the BVMA distribution system has a pH between 7 and 8.5 depending on the addition of chlorine.
The HAA were not effectively removed from water during aeration due to low Henry’s Law Constants and high boiling points of the compounds shown in Table 4-1. Comparably, chloroform, the easiest compound to remove by aeration, has a B.P. of 61.1°C and Henry’s Law constant of 0.172 dimensionless at 25°C.

The results indicated an inconsistent removal of 0-7% for all the HAAs studied, Figure 4-21.
For each HAA aeration test that was run at air flows of 0.03 m$^3$/min (1 ft$^3$/min), 0.09 m$^3$/min (3 ft$^3$/min), and 0.14 m$^3$/min (5 ft$^3$/min) the results show HAA levels decreasing and increasing in the same 7% range throughout the aeration. Theoretically, MCAA should show the most removal due to the highest Henry’s Law constant within the group of HAAs. But the results indicate MCAA having a low removal at 3%, and DBAA, the compound with the lowest Henry’s Law constant, having the highest removal at 6%. TCAA showed no removal. The other two (2) HAA compounds showed a 3% removal at the final concentration.

Figure 4-21: HAA removal at 0.09 m$^3$/min (3 ft$^3$/min) at 22°C.
4.3 Field Studies

Aeration for THM removal was conducted in the field over a period totaling 22 days. Testing involved aerating for an extended period of time in an online tank in the BVMA distribution system using an air flow of 63 ft\(^3\)/min (1.8 m\(^3\)/min) to study the effects of aeration throughout the distribution system. Prior to aeration, water samples were collected to get a baseline for the concentrations at various locations throughout the system: the entry point to the system, the Twin Rocks Tank (70,000 gallons), a location approximately 1 mile after the tank, and at the end of the distribution system after a 300,000 gallon storage tank approximately 5 miles from the Twin Rocks Tank.

The following graphs show the effects of aeration. The first vertical line shows the start of aeration. The second vertical line shows the end of aeration after 16 days of aeration. The water flow was approximately 60,000 gallons per day and during the aeration 1,121,000 gallons of water flowed through the Twin Rocks Tank. The temperature ranged from 14.6°C – 21.2°C (58.3°F- 70.2°F).

The THM results show that the aeration removed the THMs at the Twin Rocks Tank, Figure 4-22, and then carried the removal through the system, Figure 4-23. The system inlet exceeded the THM MCL of 80 µg/L for the extent of the aeration study. The THM concentration at the Twin Rocks Tank was reduced by 60%, 135 µg/L to 53 µg/L, in the first 24 hours of aeration. The following 15 days show increases and removals due to high THM concentrations, 148 µg/L to 117 µg/L, in the water coming from the wholesale system (system inlet). As the water flow through the tank increased, so did the THM concentration in the tank. The BVMA has an average flow of 63,000
gallons through the Twin Rocks Tank each day. The majority of the flow is between 6 AM and 12 PM. Once the water flow decreased, so did the THM concentration due to the effect of the aeration.

Figure 4-22: THM removal at the entry point and the Twin Rocks Tank.
The removal affected Twin Rocks and the Vintondale Tank at different retention times: two (2) days for the water to reach Twin Rocks and twelve (12) days for the Vintondale Tank to be completely filled with aerated water. Twin Rocks showed a maximum removal of 76%, 147 µg/L to 35 µg/L. The Vintondale Tank showed a removal of 56%, 55 µg/L, on the final day of aeration compared to the concentration, 125 µg/L, before the aeration. Once the aeration was shut off, the TTHM concentration increased at all locations in the distribution system. In less than two (2) days, both the Twin Rocks Tank and the Twin Rocks sampling location were exceeding the THM MCL. It took eleven (11) days for the Vintondale location to exceed the MCL.

Figure 4-23: THM removal at 4 locations in the BVMA distribution system.
Chloroform removal is similar to that of the TTHM removal, Figure 4-25.

Figure 4-25: Chloroform removal at the entry point and the Twin Rocks Tank.

Bromodichloromethane removal is similar to that of chloroform, Figure 4-26.

Figure 4-26: Bromodichloromethane removal at the entry point and the Twin Rocks Tank.
4.4 Mathematical modeling

The distribution equilibrium of a compound in the aqueous ($[A]_{aq}$) and gas phases ($[A]_{air}$) can be characterized by the dimensionless Henry’s Law constant Eq. 4.3

$$H = \frac{[A]_{air}}{[A]_{aq}}$$  \hspace{1cm} 4.3

To predict the aeration efficiency during warmer temperatures and higher THM concentrations, the dimensionless Henry’s law constants were applied to the data using the appropriate expression that was derived from Eq. 4.4

$$V_w C = y Q_{air}$$  \hspace{1cm} 4.4

where $V_w$ is the volume of water, $C$ is the chloroform concentration, $y$ is the chloroform concentration of air, and $Q_{air}$ is the flow of air into the water. The concentration of chloroform in air, $y$, was then substituted for the Henry’s Law constant, $H$, and the concentration, $C$, from the following Eq. 4.5

$$y = HC$$  \hspace{1cm} 4.5

$$V_w dC = C_{in} Qdt - CQdt - CHQ_{air} dt$$ \hspace{1cm} 4.6

Eq. 4.6 shows the mass balance of an online tank that was use to derive the mathematical modeling for flowing tanks where $C_{in}$ is the influent concentration of chloroform, $Q$ is the flow of water, and $t$ is time.

Equation 4.6 was then rearranged and simplified to form Eq. 4.7

$$V_w dC = [C(Q + HQ_{air}) - C_{in} Q](-dt)$$  \hspace{1cm} 4.7
Equation 4.7 was then integrated to form Eq. 4.8

\[
\int \frac{dC}{C(Q + HQ_{\text{air}}) - C_{\text{in}}Q} = \int - \frac{dt}{V_w}
\]

The integrated form was then rearranged Eq. 4.9:

\[
\frac{1}{Q + HQ_{\text{air}}} \ln[C(Q + HQ_{\text{air}}) - C_{\text{in}}Q] = -\frac{t}{V_w}
\]

Equation 4.9 was then taken from \(C_0\) to \(C\) on the left and the right from 0 to \(t\) and rearranged, Eq. 4.10, then rearranged and the exponential taken to form a more workable equation, Eq. 4.11.

\[
\ln[(Q + HQ_{\text{air}})C - C_{\text{in}}Q] = \ln[(Q + HQ_{\text{air}})C_0 - C_{\text{in}}Q] - \left(\frac{(Q + HQ_{\text{air}})t}{V_w}\right)
\]

\[
C = \frac{C_0(Q + HQ_{\text{air}}) - C_{\text{in}}Q}{(Q + HQ_{\text{air}})e^{-\left(\frac{(Q + HQ_{\text{air}})t}{V_w}\right)}} + \left(\frac{C_{\text{in}}Q}{Q + HQ_{\text{air}}}\right)
\]

Eq. 4.12 shows Equation 4-11 when the water flow, \(Q\), is zero (0).

\[
C = C_0 e^{-\left(\frac{HQ_{\text{air}}}{V_w}\right)}
\]
4.4.1 Mathematical modeling for pilot studies

Mathematical modeling was done on the pilot studies to evaluate the model against the actual sampling results. Figure 4-27 shows the mathematical modeling results for chloroform compared with the actual concentration. The modeling results match the actual concentration for each temperature and air flow.

In addition to chloroform, the other THM species that were studied can also be modeled. Bromodichloromethane had the highest removal percentage of the remaining THMs followed by dibromochloromethane and bromoform respectively. Figure 4-28 shows the modeling results for bromodichloromethane, dibromochloromethane, and bromoform. The below models show that as the THM species become more brominated, the removal percentage decreases.
4.4.2 Mathematical modeling for field studies

Mathematical modeling can be used to estimate THM removal with different air flows, tank sizes, water flows and water temperatures. The field testing showed the need for an adjustment of temperature and water flows. Although the tank size remained 70,000 gallons, the amount of water flowing through the tank depended on the usage beyond the tank. Figure 4-29 shows the actual results from the field test and mathematical modeling to correspond with the field testing. The modeling used a water flow of 63,000 gallons of water and an air flow of 63 ft$^3$/min.

Figure 4-28: Mathematical modeling of pilot study results for bromodichloromethane, dibromochloromethane, and bromoform with an air flow of 0.09 m$^3$/min at 17°C.
Figure 4-29: Mathematical modeling for a flowing tank over an extended period of time compared to the actual results from the field testing.
Chapter 5

Conclusions and Recommendations

The objective of this study was to investigate aeration as a method for the removal of DBPs in a consecutive system (BVMA) and to evaluate aeration’s effectiveness on THM concentrations at the maximum residence time. Major conclusions from this study are:

- Air flow had the greatest effect on THM removal from water. As the air flow increased in the pilot batch studies, the removal of THMs increased from 92% to 99% for chloroform and 70% to 95% for THMs.
- In the field study, a 70,000 gallon tank with a water flow of 70,000 gallons per day was aerated for an extended period of time utilizing an air flow of 1.7 m$^3$/min (63 ft$^3$/min). The results showed removals of up to 76% for chloroform and up to 75% for THMs.
- Aeration can be used at the beginning of the distribution system for the consecutive system, the Twin Rocks Tank, to reduce the THM concentration throughout the distribution system.
- Temperature also affects the removal of THMs from water. As the temperature increased, the removal increased in the pilot studies from 23% to 71% for chloroform at the lowest air flow of 0.03 m$^3$/min (1 ft$^3$/min).
- The mathematical modeling of this study provides for the assessment of potential impacts of aeration on different size tanks, water flows, air flows,
temperature, and time. HAA showed no removal due to aeration in both pilot and field studies.

Based upon the potential relevance to other consecutive systems, future studies should include dissolved oxygen and bacteria sampling throughout the BVMA along with more DBP sampling throughout the system. The pH should also be monitored throughout the system with no addition of chlorine.

Finally, the results of this study indicate that aeration can be used to control THMs in consecutive systems. Additionally, aeration could also be used for “hot spots” or areas of high THMs in larger systems. The results of this study are supported by laboratory studies, field studies, and mathematical modeling.
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