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Integrating Spray Aeration and Granular Activated Carbon for Disinfection By-Product Control in a Potable Water System

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INTEGRATING SPRAY AERATION AND GRANULAR ACTIVATED CARBON FOR DISINFECTION BY-PRODUCT CONTROL IN A POTABLE WATER SYSTEM

by

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ABSTRACT

Public water systems add disinfectants in water treatment to inactivate microbial pathogens. Chlorine, when used as a disinfectant, reacts with natural organic matter in the water to form trihalomethane (THM) and haloacetic acid (HAA_5) disinfection by-products (DBPs), which are suspected carcinogens. The Safe Drinking Water Act's Disinfectant and Disinfection By-Product (D/DBP) Rules were promulgated by the U.S. Environmental Protection Agency to regulate the amount of DBPs in water systems. Regulatory compliance is based on maximum contaminant levels (MCL), measured as a locational running annual average (LRAA), for total THM (TTHM) and HAA_5 of 80 µg/L and 60 µg/L, respectively. Regulated DBPs, if consumed in excess of EPA's MCL standard over many years, may increase chronic health risks.

In order to comply with the D/DBP Rules, the County of Maui Department of Water Supply (DWS) adopted two DBP control technologies. A GridBee® spray-aeration process was place into DWS's Lower Kula water system's Brooks ground storage tank in February of 2013. In March of 2015 the second DBP control technology, granular activated carbon (GAC), was integrated into DWS's Pi'iholo surface water treatment plant. To investigate the integration effectiveness of GAC and spray-aeration into a water system for DBP control, DBP data was gathered from the system between August of 2011 and August 2016, and analyzed relative to cost and performance.

Prior to the spray aeration and GAC integration, it was found that TTHM levels at the LRAA compliance site ranged between 58.5 µg/L and 125 µg/L (at times exceeding the MCL). Additionally, HAA_5 levels at the LRAA compliance site ranged between 21.2 and 52.0 µg/L. The concerted efforts of the GAC and GridBee® system was found to reduce LRAA TTHM and HAA_5 concentrations to 38.5 µg/L and 20.5 µg/L, respectively, in the Lower Kula system. Hypothesis testing utilizing t-Tests confirmed that TTHMs levels were controlled by the spray aeration system and the GAC was responsible for controlling HAA_5 formation. Although TTHM levels were reduced by 58 percent, and HAA_5 levels by 48 percent, the estimated cumulative annual operation and maintenance (O&M) cost of the two systems was $1,036,000. In light of the cost analysis, total organic carbon (TOC)-based models for predicting LRAA TTHM and HAA_5 levels were developed as equation (i) and (ii), respectively:

$$\text{TTHM } \mu\text{g/L} = (32.5 \text{ x } (\text{TOC ppm})) + 5.59 \tag{i}$$

$$\text{HAA}_5 \text{ } \mu\text{g/L} = (8.37 \text{ x } (\text{TOC ppm})) + 12.4 \tag{ii}$$

The TTHM model yielded an R^2 of 0.93, and the HAA_5 model had an R^2 of 0.52. F-Tests comparing predicted LRAA TTHM and HAA_5 levels to actual LRAA TTHM and HAA_5 levels determined no statistically-significant difference. With the knowledge of how the GAC and spray aerator controlled DBPs in the water system, a cost-effective and practical treatment operating parameter was developed. The parameter, Pi'iholo water plant filter effluent TOC content, can serve as an indicator that operators would use to alter DBP treatment process flow set points to achieve cost-effective treatment. Furthermore, the significant annual cost contribution by the GAC, coupled with HAA_5 levels below DWS's MCLG, led to the recommendation of variable frequency drive (VFD) pumps for the GAC system. The addition of VFD pumps should reduce the frequency of carbon change outs while preserving adequate HAA_5 control in the system.

For my parents and siblings, who always find a way to diffuse my stress and empower me to continue to challenge my limits, and for my amazing group of friends, who I hope understand that my success is in large part due to their unconditional and loving support. Aim for the stars and keep on swimming guys!

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LIST OF ACRONYMS

ACH	Aluminum Chlorohydrate
CT	Container Type
D/DBP	Disinfectants and Disinfection Byproducts
v	Degrees of Freedom
Dr	Drive
GC	Gas Chromatograph
HAA_5	Haloacetic Acids
Hyd	Hydrant
HT	Holding Time
IDSE	Initial Distribution System Evaluation
IESWTR	Interim Enhanced Surface Water Treatment Rule
I-stat	Industrial Statistic
LCL	Lower Control Level
LRAA	Locational Running Annual Average
LWL	Lower Warning Level
MCLG	Maximum Contaminant Level Goal
MG	Million Gallon
MGD	Million Gallon per Day
MRDL	Maximum Residual Disinfectant Level
MRDLG	Maximum Residual Disinfectant Level Goal
MRL	Method Reporting Level

MTZ	Mass Transfer Zone
NIST	National Institute of Standards and Technology
NOM	Natural Organic Matter
O&M	Operations and Maintenance
RAA	Running Annual Average
Rd	Road
RPD	Relative Percent Difference
SDWA	Safe Drinking Water Act
SM	Standard Method
SP	Standpipe
SV	Sample Volume
TFE	Tetrafluoroethylene
TOC	Total Organic Carbon
UCF	University of Central Florida
UCL	Upper Control Level
US	United States
UV	Ultraviolet
UWL	Upper Warning Level
VFD	Variable Frequency Drive
WTP	Water Treatment Plant

CHAPTER 1: INTRODUCTION

In the United States (US), public water purveyors are tasked with providing safe drinking water at an affordable cost to the consumer. The critical process step in water treatment plants (WTP) is disinfection, which requires the inactivation of pathogenic microorganisms (primary disinfection) and the maintenance of a stable disinfectant residual in the distribution system (secondary disinfection) (Crittenden, et al., 2005). Although disinfection has significantly decreased consumer exposure to waterborne diseases throughout the US, the same unit process is responsible for an increase in consumer exposure to disinfection by-products (DBPs) (Reynolds & Richards, 1996).

DBPs, many of which are suspected chronic carcinogenic compounds, are formed when natural organic matter (NOM) chemically reacts with a disinfectant (Richardson, et al., 2007). Due to the growing health concerns with DBPs, the Environmental Protection Agency (EPA) enacted the Stage 1 (1998) and Stage 2 (2006) Disinfectant and Disinfection By-Products Rules (D/DBP Rules). Aimed at reducing the public's exposure to high levels of DBPs, the DBP Rule set the maximum contaminant level (MCL) for total trihalomethanes (TTHMs) at 80 µg/L and haloacetic acids (HAA_5) at 60 µg/L (USEPA, 2010). In order for utilities to comply with the DBP Rule while providing adequate disinfection, five approaches have emerged: (i) reduction of disinfectant dose and residual, (ii) improved distribution system management, (iii) implementation of alternative primary and/or secondary disinfectants, (iv) reduction of NOM concentrations prior to disinfection, and (v) removal of formed DBPs (Clark, et al., 1994; Crittenden, et al., 2005).

Each of the approaches presented have associated advantages and disadvantages. The first three DBP control options (i, ii, iii) often are the most economical, but are limited by disinfection requirements and infrastructure capabilities. DBP control strategy (iii) has been widely adopted to comply with the current DBP Rule, but may create future problems as regulations expand to cover non-chlorine based DBPs. The last two tactics for DBP control (iv and v) usually improve the overall water quality for the consumer, but require higher capital and O&M investment. Ultimately, utilities must select the appropriate method(s) to maximize DBP control, minimize operation and maintenance (O&M) costs, and maintain adequate primary and secondary disinfection.

The research presented in this document had two major goals: (1) expand the body of knowledge in the field of DBP control for volcanic surface waters with high NOM concentrations, and (2) develop a cost-effective and practical treatment operating parameter to serve as an indicator that operators would use to alter process flow and treatment set points. Through a partnership between the University of Central Florida (UCF) and the County of Maui Department of Water Supply (DWS), the project's research objectives investigated the implementation of DBP control strategies (iv) and (v), on the island of Maui, Hawaii.

CHAPTER 2: LITERATURE REVIEW

In response to growing public concern with regards to drinking water, President Ford signed into law the Safe Drinking Water Act (SDWA) in 1974 (Hendricks, 2006). Overseen by the EPA, the SDWA established enforceable drinking water maximum contaminant levels (MCLs) for contaminants with known or suspected detrimental effects to human health (USEPA, 2015). As research into drinking water contaminants evolved, DBPs continued to be found in water supplies, many of which were suspected carcinogens (Hendricks, 2006; Richardson, et al., 2007; Kim, et al., 2002). Consequently, the SDWA was further amended to control and reduce public exposure to DBPs.

EPA DBP Regulations

The Stage 1 Disinfectants and Disinfection Byproducts (D/DBP) Rule came into effect in 1996 and established: (i) maximum residual disinfection levels (MRDLs) and goals (MRDLGs) for disinfectants, (ii) MCLs and maximum contaminant level goals (MCLGs) for DBPs, and (iii) a running annual average (RAA) sampling procedure for monitoring and compliance. The Stage 1 D/DBP Rule was prepared to focus on chlorine DBPs, and set the MCL for TTHMs at 80 µg/L and for HAA_5 at 60 µg/L (USEPA, 2010). TTHMs is the sum of chloroform, bromodichloromethane, dibromochloromethane, and bromoform concentrations in a water sample. HAA_5 refers to the sum of the concentrations of monochloroacetic acid, dichloroacetic acid, trichloroacetic acid, bromoacetic acid, and dibromoacetic acid in a water sample. At the same time, the Interim Enhanced Surface Water Treatment Rule (IESWTR) was enacted to balance the need for further treatment to reduce the health risk presented by microbial contaminants, such as *Cryptosporidium* and *Giardia*, and potential increases in DBPs.

In 2006, the Stage 2 D/DBP Rule was enacted, modifying the 1996 Stage 1 D/DBP Rule. One of the primary revisions introduced by the 2006 amendment involved modifying the use of a running annual average (RAA) based on sampling four locations each quarter to a locational running annual average (LRAA) for compliance determinations. In addition, new classes of DBPs were added. Under the new sampling requirements, sampling points are selected based on an initial distribution system evaluation (IDSE) in order to identify high DBP risk locations. Table 1 contains a summary of the Stage 2 D/DBP Rule.

Table 1: Regulated Contaminants and Disinfectants

	Stage 2 DBPR	
Regulated Contaminants	MCL (mg/L)	MCLG (mg/L)
TTHM	0.08	
Chloroform		0.07
Bromodichloromethane		Zero
Dibromochloromethane		0.06
Bromoform		Zero
HAA_5	0.06	
Monochloroacetic acid		0.07
Dichloroacetic acid		Zero
Trichloroacetic acid		0.2
Bromoacetic acid		-
Dibromoacetic acid		-
Bromate	0.01	Zero
Chlorite	1.0	0.8
Regulated Disinfectants	MRDL (mg/L)	MRDLG (mg/L)
Chlorine	4.0 as Cl_2	4
Chloramines	4.0 as Cl_2	4
Chlorine Dioxide	0.8	0.8

*(Adapted from USEPA, 2010)

DBP Formation Chemistry

DBPs are formed through the chemical interaction between a disinfectant and NOM (Crittenden, et al., 2005; Kawamura, 2000). As illustrated by Figure 1, DBP formation chemistry is influenced by several factors including: (i) water pH, (ii) water temperature, (iii) contact time, (iv) chlorine residual concentration, (v) total organic carbon (TOC) concentration, and (vi) presence and concentration of bromide (Sadiq & Rodriguez, 2004).

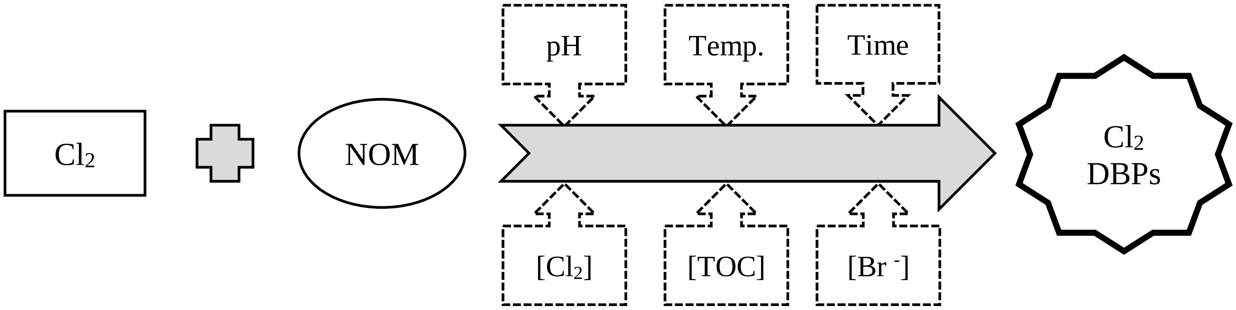

Figure 1: Factors Affecting DBP Formation

Water pH can affect the speciation and quantity of DBPs formed. At alkaline pH TTHM formation is favored, while at acidic pH HAA_5 formation is favored (Kawamura, 2000). Studies have shown that neutral waters produce the highest concentrations of DBPs (Crittenden, et al., 2005; Kim, et al., 2002). Another important difference between TTHMs and HAA_5 is that HAA_5 can be biologically degraded, which can cause an eventual decrease in HAA_5 concentration with time. DBP formation is enhanced at elevated water temperatures through increased reaction rates. Similarly, long distribution system water ages increase the contact time available for chlorine and NOM to form DBPs. NOM speciation and concentration significantly impacts DBP formation as certain NOM fractions are more reactive in the presence of a disinfectant (Reckhow & Singer, 1990). Additionally, the presence of bromide in a disinfected water produces brominated DBPs which are suspected to be more carcinogenic than chlorinated DBPs (Richardson, et al., 2007).

As previously discussed, the Stage 2 D/DBP Rule set forth MCLs for the two main chlorine DBPs, TTHMs and HAA_5 (USEPA, 2010). Nevertheless, public utilities must maintain proper pathogen inactivation through disinfection. Thus, strategies for DBP compliance were developed aimed at striking an adequate balance between microbial and pathogenic control and DBP control.

DBP Control Strategies

Utilizing the six key parameters affecting DBP formation, five major strategies for controlling DBP formation in a water distribution system have been reported by Crittenden and colleagues (2005). As shown on Figure 2, DBP control can be achieved by employing one or more of the following strategies: (i) decreasing chlorine dose and residual, (ii) decreasing water age through distribution system management, (iii) implementing an alternative primary and/or secondary disinfectant, (iv) enhancing water treatment to reduce DBP precursor levels prior to disinfection, and (v) remove DBPs after they are formed (Crittenden, et al., 2005). Clark, et al. (1994) found that the least expensive approach to DBP control were (i) and (ii), the least desirable was (v), and the most effective (iv).

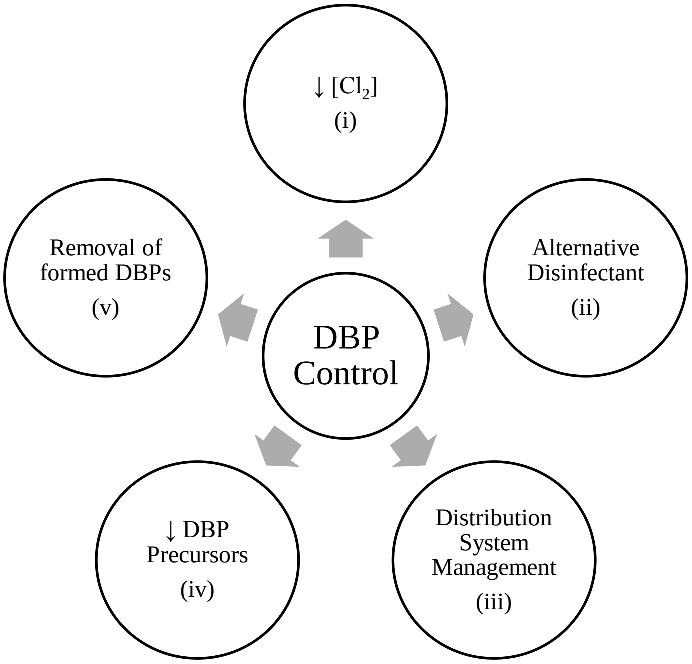

Figure 2: DBP Control Strategies

Reducing Chlorine Dose and Residual

Reducing chlorine dose and residual has been shown to decrease the quantity of DBPs formed, but is a DBP control strategy with strict limits. Water disinfection is a necessary step in a water treatment plant for the inactivation of pathogenic microorganisms, which cause diseases such as cholera and typhoid. Therefore, there is a limit to how low the chlorine dose and residual can be reduced at a water treatment plant for DBP control. Chlorine dose and residual adjustment is typically used in conjunction with one or more strategies in order to achieve compliance levels for the Stage 2 D/DBP Rule.

Alternative Disinfectant

Notably, disinfection can be separated into two phases, primary disinfection and secondary disinfection. Primary disinfection consists of the disinfectant dose required for the oxidation of compounds in water, also referred to as demand (Reynolds, et al., 1996). Compounds oxidized by primary disinfection are reducing agents like iron, manganese, sulfide, nitrite, and others. Secondary disinfection refers to the amount of disinfectant dosed above the demand, in order to generate a stable free residual for the distribution system. The main objective of secondary disinfection is the suppression of bacteriological regrowth and other forms of contamination in finished water flowing through a distribution system.

As a result, the use of alternative disinfectants to replace primary or secondary disinfection has been a popular strategy for meeting EPA DBP regulations. Water purveyors can replace the use of chlorine for primary disinfection to treat water with chlorine dioxide, ozone, and ultraviolet (UV) irradiation (Crittenden, et al., 2005; Sawyer, et al., 2003;Kawamura, 2000). The primary alternative secondary disinfectant typically used is monochloramine. Alternative disinfectants can significantly reduce the generation of regulated DBPs, but have limitations of their own. Chlorine dioxide disinfection leads to the formation of chlorite and chlorate ions, which are also regulated due to their potential health risks. Ozone can be used as a primary disinfectant in the absence of significant bromide levels, but cannot be used as a secondary disinfectant as it does not produce a stable residual. Similarly, UV irradiation is an effective primary disinfectant, but produces no residual. The most commonly used disinfectant alternative today are chloramines due to their low formation yield of regulated DBPs. Yet, chloramine DBPs have come under increasing scrutiny and may soon be regulated due to their higher genotoxicity when compared to chlorine DBPs (Bougeard, et al., 2010; Richardson, et al., 2007).

Distribution System Management

Another DBP control route public water purveyors have at their disposal is distribution system management. While the previous two strategies target disinfectant residual level and type to control DBPs, distribution system management targets the DBP formation factors water pH, temperature, and contact time. As previously stated, DBP formation and speciation is affected in large part by water pH. Alkaline waters favor TTHM formation, acidic water favor HAA_5 formation, and neutral waters yield the highest formation potential (Crittenden, et al., 2005; Kim, et al., 2002). The addition of a pH adjustment step before or after disinfection can help utilities control DBP formation and speciation throughout their distribution system.

Furthermore, DBP formation is a continuous reaction between available NOM and disinfectant. As long as there is disinfectant residual and NOM in the water, DBPs will continue to form, albeit less amounts will form. Thus, tactics such as reducing water age by eliminating dead ends in a pipeline and employing routine flushing events can help control DBP formation. Finally, although usually not economically feasible, DBP formation can be control by reducing distribution system water temperatures. Colder water temperatures inhibit DBP formation as reaction rates, which are temperature dependent, are reduced.

Removing Precursors and DBPs

The last two strategies for DBP control available to utilities are to improve the removal of DBP precursors and remove formed DBPs. Although these two strategies can be more effective at successfully controlling DBPs in a distribution system, they generally require larger capital investments and increased O&M costs. Improved removal efficiencies for DBP precursors has been shown to be possible with enhanced coagulation, granular activated carbon (GAC) filtration, and membranes (Badawy, et al., 2012; Kim & Kang, 2008; Reckhow & Singer, 1990). Technologies available for the removal of formed DBPs include GAC filtration, biologically active GAC filtration, and spray aeration (Kawamura, 2000). Although GAC and biologically active GAC filtration can be used to treat TTHMs and HAA_5, spray aeration is an effective technology for TTHM removal only due to their favorable Henry's Law constants (Clark, et al., 1994;

Nicholson, et al., 1984). However, Duranceau and Smith (2016) found that TTHM removal efficiency through spray aeration decreases in the presence of bromide.

Applicable DBP Treatment Technologies

GAC Technology

In response to stricter regulations for organic contaminants and DBPs, GAC filters became a popular treatment choice in drinking water treatment. GAC treatment is governed by the principles of adsorption, where the organic contaminant in water is the adsorbate and the GAC is the adsorbent (Sawyer, et al., 2003). There are two types of adsorption, physical adsorption and chemical adsorption or chemisorption. In drinking water treatment, physical adsorption is the main pathway for removal of contaminants and is limited by the absorbent's surface area and the mass transfer rate (Crittenden, et al., 2005). Physical adsorption relies on weak forces, such as van der Waals forces, to bind and trap organics in the pores of the absorbent. Although the bound organics are free to move along the surface of the GAC granule, the van der Waals forces are strong enough to form superimposed layers of contaminants on each site, increasing the removal capacity of the media (Crittenden, et al., 2005; Sawyer, et al., 2003).

In terms of operations, there are three important treatment concepts in a GAC system: (i) the mass transfer zone (MTZ), (ii) breakthrough, and (iii) exhaustion. GAC systems are similar in nature to sand filters, with the exception that they tend to have longer lengths. The MTZ on a GAC contactor unit is the area of media where equilibrium has not been reached and the adsorbate is being actively transferred, or deposited, on the absorbent (Reynolds, et al., 1996). As the sites on a GAC unit become saturated, the MTZ continuously moves down the GAC contactor column until breakthrough occurs. Breakthrough is defined as the point at which the concentration of the contaminant in the effluent reaches a preset value (Reynolds, et al., 1996). Contaminant removal continues to occur inside the contacting bed after breakthrough until the entire bed is saturated and equilibrium is reached.

Once equilibrium has been reached, due to the reversible nature of physical adsorption, contaminants can at times leach off of the absorbent and return to the water stream. Thus, effluent contaminant concentrations become nearly equal to influent contaminant concentration and the bed is said to have reach exhaustion (Reynolds, et al., 1996). An exhausted GAC contactor may still have contaminant removal capacity through biological degradation of organics as opposed to physical adsorption of organics. Although less efficient, biologically active GAC contactors have been shown to reduce TOC concentrations and thus extend the life of the bed (Netcher & Duranceau, 2016; Crittenden, et al., 2005). Whether the removal technique is biological degradation or physical adsorption, GAC contactors need to be frequently backwashed to maintain adequate operating pressure drops as the filter becomes clogged with suspended matter and biological growth (Hendricks, 2006).

The major drawback to GAC treatment is the high O&M costs associated with regeneration or replacement of the media (Kawamura, 2000). GAC filter bed life is largely dependent on influent water quality. At approximately $2,000 per ton, GAC replacement costs can quickly render the technology economically impractical to implement (Kawamura, 2000). Another drawback to GAC is the requirement of lined steel contactors due to corrosive nature of damp carbon (Hendricks, 2006). Nevertheless, GAC is a powerful technology for the control of organics, DBP precursors, and DBPs and breakthrough models have been established (Sulaymon, et al., 2010; Zachman & Summers, 2010).

Spray Aeration Technology

Due to the significant O&M costs associated with GAC treatment for the removal of DBP precursors, the use of spray aeration for the control of TTHMs in distribution system water is increasing in popularity. Spray aeration has been employed at WTP to remove strippable contaminants from water, such as hydrogen sulfide. When spray aeration systems are implemented in tanks throughout a distribution system, the technology has been shown to decrease TTHM concentrations in water (Cecchetti, et al., 2014; Brooke, et al., 2011). This phenomenon can be explained through Henry's Law (Equation 1), which governs constituent equilibrium concentrations in gas-liquid interfaces (Sawyer, et al., 2003).

$$K_H = \frac{P_{gas}}{C_{equil}} \qquad \textbf{(1)}$$

Where:

K_H is the Henry's Law Constant at a given temperature

P_{gas} is the partial pressure of the constituent above the liquid

C_{equil} is the concentration of the dissolved constituent in liquid at equilibrium

In the case of dilute solutions and low gas pressures, the concentration of a dissolved constituent in a volume of liquid is directly proportional to the partial pressure of the constituent in the gas phase above the liquid (Ghosh, et al., 2015). The noticeable decrease in TTHM concentrations before and after spray aeration is due to the favorable Henry's Law constants associated with the TTHM species. Table 2 includes a list of Henry's Law constants for the regulated TTHM species. Chloroform, with has the highest Henry's constant of the four species, is the most volatile while bromoform is the least volatile. Waters whose chemistries favor chloroform formation can achieve high TTHM removal efficiencies with spray aeration treatment.

Table 2: Henry's Law Constants for Selected THM Species at 20°C and 1 atm pressure

Species Name	Chemical Formula	Henry's Law Constant (Dimensionless)	Source
Chloroform	$CHCl_3$	0.1500	Ghosh, et al., 2015
Bromodichloromethane	$CHCl_2Br$	0.0656	Ghosh, et al., 2015
Dibromochloromethane	$ChClBr_2$	0.0321	Ghosh, et al., 2015
Bromoform	$CHBr_3$	0.0219	Ghosh, et al., 2015

The spray aeration process can also be described by Two-Film theory (Equation 2), which describes the mass transport of solute across a gas-liquid interface using equilibrium principles as a driving force, to strip TTHMs from water (Hendricks, 2006). In Two-Film theory, the solute is transferred from the water to the air-water interface through diffusion driven by the concentration gradient between them. Afterwards, a concentration discontinuity occurs at the air-water interface based on Henry's law and the partitions of air (Crittenden, et al., 2005). Subsequently, the concentration gradient between the solute in the air-water interface and the air drives the solute to diffuse into the air. Once the solute reaches the air, the compound is said to have been stripped from the water and the treatment is complete.

$$N_A = K_L(C_b - y_b/H) \qquad \textbf{(2)}$$

Where:

N_A is the mass flux of constituent A across air-water interface

K_L is the overall mass transfer coefficient

C_b is the liquid-phase concentration of constituent A in the bulk solution

Y_b is the gas-phase concentration of constituent A in the bulk solution

H is the dimensionless Henry's Law constant

Diffusion driven processes are heavily reliant on concentration gradients and temperature to achieve high removal rates. Thus, the placement of the spray aeration unit in the distribution system and the use of air circulators can significantly increase removal rates and decrease TTHM concentrations for consumers. However, as previously mentioned, DBPs are formed continuously as long as there is NOM and disinfectant residual in the water. Therefore, careful consideration should be taken into the re-formation of TTHMs after spray aerations in particularly long distribution systems (Duranceau and Smith, 2016; Smith, 2015).

CHAPTER 3: EXISTING CONDITIONS

In contrast to groundwater WTPs, compliance with the Stage 2 D/DBP Rule has been more elusive for WTPs treating surface water. DBP formation potentials tend to be significantly higher for surface water plants due to the increased organic loading the treatment plant receives. Although there are several strategies for controlling DBPs, the effectiveness of their implementation is site specific. With this in mind, the University of Central Florida (UCF) partnered with the County of Maui DWS to assess the effectiveness of two DBP control methods – DBP precursor removal and TTHM removal – for a full-scale volcanic surface water treatment plant.

Pi’iholo WTP

The Pi’iholo WTP is an 8.0 MGD surface water treatment plant located at an elevation of approximately 2,860 ft on the slopes of Mount Haleakala on the island of Maui (Figure 3). Six raw water intakes throughout the Makawao State Forest watershed, and an additional intake fed by the Waikamoi Reservoirs’ overflow pipe, supply water to the 50 MG Pi’iholo raw water reservoir. Depending on raw water quality conditions, aluminum chlorohydrate (ACH) and/or polymer are added for coagulation and flocculation prior to filtration using anthracite-sand media filters. Historically, the filtered water was disinfected with chlorine and pH adjusted with soda ash (Na_2CO_3) to 8.8 pH units prior to being gravity fed into the distribution system (Figure 4).

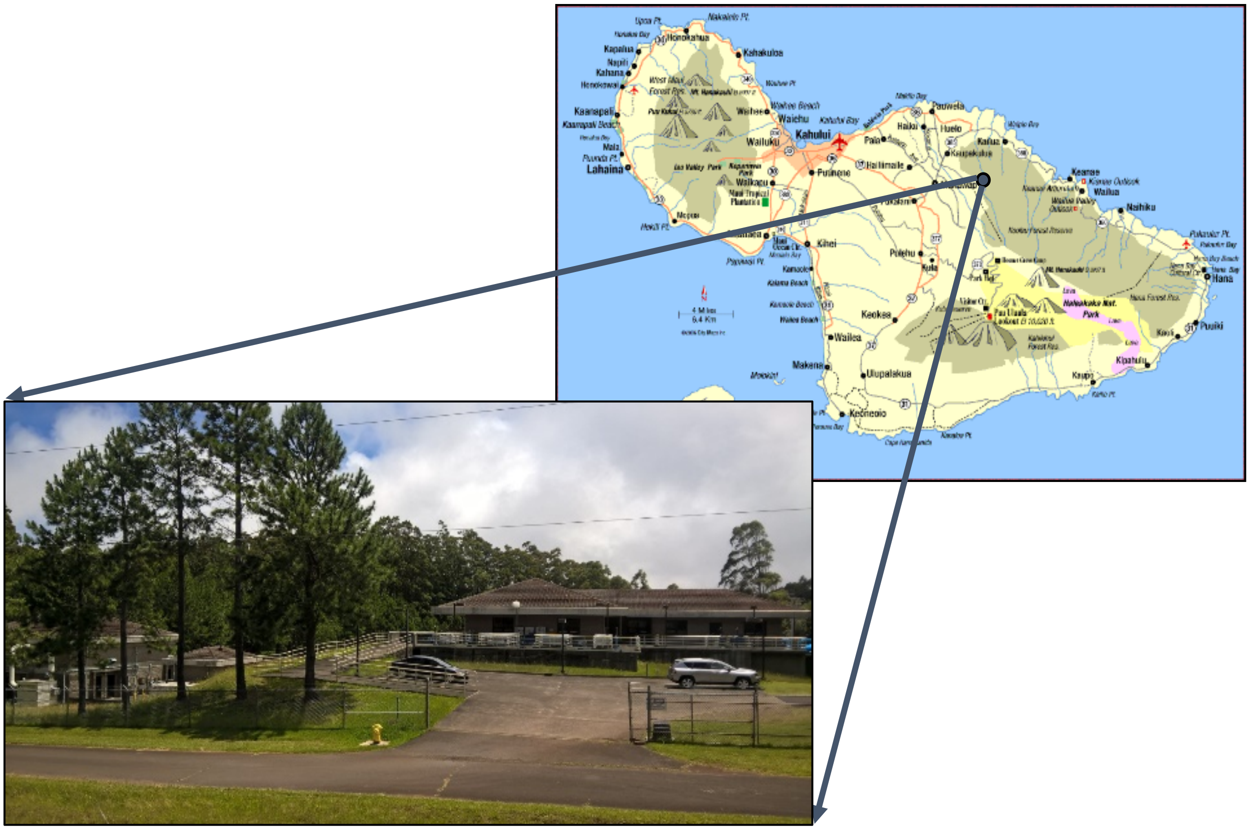

Figure 3: Pi'iholo WTP (Map adapted from Google Images)

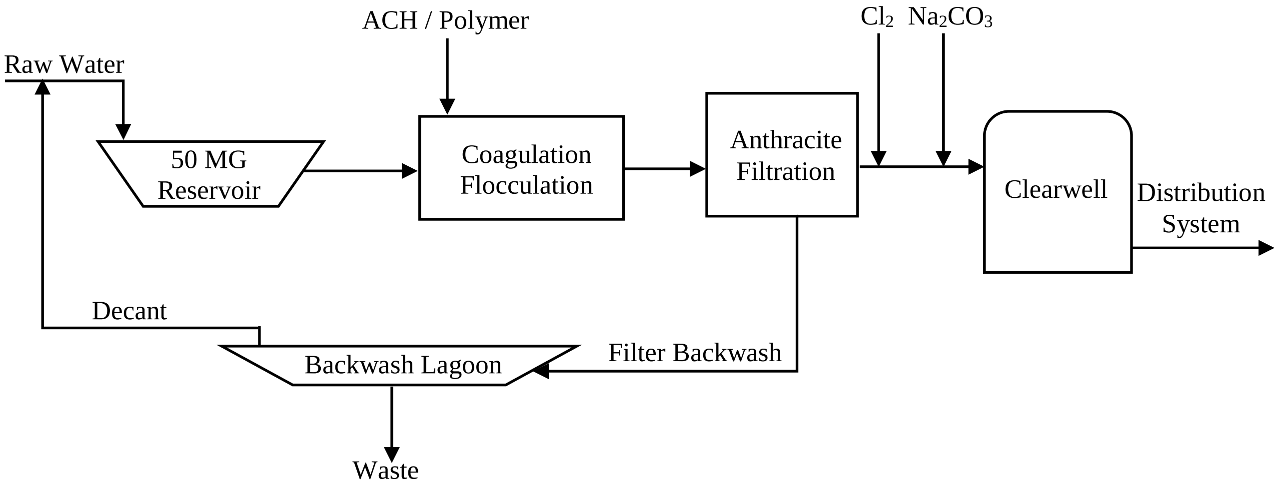

Figure 4: Historical Pi'iholo WTP Treatment Train Schematic

Due to high DBP levels and the enactment of the Stage 2 D/DBP Rule, the Pi’iholo WTP anthracite-sand filters were refurbished in May of 2014, and a 4.0 MG GAC system installed in March of 2015 (Figure 5). Figure 6 illustrates the current treatment train used at the Pi’iholo WTP, with the new GAC bypass. A fraction of the anthracite filter effluent is treated by parallel GAC trains composed of two vessels in series each. The effluent from the two GAC trains is mixed and blended back with the remainder of the anthracite filter effluent prior to disinfection and pH adjustment. The main objective of the GAC system is to reduce DBP precursors and thus control HAA_5 formation in the distribution system. Pi’iholo WTP supplies water to the Lower Kula distribution system, but can also feed the Makawao distribution system and be pumped into the Upper Kula distribution system.

Figure 5: Pi'iholo WTP 4.0 MG GAC System

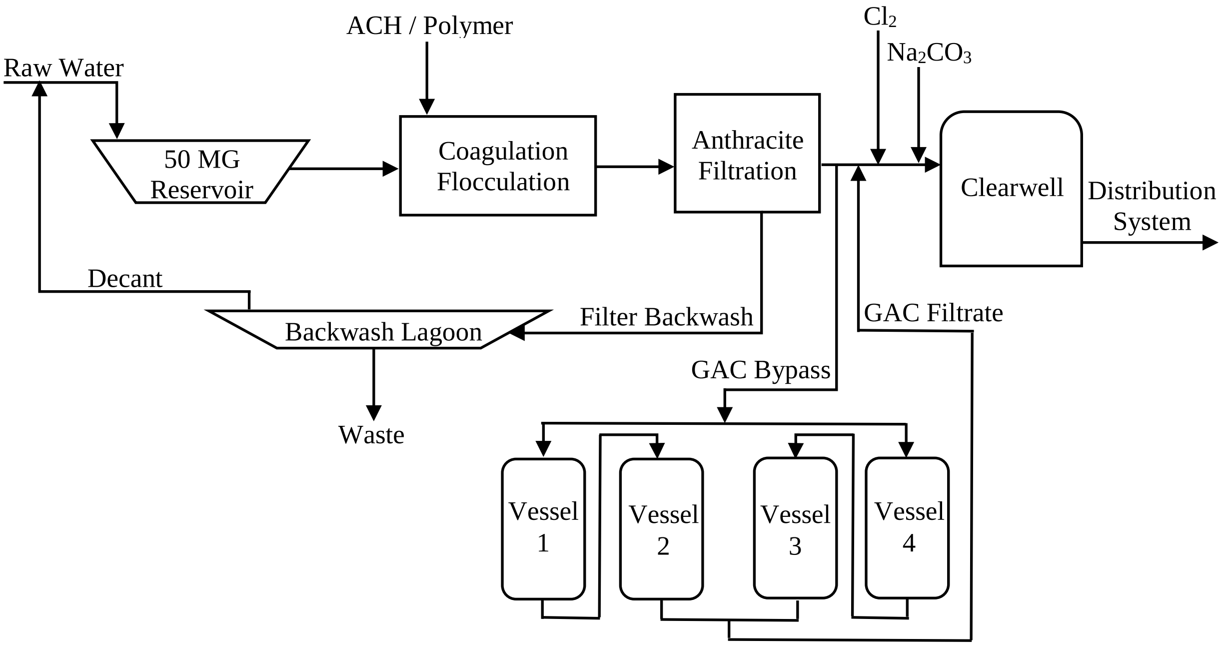

Figure 6: Current Pi'iholo WTP Treatment Train Schematic

Lower Kula Distribution System

The Pi'iholo WTP is the mid-elevation plant (2860 ft) serving the Lower Kula system in Upcountry Maui. In the Upcountry system, the three distribution systems are interconnected and are able to transfer water during times of drought. Although the Makawao and Lower Kula systems operate using free chlorine as the secondary disinfectant, due to high formation potentials, the Upper Kula system relies on chloramines for secondary residual. Pi'iholo has the ability to provide water to the three systems, but in times of drought, the Kamole WTP is used to supply water to both the Lower and Upper Kula systems.

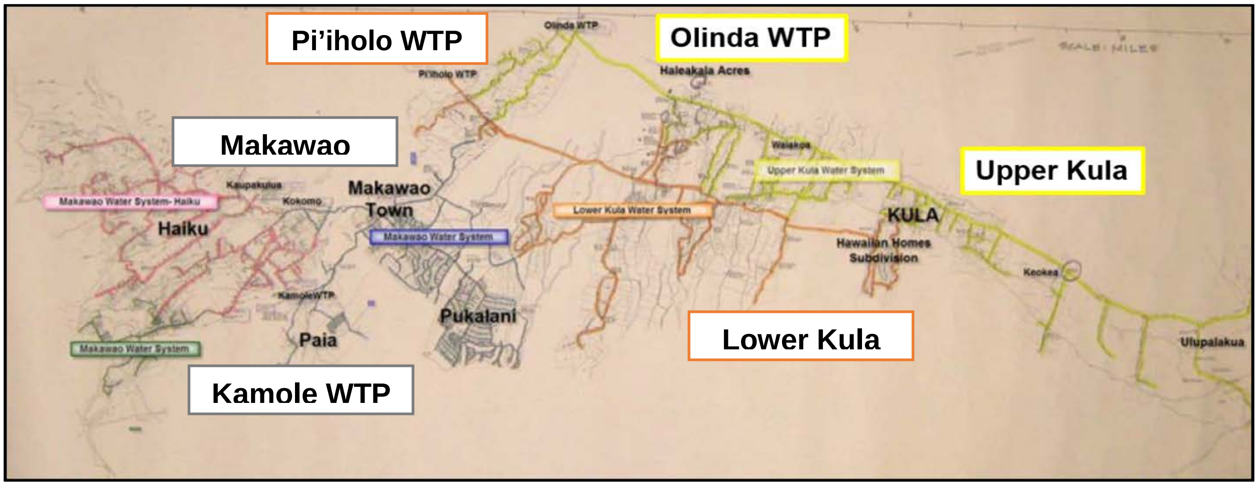

Figure 7: Upcountry Maui Distribution System Map (Adapted from Davis, et al., 2008)

Roughly serving a population of 7,000, the Lower Kula system has an approximate water age of 4 days measured from the Pi'iholo WTP to the furthest point in the system, which is the Hawaiian Homes Subdivision. In order to control TTHM levels throughout the Lower Kula distribution system, a GridBee® spray aeration system was installed at the first distribution system tank, Brooks Tank. The spray aeration system can operate at no capacity (offline), half capacity (1 blower), and full capacity (2 blowers). Pilot tests performed by DWS with the help of UCF determined that TTHM levels would be primarily controlled through spray aeration and HAA_5 formation would be controlled through GAC (Rodriguez and Duranceau, 2016).

CHAPTER 4: METHODOLOGY

This research focused on the assessment of two DBP control technologies, GAC for DBP precursor removal and spray aeration for TTHM removal, on a full-scale surface water treatment plant.

Experimental Set-up

To evaluate the cost effectiveness of the DBP control methods employed at the Pi'iholo WTP, the study was separated into two main objectives: (1) an assessment of the efficiency of the DBP control methods, and (2) an O&M cost analysis of the DBP control methods. Table 3 summarizes the data gathering timespans, utilizing UCF and DWS datasets, used to achieve the research goals. As shown on Figure 8, spray aeration was evaluated for TTHM reduction, GAC for HAA_5 reduction, and the concerted effort of both technologies for system DBP reduction. The development of a procedure to establish a treatment indicator parameter for DBP control maximization and O&M cost minimization was also studied.

Table 3: Data Gathering Timespan for Research Objectives

Research Objective	Data Gathering Timespan
Efficiency assessment of DBP control methods	08/2011 to 08/2016
Cost analysis of DBP control methods	08/2015 to 08/2016

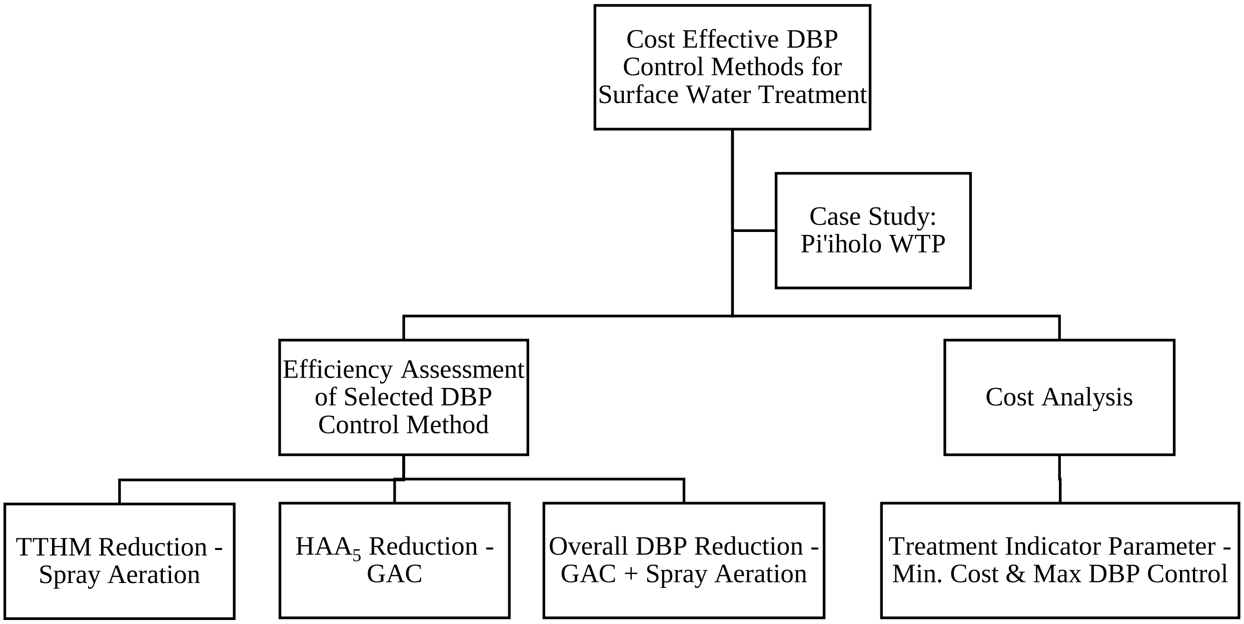

Figure 8: Experimental Set-Up

Selected Water Quality Parameters

To achieve a comprehensive analysis of the DBPs formation in the Lower Kula system, several water quality parameters were monitored. Table 4 lists the water quality parameters monitored in the distribution system, as well as the water quality parameters monitored at the Pi’iholo WTP. Water quality analysis were conducted in accordance to Standard Methods for the Examination of Water & Wastewater (Eaton, et al., 2005) and have been summarized in Appendix A. Bromide was not monitored for this project as sampling determined bromide to be absent from the source water.

Table 4: Water Quality Monitoring Matrix

Location	TTHM (μg/L)	HAA_5 (μg/L)	pH	Temperature (°C)	TOC (ppm)	Cl_2 (mg/L)	UV_{254} (cm^{-1})
Lower Kula	✓	✓	✓	✓	✓	✓	
Pi’iholo			✓	✓	✓	✓	✓

Identified Treatment Scenarios

A full-scale assessment of GAC for precursor removal and spray aeration for TTHM stripping as control strategies for DBP formation was conducted using information collected at the Pi’iholo WTP and Brooks storage tank system. The selected technologies were implemented in a step-wise manner, with the spray aeration system coming online in February of 2013 and the GAC system being placed online in March of 2015. Furthermore, the spray aeration system operated at half capacity from start-up until March of 2016. Based on the implementation dates for the DBP control technologies, four treatment scenarios were evaluated: (1) Historical, (2) GridBee® at half capacity, (3) GridBee® at half capacity with GAC, and (4) GridBee® at full capacity with GAC. Figure 9 illustrates the treatment scheme used during the each of the four treatment scenarios, respectively. Treatment scenario 3 was used to develop a DBP formation model based on an indicator parameter, and treatment scenario 4 was used to validate the model.

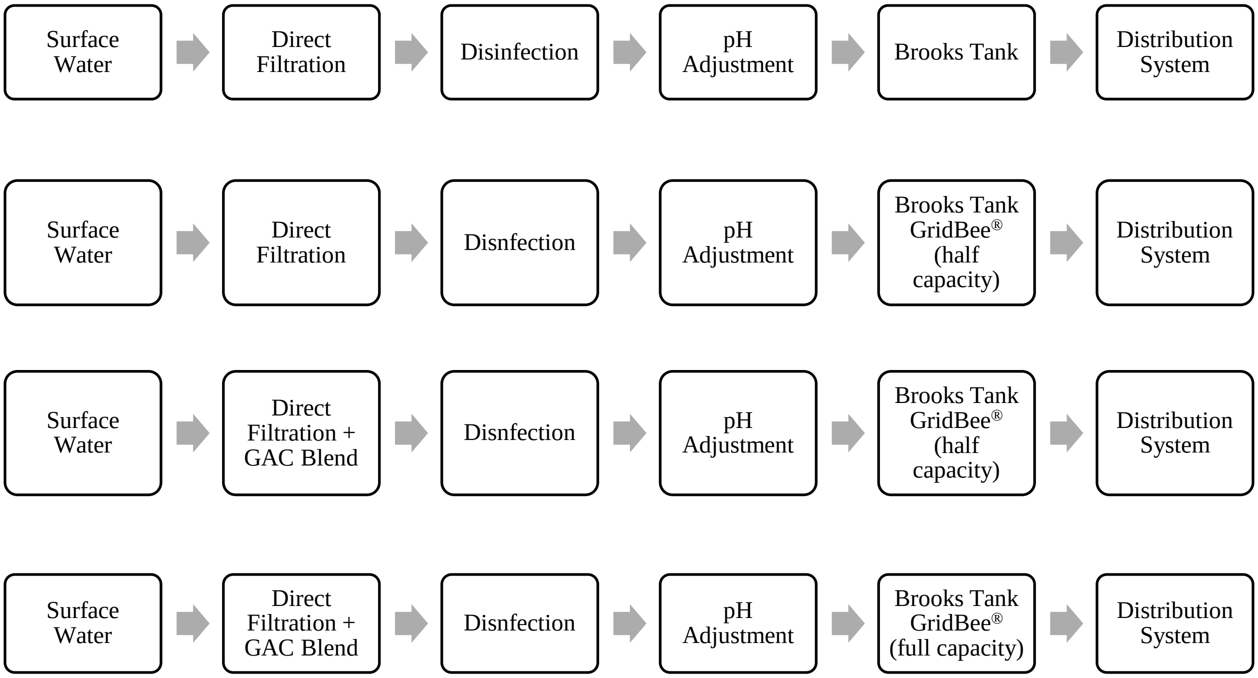

Figure 9: Treatment Scenarios Identified for DBP Control Assessment

Lower Kula Distribution System Sampling Sites

For the purpose of this study, eight sites throughout the Lower Kula distribution system were selected for DBP monitoring. They were comprised of 4 compliance sites currently in use by the County of Maui DWS, and an additional 4 sites identified by UCF. The DWS compliance sites are Piliwale Rd SP 335, Kula Kai Hyd 89, Naalae Rd SP 320, and Pueo Dr Hyd 515. The additional four sampling sites (Ehu Rd SP 52, Brooks Influent, Brooks Effluent, and Pueo Dr Hyd 512) were selected by UCF, considering water age, to obtain an overview of the entire distribution system. Sample sites Brooks Influent and Brooks Effluent were primarily selected to assess the efficiency of the GridBee® system. Ehu Rd SP 52 was monitored to examine the DBP formation chemistry between the Pi'iholo WTP clearwell and the GridBee® system at the Brooks Tank. The LRAA site for the Lower Kula distribution system is Pueo Dr Hyd 515, which is the end of the line in the Hawaiian Homes Subdivision. Pictures of each sampling site are presented in Figure 10.

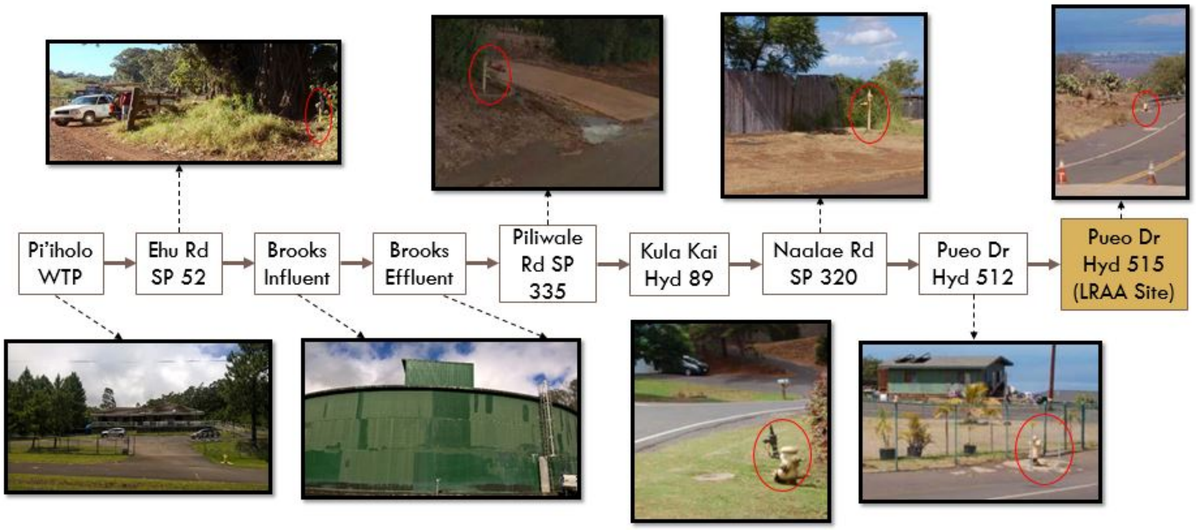

Figure 10: Lower Kula Distribution System Sampling Sites

<u>Sample Collection, Shipment, and Analysis</u>

On average, UCF performed 3 site visits per year for 5 years for data gathering purposes. Due to the study's location, planning for sample collection, preservation, and shipment was a vital part of this project. Glassware used for this project was cleaned at UCF using Decon™ Dri-Clean™ detergent (Fisher scientific, cat. # 04-355-75) and 1:1 hydrochloric acid, then rinsed with distilled water. In addition to being cleaned, amber glass bottles and vials were ashed at 400°C for 2 hours. Table 5 lists pertinent information on each of the chemical reagents used for this project. Sample collection and preservation were performed in accordance to <u>Standard Methods for the Examination of Water & Wastewater</u> (Eaton, et al., 2005) as summarized in Appendix A.

Table 5: Chemical Reagent Information

Chemical Name	Chemical Formula	Catalog #	Vendor	Primary Use
Sodium Sulfite	Na_2SO_3	S430-500	Fisher Scientific	TTHM Quenching
Ammonium Chloride	NH_4Cl	A661-500	Fisher Scientific	HAA_5 Quenching
Sodium Hypochlorite	NaOCl	LC246302	Fisher Scientific	Cl_2 Dosing
TTHM Calibration Mix	-	CRM47904	Sigma Aldrich	TTHM Analysis
DPD Free Cl_2 Powder Pillows	-	09-053-218	Fisher Scientific	Free Cl_2 Reading
pH 7.0 Buffer Solutions	-	SB107-20	Fisher Scientific	Standardization
pH 10.0 Buffer Solutions	-	SB115-500	Fisher Scientific	Standardization
pH 4.0 Buffer Solutions	-	SB101-500	Fisher Scientific	Standardization

Sample Collection and In-Situ Analysis

During each sampling event the following parameters were monitored at each Lower Kula Site: pH, temperature, TOC, free Cl_2 residual, TTHMs, and HAA_5. DBP samples were quenched immediately after collection to determine the instantaneous DBP concentration at each Lower Kula site. Collected TTHM samples were quenched by adding 1 mL of a 100 g/L solution of sodium sulfite to the bottle, making sure to have no air bubbles in the bottle after capping. HAA_5 samples were quenched using 1 mL of 50 g/L ammonium chloride, and checked for air bubbles after capping. If air bubbles were found, samples were uncapped and an additional couple of drops of quenching agent added to remove them.

Beakers were used to obtain water samples for on-site pH, temperature, and free Cl_2 readings. TOC samples were collected using 40 mL vials and analyzed at the Pi'iholo WTP lab.

Other pertinent data such as Brooks Tank water height, effluent rate, and Pi’iholo WTP effluent UV_{254} were collected at each sampling event. A sample data log sheet used for Lower Kula DBP sampling has been included on Appendix B.

Sample Shipment & DBP Analysis

Cleaned and ashed amber glass bottles and vials were transported to the Pi’iholo WTP ahead of each site visit in coolers using FedEx 2Day shipping. Glassware was carefully packed with bubble wrap and thawed iced packs, along with other sampling equipment listed on Table 6. At the end of the site visit, the samples were packed in coolers with bubble wrap and frozen ice packs and shipped back to UCF using FedEx 2Day shipping. The coolers received at UCF were carefully unpacked, and the samples were stored in a 4°C walk-in cooler in the drinking water laboratories until further analysis. TTHM samples were analyzed at UCF following Standard Method 6232B using hexane as the solvent. HAA_5 samples were sent to Advanced Environmental Laboratories (380 North Lake Blvd., Suite 1048, Altamonte Springs, FL 32701) for analysis.

Table 6: General Shipping Inventory

Item Name	Volume	Primary Use
Beakers	250 mL	pH/Temperature reading
Volumetric flask	100 mL	Quenching reagent preparation
Small amber bottle	60 mL	TTHM sampling
Medium amber bottle	250 mL	HAA_5 sampling
Clear or amber vial	40 mL	TOC sampling
Disposable plastic transfer pipette	2 mL	Sample quenching
Small labels	-	Vial labeling
Medium labels	-	Bottle labeling
Kimwipes	-	Sample drying
Paper towels	-	Sample drying
Ice packs	-	Sample cooling

Analytical Equipment

The analytical equipment used for this project, with pertinent information, has been tabulated on Table 7. Prior to each sampling event, the pH/temperature probe was standardized using pH buffer solutions. At each site, the colorimeter was tared using sample water. The online TOC analyzer at Pi’iholo was flushed and maintained by the operators daily. Standard curves were generated at UCF for each round of TTHM analysis. The chloroform detection level was 5 ppb, while the remaining three species had a 1 ppb detection level. Pictures of UCF’s gas chromatograph (GC) and Pi’iholo’s TOC analyzer has been included on Figure 11.

Table 7: Analytical Equipment Information

Equipment Name	Location	Make	Model	Analyte
Gas Chromatograph	UCF	Agilent Technologies	6890N	TTHM
Gas Chromatograph	Advanced Environmental Laboratories	Perkin Elmer	Clarus 500	HAA_5
pH/Temperature Probe	Pi’iholo	Eutech Instruments	pHTestr 30	pH/Temperature
TOC Analyzer	Pi’iholo	Sievers	5310 C	TOC
Portable Colorimeter	Pi’iholo	HACH	DR 820	Cl_2 Residual
Spectrophotometer	Pi’iholo	HACH	DR 6000	UV_{254}

Figure 11: UCF’s Gas Chromatograph (Left) and Pi’iholo’s TOC Analyzer (right)

Data Analysis And Cost Assumptions

In order to determine the cost effectiveness of spray aeration and GAC on DBP control at the Pi'iholo WTP, gathered data was analyzed utilizing Microsoft Excel. Statistical methods were used to interpret the data gathered and present the results of the research project (Mendenhall, et al., 2007). Mean, standard deviation, and sample variance were used to analyze data sets obtained throughout this research project. Equations 3, 4, and 5 illustrate the equations used to calculate the mean, standard deviation, and variance, respectively. Hypothesis testing was also used to ascertain the statistical significance between data sets acquired.

$$\bar{y} = \frac{\sum_{i=1}^{n} y_i}{n} \qquad \textbf{(3)}$$

$$s = \sqrt{s^2} \qquad \textbf{(4)}$$

$$s^2 = \frac{\sum_{i=1}^{n} (y_i - \bar{y})^2}{n-1} \qquad \textbf{(5)}$$

Where:

y_i is an observed measurement

n is the number of measurements

For the development of a treatment operating parameter to serve as an indicator for operators to adjust DBP treatment process flow set points, the obtained data set was split into two – 75% of the acquired data points were assigned to the training set and the remaining 25% to the validation set. TOC vs TTHM and TOC vs HAA_5 scatter plot were created utilizing the training data set. This analysis employed Pi'iholo anthracite filter effluent TOC concentrations plotted against TTHMs and HAA_5 concentrations at the LRAA site. TOC values were obtained by averaging the previous 4 days' (exclusive) TOC values for the filter effluent with respect to the DBP sampling date. Linear regressions were created to obtain a model for predicting DBP levels at the LRAA site based on filter effluent TOC. Coefficient of determination were computed for each linear regression using Excel (Equation 6). Using the validation data set, predicted TTHM and HAA_5 values were computed and compared to measured values. In order to validate the generated DBP model, hypothesis testing was used.

$$R^2 = 1 - \frac{SSE}{SS_{yy}} \qquad \textbf{(6)}$$

Where:

SSE is the sum of squared residuals

SS_{yy} is the sum of total squares

Projected annual O&M costs for the GridBee® and GAC were based on a monthly electrical bill for the GridBee® and a carbon change out bill for the GAC provided by the County of Maui DWS. Table 8 and Table 9 summarizes the provided costs data and assumptions made for the cost analysis of the GridBee® and the GAC, respectively.

Table 8: GridBee® O&M Cost & Assumptions

# of Aerators	# of Blowers	Duration	Total Cost
7	1	24 hours/day, 7 days/week	$15,000/month
Assumptions			
Electricity unit price in Maui, HI = $0.33/kWh			
Electricity rate is constant throughout year			
GridBee® kWh usage is constant throughout year			
Maintenance work cost not included			

Table 9: GAC O&M Cost & Assumptions

Vessel Capacity	Unit Price	# of Vessels	Carbon Cost	Removal & Disposal Cost	Total Cost
30,000 lbs C / Vessel	$2.50/lb C	2	$150,000	$64,000	$241,000 / change out
Assumptions					
GAC system operated as two parallel trains, each with 2 vessels in series					
Carbon change out for 2 vessels required every 3 months					
Carbon change out cost constant throughout year					
Maintenance work cost not included					

Field and Laboratory Quality Control and Assurance

To ensure the quality of the data gathered for this project, method 1020B from Standard Methods for the Examination of Water and Wastewater was followed (Eaton, et al., 2005). One TOC, TTHM, and HAA_5 field duplicate sample for was collected for every 5 samples to ensure sampling technique precision. Lab analysis for TTHMs were replicated on every fifth sample to check equipment precision. Also, a lab TTHM spike was included to ensure equipment accuracy.

Equation 7 was used to calculate relative percent difference (RPD) for field TOC, TTHM, and HAA_5 duplicates, and lab TTHM replicates. In addition, Equation 8 was used to compute the industrial statistic (I-stat) between field duplicate samples and lab replicate samples. A precision control chart was developed for each statistic calculated to monitor variations in the sampling technique and lab equipment, and identify any outliers or quality control violations. Equation 9 and 10 were used to calculate the upper warning level (UWL) and upper control level (UCL) for the precision control charts, respectively.

$$RPD = \frac{|sample\ result - duplicate\ result|}{(sample\ result + duplicate\ result)/2} \times 100\% \qquad \textbf{(7)}$$

$$I = \frac{(sample\ result - duplicate\ result)}{(sample\ result + duplicate\ result)} \quad \textbf{(8)}$$

$$UWL = x_{avg} + 2s \quad \textbf{(9)}$$

$$UCL = x_{avg} + 3s \quad \textbf{(10)}$$

Where:

x_{avg} is the data set's average

s is the data set's standard deviation

To monitor equipment accuracy, % recovery for spiked TTHM samples was computed using Equation 11. An accuracy control chart was developed using the calculated % Recoveries. The UWL and UCL for the accuracy control chart were calculated in the same manner as in the precision control chart. A lower warning level (LWL) and lower control level (LCL) for the accuracy control chart was calculated using Equations 12 and 13, respectively. The developed precision and accuracy control charts for this study can be found on Appendix C.

$$\frac{(spiked\ sample\ result - sample\ result)}{spike\ concentration} \times 100\% \quad \textbf{(11)}$$

$$LWL = x_{avg} - \ 2s \quad \textbf{(12)}$$

$$LCL = x_{avg} - \ 3s \quad \textbf{(13)}$$

CHAPTER 5: RESULTS & DISCUSSION

At the Pi'iholo WTP, two DBP control measures were investigated: (1) precursor removal through GAC treatment, and (2) TTHM removal through spray aeration. The implemented DBP control technologies were assessed in terms of efficiency at controlling TTHM and HAA_5 levels in the Lower Kula distribution system and annual O&M cost. Using the results from the efficiency and cost evaluation, DBP formation models were developed to assist WTP operators maximize DBP control in Lower Kula while minimizing annual O&M costs.

Assessment of Implemented DBP Control Technologies

The County of Maui DWS has set MCLGs for the Lower Kula distribution system at 40 µg/L for TTHMs and 30 µg/L for HAA_5. As a result, the Pi'iholo WTP was retrofitted with GAC and a spray aeration system was placed into the distribution system. To evaluate the effectiveness of the implemented DBP control strategies, DBP data for the Lower Kula system was gathered by UCF and the County of Maui DWS between August of 2011 and 2016. For the efficiency evaluation, the compiled Lower Kula LRAA DBP data points were segregated into four data sets based on the four treatment scenarios identified. The raw DBP data collected for this analysis has been included in Appendix D.

Using the Excel descriptive statistics analysis, each data set's count, mean, minimum value, maximum value, variance, and standard deviation was calculated. The results from the statistical analysis has been included on Table 10 for TTHMs and Table 11 for HAA_5. A decrease in mean TTHM concentration at the LRAA site was identified between the first and second treatment scenario and the third and fourth treatment scenario. Comparatively, a decrease in mean HAA_5

concentration at the LRAA site was identified between the second and third treatment scenario and the third and fourth treatment scenario.

Table 10: TTHM LRAA Data Set Statistical Analysis

Treatment Scenario	Count	Mean ($\overline{y}$)	Minimum	Maximum	Variance (s^2)	Standard Deviation (s)
Historical	14.0	90.9	58.5	125	511	22.6
GridBee® at half capacity	18.0	58.5	41.5	75.4	129	11.3
GridBee® at half capacity with GAC	19.0	59.4	35.1	78.7	206	14.3
GridBee® at full capacity with GAC	7.0	38.5	33.5	46.3	24.4	4.94

Table 11: HAA_5 LRAA Data Set Statistical Analysis

Treatment Scenario	Count	Mean ($\bar{y}$)	Minimum	Maximum	Variance (s^2)	Standard Deviation (s)
Historical	14.0	39.6	21.2	52.0	79.3	8.90
GridBee® at half capacity	18.0	44.1	31.7	53.0	49.4	7.03
GridBee® at half capacity with GAC	19.0	29.4	21.8	45.7	35.4	5.95
GridBee® at full capacity with GAC	7.0	20.5	17.1	24.1	6.99	2.64

These results suggest that in the Lower Kula system, TTHM formation is controlled by the spray aeration system and HAA_5 formation is primarily controlled by the GAC system. Welsh's t-Test, also known as unequal variances t-Test, was utilized to statistical validate the hypothesis proposed. This modified t-Test (Welsh's t-Test) was selected as it can provide more reliable results when two samples have unequal variances and sample sizes (Ruxton, 2006). Equation 14 was utilized to calculate degrees of freedom for Welsh's t-test. The established null hypothesis was that there was no statistical difference in the mean LRAA TTHM and HAA_5 concentrations between the identified treatment scenarios. The alternative hypothesis was that there was a statistical difference in the mean LRAA TTHM and HAA_5 concentrations between the identified treatment scenarios. Welsh's t-tests were performed to evaluate the data sets at a confidence level of 95%.

$$\boldsymbol{v} = \frac{\left(\frac{s_1^2}{n_1}+\frac{s_2^2}{n_2}\right)^2}{\frac{s_1^4}{n_1^2(n_1-1)}+\frac{s_2^4}{n_2^2(n_2-1)}} \tag{14}$$

Where:

n_i is the sample size for the i^{th} data set

s_i is the standard deviation for the i^{th} data set

s_i^2 is the variance for the i^{th} data set

The results for the t-test have been compiled on Table 12 for TTHMs and Table 13 for HAA_5. With regards to the TTHM values, the null hypothesis was rejected for test # 1 and 3 as the calculated t-value was greater than the two-tail t-critical. The null hypothesis was not rejected on test # 2 because the t-value was less than the two-tail t-critical. For the HAA_5 data t- tests, the calculated t-value was greater than the two-tail t-critical on test # 2 and 3 leading to the rejection of the null hypothesis. Therefore, the hypothesis relating TTHM control to spray aeration and HAA_5 control to GAC was statistically validated.

A graphical representation of the mean LRAA DBP levels under each treatment scenario can be seen on Figure 12. The generated bar graph supports the findings of the t-test and include statistically significant percent reduction numbers between the treatment scenarios. A comparison between the TTHM levels in late-2012 and early-2016 for the 8 Lower Kula sites has been included in Figure 13. Similarly, Figure 14 shows a bar chart comparison between HAA_5 levels in mid-2014 and early-2016 for the 8 Lower Kula sites. In both cases, TTHM and HAA_5 levels at the LRAA site have gone from out of compliance with the Stage 2 D/DBP Rule to below the County of Maui DWS's MCLG of 40 µg/L and 30 µg/L, respectively.

Table 12: TTHM t-Test Summary

Test #	Data Set 1	Data Set 2	Degrees of Freedom (v)	Calculated t-statistic	Two-tail t-critical	Result	Reject Null Hypothesis? (Y/N)
1	Historical	GridBee® at half capacity	18.0	4.90	2.10	t-stat > t-critical	Y
2	GridBee® at half capacity	GridBee® at half capacity with GAC	35.0	-0.232	2.03	t-stat < t-critical	N
3	GridBee® at half capacity with GAC	GridBee® at full capacity with GAC	25.0	5.63	2.06	t-stat > t-critical	Y

Table 13: HAA_5 t-Test Summary

Test #	Data Set 1	Data Set 2	Degrees of Freedom (v)	Calculated t-statistic	Two-tail t-critical	Result	Reject Null Hypothesis? (Y/N)
1	Historical	GridBee® at half capacity	24.0	-1.57	2.06	t-stat < t-critical	N
2	GridBee® at half capacity	GridBee® at half capacity with GAC	34.0	6.91	2.03	t-stat > t-critical	Y
3	GridBee® at half capacity with GAC	GridBee® at full capacity with GAC	23.0	5.35	2.07	t-stat > t-critical	Y

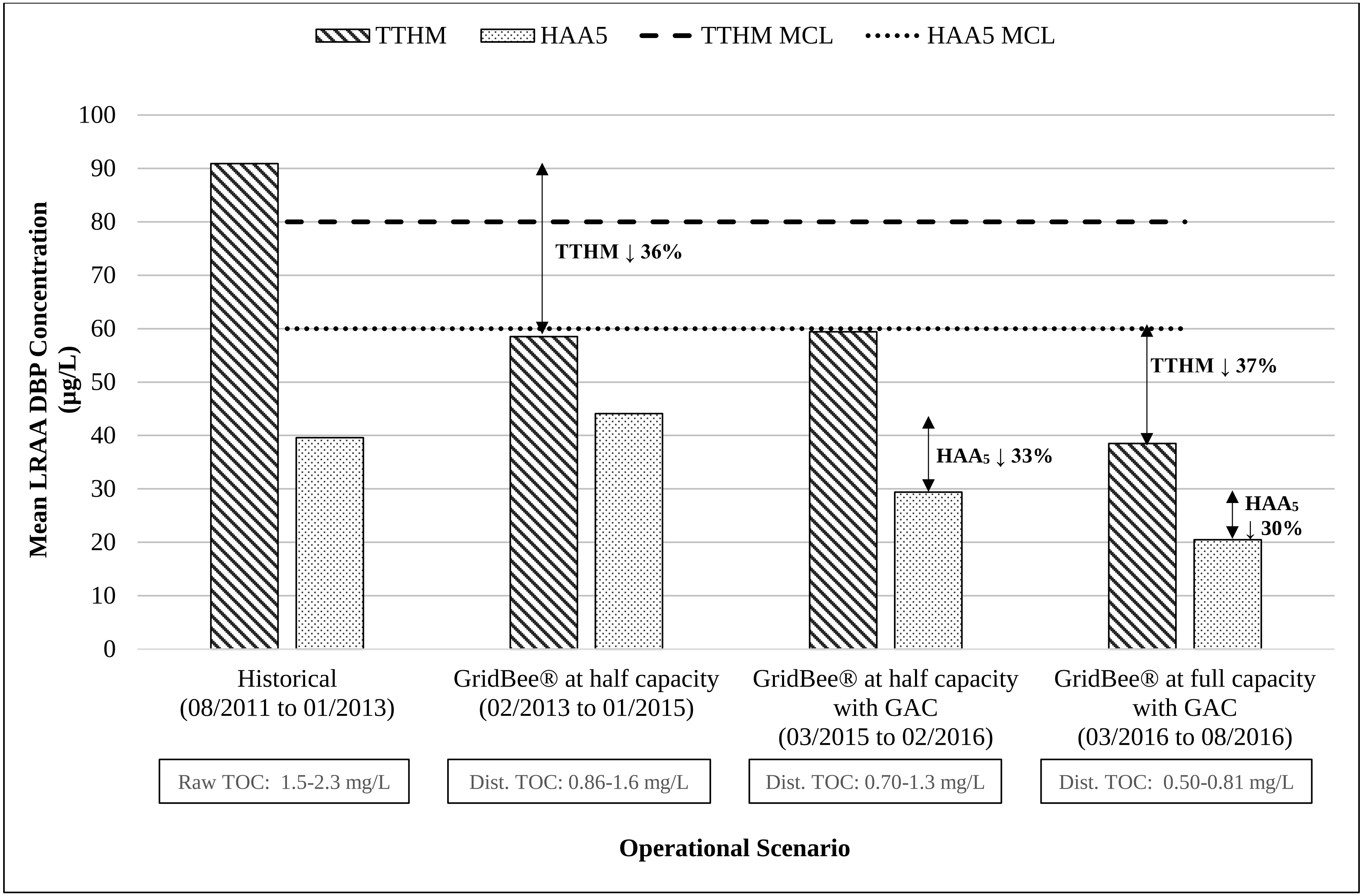

Figure 12: Pueo Dr Hyd 515 DBP Formation Analysis

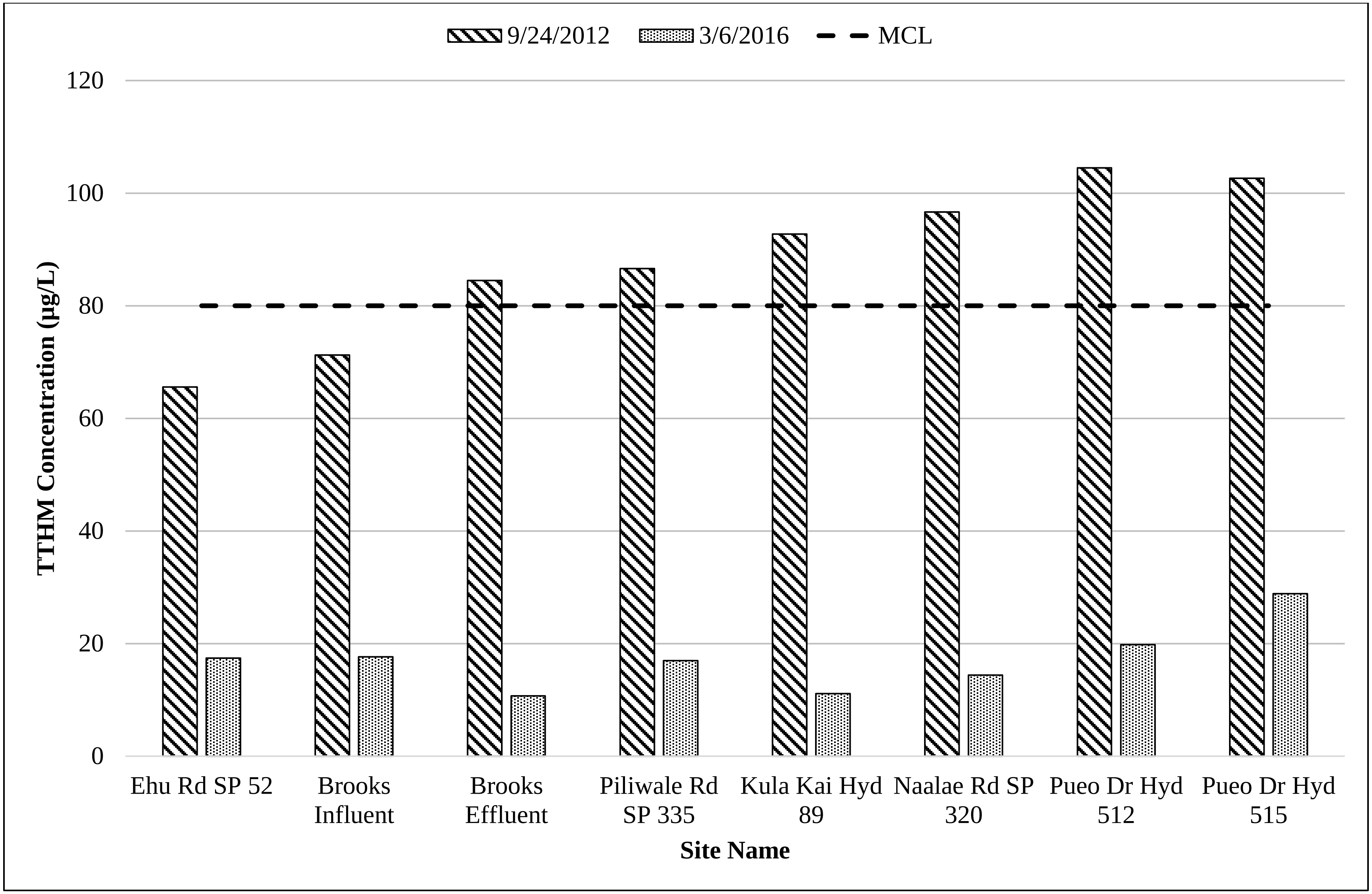

Figure 13: Lower Kula Distribution System TTHM Formation Comparison Analysis

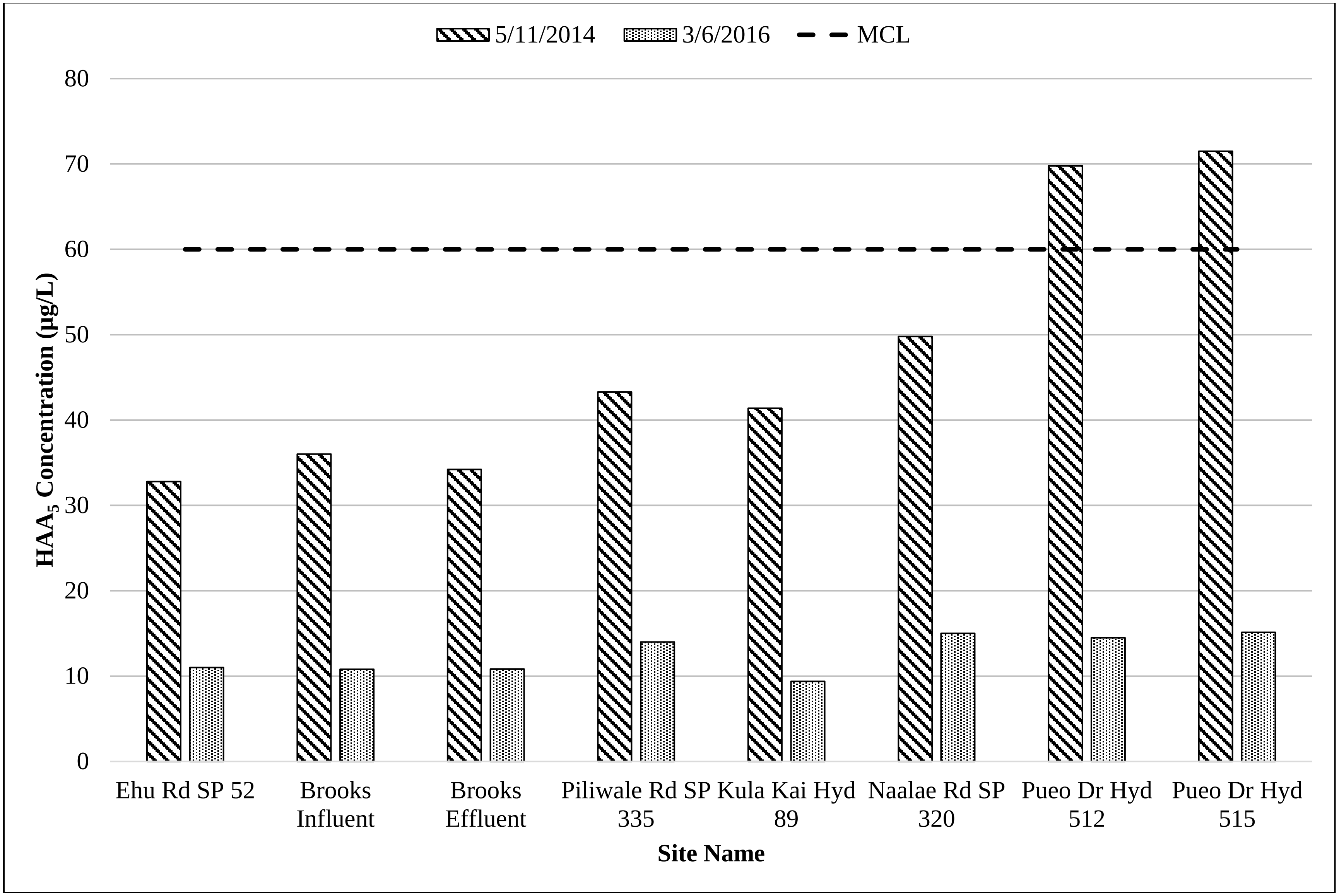

Figure 14: Lower Kula Distribution System HAA_5 Formation Comparison Analysis

Operational & Maintenance Cost Analysis

Utilizing the provided costs and assumptions on Table 8 and Table 9, O&M costs for the GAC system and GridBee® system were computed at 3-month intervals. Furthermore, individual and combined annual O&M cost were calculated. The results of the cost analysis has been tabularized on Table 14 and graphically represented in Figure 15. As can be seen from the bar chart, DWS's largest contributor to O&M costs, out of the two DBP control systems, is the GAC system. The projected combined O&M costs for the DBP control systems is above $1,000,000. Notably, the contribution from the GridBee® to the cumulative annual O&M cost is expected to increase as the electrical costs provided by DWS were based on the continuous operation of the GridBee® at half capacity. The GridBee® has been continuously running at full capacity since June of 2016.

Table 14: Projected O&M Costs

Time Frame	GAC System	GridBee® System	Combined
January to March	$214,000	$45,000	$259,000
April to June	$214,000	$45,000	$259,000
July to September	$214,000	$45,000	$259,000
October to December	$214,000	$45,000	$259,000
Annual	$856,000	$180,000	$1,036,000

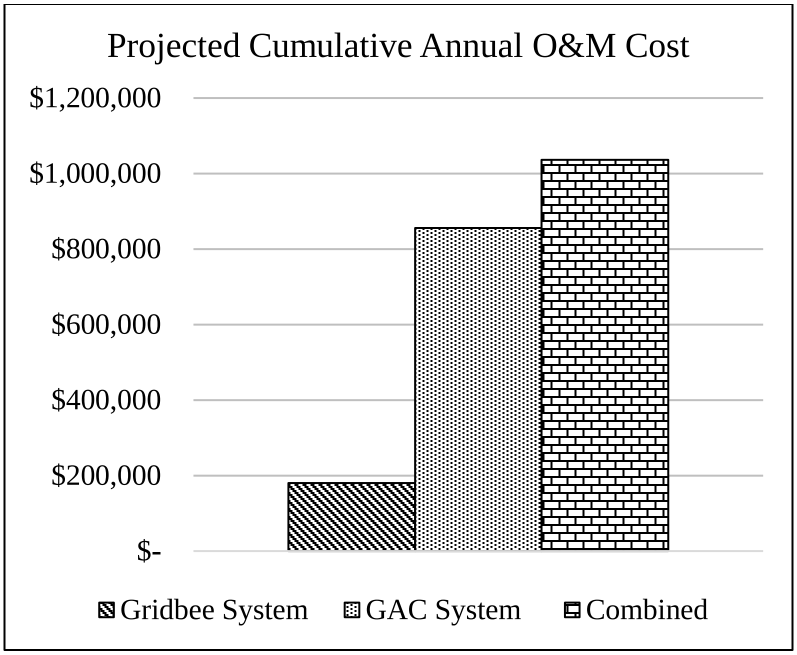

Figure 15: Projected Cumulative Annual O&M Cost

Identified Indicator Parameter For DBP Control & Cost Minimization

In light of the O&M cost results, the development of an indicator parameter to maximize DBP control while minimizing O&M costs was investigated. The Pi'iholo WTP is usually fed by the Makawao State Forrest watershed, but during times of drought Kamole WTP finished water is pumped to the raw water reservoir. To take into account the different water chemistries that the Pi'iholo WTP can experience, the anthracite filter effluent was selected as the sampling point. The filter effluent is upstream of both DBP control technologies, allowing for the single location to be the determinant in how to operate the process. The selected monitoring parameter was filter effluent TOC as previous studies have shown good correlation between TOC and DBPs (Pifer & Fairey, 2013).

The raw data was collected from August of 2015 to August of 2016 has been included in Appendix E. The data collection start date was identified based on the closure of Pi'iholo's raw water intake 1, which is fed by the overflow from the higher elevation Waikamoi reservoirs (high organic acid content). The data points were separated into two data sets, a training data set from August 2015 to March 2016 and a validation data set from June 2016 to August 2016. The data sets were identified based on the treatment scenario which they fell under – GridBee® at half capacity with GAC for the training set and GridBee® at full capacity with GAC for the validation set.

The training data set was visually analyzed by categorizing the data points based on TOC concentration ranges. The four identified groups can be found on Table 15 with the following TOC ranges: (1) 0.691 ppm – 0.742 ppm, (2) 1.00 ppm – 1.37 ppm, (3) 1.44 ppm – 1.59 ppm, and (4) 1.70 ppm – 2.00 ppm. Each group within the training set was statistically analyzed by calculating mean and standard deviations and the results were summarized on Table 16.

Table 15: Identified Filter TOC vs LRAA DBP Training Set Groups

Group #	Date	Season	Filter TOC (ppm)	TTHM (μg/L)	HAA_5 (μg/L)
1	8/14/2015	Dry	2.00	65.0	26.0
	8/26/2015	Dry	1.80	67.0	22.0
	9/4/2015	Dry	1.71	61.0	30.0
	8/6/2015	Dry	1.70	64.0	31.0
2	9/11/2015	Dry	1.59	58.0	27.0
	9/25/2015	Dry	1.55	52.0	27.0
	8/19/2015	Dry	1.50	53.0	24.0
	10/2/2015	Dry	1.48	56.0	35.0
	9/18/2015	Dry	1.44	57.0	25.0
3	11/13/2015	Wet	1.37	45.0	23.0
	10/9/2015	Dry	1.18	49.0	25.0
	11/6/2015	Wet	1.15	42.0	20.0
	10/29/2015	Dry	1.03	42.0	21.0
	12/18/2015	Wet	1.00	36.0	23.0
4	3/6/2016	Wet	0.742	28.8	15.2
	3/2/2016	Wet	0.691	25.3	30.4
		Mean	1.37	50.07	25.28
		Standard Deviation	0.376	12.6556	4.8537

Table 16: Analyzed Training Set

Pi'iholo Filter Effluent TOC Range (ppm)	Lower Kula LRRA Site Mean TTHM (µg/L)	Lower Kula LRRA Site Mean HAA_5 (µg/L)	Treatment Scenario #
0.69-0.74	27 ± 2.5	23 ± 11	3
1.0-1.4	43 ± 4.8	22 ± 1.9	3
1.4-1.6	55 ± 2.6	28 ± 4.3	3
1.7-2.0	64 ± 2.5	27 ± 4.1	3

With the exception of HAA_5's for the TOC range 0.69-0.74, standard deviations within the groups for TTHM and HAA_5 were below 5. As a result, a TOC-based treatment scheme was developed and can be found on Table 17. The TOC-based treatment scenarios projected no need for GAC treatment unless the filter effluent TOC was above 1.2 ppm. Furthermore, GridBee® at half capacity would be needed when TOC was between 0.75 ppm and 1.0 ppm and full capacity at TOC levels above 1.0 ppm.

Table 17: Estimated TOC-Based Treatment Scenarios

Pi'iholo Filter Effluent TOC Range (ppm)	Treatment
< 0.75	No GAC | No GridBee®
0.75 - 1.0	No GAC | 1 Blower
1.0 – 1.2	No GAC | 2 Blower
> 1.2	GAC | 2 Blowers

A scatter plot using the training set was generated, with the x-axis being TOC in ppm and the y-axis being LRAA TTHM or HAA_5 in µg/L. Two points from the TOC vs HAA_5 scatter plot were removed because they were suspected outliers (0.691ppm, 30.4 µg/L and 1.48 ppm, 35 µg/L). As shown on Figure 16, linear trend lines were added to both data sets to obtain model equations.

The R^2 for the TOC vs TTHM and TOC vs HAA_5 trend lines were found to be 0.93 and 0.52, respectively. Equation 15 and Equation 16 describe the developed filter effluent TOC models for Lower Kula LRAA TTHM and HAA_5, respectively.

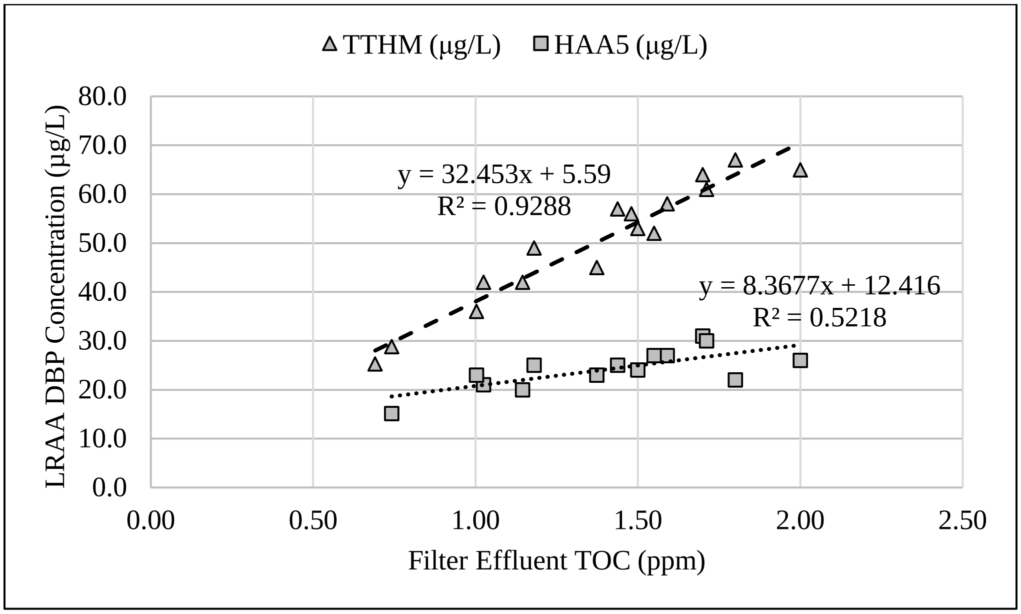

Figure 16: Filter TOC vs LRAA DBP Model

$$TTHM\,\frac{\mu g}{L} = \left(32.5 \times (TOC\ ppm)\right) + 5.59 \qquad \textbf{(15)}$$

$$HAA_5\,\frac{\mu g}{L} = \left(8.37 \times (TOC\ ppm)\right) + 12.4 \qquad \textbf{(16)}$$

The validation data set, shown on Table 18, was used to statistically analyze the developed TOC-based TTHM and HAA_5 models. The null hypothesis was that there was no difference between the predicted and actual TTHM and HAA_5 concentrations. The alternative hypothesis was that there was a difference between the predicted and actual TTHM and HAA_5 concentrations. An F-test, with a confidence level of 95, was used to evaluate the statistical significance of the variance between the predicted and actual DBP values.

Table 18: Identified Filter TOC vs LRAA DBP Validation Set

Date	Filter TOC (ppm)	TTHM (µg/L)	HAA_5 (µg/L)
6/12/2016	1.21	43.8	20.5
7/8/2016	1.03	44.1	15.8
7/15/2016	1.09	43.5	16.8
7/29/2016	0.91	42.4	18.6
8/14/2016	1.46	55.4	25.1

Table 19 summarizes the F-Test results on the TTHM model, which found that the null hypothesis could not be rejected. Since the null hypothesis wasn't rejected, no statistical significance between the predicted and actual TTHM concentrations was found. Similarly, Table 20 summarizes the F-Test results on the HAA_5 model which found that there was no statistical significance between the predicted and actual HAA_5 concentrations. The results from the F-Test concluded that the developed TOC-based TTHM and HAA_5 models can be used to predict LRAA concentrations for the Lower Kula distribution system.

Table 19: F-Test between Predicted (Model) TTHMs and Actual TTHMs (Validation Set)

Filter Effluent TOC (ppm)	LRAA Predicted TTHM (µg/L)	LRAA Actual TTHM (µg/L)	Calculated F-value	F-critical (one tail)	Result	Reject Null Hypothesis? (Y/N)
1.21	44.7	43.8	0.718	5.32	F-value < F-critical	N
1.03	39.2	44.1				
1.09	40.8	43.5				
0.910	35.1	42.4				
1.46	53.0	55.4				

Table 20: F-Test between Predicted (Model) HAA_5 and Actual HAA_5 (Validation Set)

Filter Effluent TOC (ppm)	LRAA Predicted HAA_5 (µg/L)	LRAA Actual HAA_5 (µg/L)	Calculated F-value	F-critical (one tail)	Result	Reject Null Hypothesis? (Y/N)
1.21	22.5	20.5	2.01	5.32	F-value < F-critical	N
1.03	21.1	15.8				
1.09	21.5	16.8				
0.910	20.0	18.6				
1.46	24.6	25.1				

CHAPTER 6: CONCLUSIONS

The Stage 2 D/DBP Rule requires drinking water distribution systems' TTHM and HAA_5 levels at the LRAA site, and other compliance sites, to be at or below 80 µg/L and 60 µg/L, respectively. In order to comply, surface water treatment plants implemented DBP control strategies such as GAC and spray aeration. GAC treatment targets the removal of the organic precursors which react to form DBPs, and spray aeration targets the removal of formed TTHMs. For this study, UCF partnered with the County of Maui DWS to conduct a full-scale assessment of their GAC and GridBee® system at the Pi'iholo WTP for DBP control throughout the Lower Kula system.

DBP data was gathered and analyzed from August of 2011 to August of 2016 by UCF and DWS. Prior to the spray aeration and GAC integration, it was found that TTHM levels at the LRAA compliance site ranged between 58.5 µg/L and 125 µg/L (at times exceeding the MCL). Additionally, HAA_5 levels at the LRAA compliance site ranged between 21.2 and 52.0 µg/L. The concerted efforts of the GAC and GridBee® system was found to reduce LRAA TTHM and HAA_5 concentrations to 38.5 µg/L and 20.5 µg/L, respectively, in the Lower Kula system. Hypothesis testing utilizing t-Tests confirmed that TTHMs levels were controlled by the spray aeration system and the GAC was primarily responsible for controlling HAA_5 formation. Although TTHM levels were reduced by 58 percent, and HAA_5 levels by 48 percent, the estimated cumulative annual operation and maintenance (O&M) cost of the two systems was $1,036,000.

In light of the cost analysis, total organic carbon (TOC)-based models for predicting LRAA TTHM and HAA_5 levels were developed as equation (15) and (16), respectively. The TTHM model yielded an R^2 of 0.93, and the HAA_5 model had an R^2 of 0.52. F-Tests comparing predicted LRAA TTHM and HAA_5 levels to actual LRAA TTHM and HAA_5 levels determined no statistically-significant difference. With the knowledge of how the GAC and spray aerator controlled DBPs in the water system, a cost-effective and practical treatment operating parameter was developed. The parameter, Pi'iholo water plant filter effluent TOC content, can serve as an indicator that operators would use to alter DBP treatment process flow set points to achieve cost-effective treatment.

$$TTHM \frac{\mu g}{L} = \left(32.453 \times (TOC\ ppm)\right) + 5.59 \qquad \textbf{(15)}$$

$$HAA_5 \frac{\mu g}{L} = \left(8.3677 \times (TOC\ ppm)\right) + 12.4 \qquad \textbf{(16)}$$

CHAPTER 7: RECOMMENDATIONS

A significant improvement in Lower Kula LRAA TTHM and HAA_5 levels has been achieved through the introduction of two DBP control technologies, GAC and spray aeration. At the same time, annual O&M costs for the continued usage of the two technologies has been estimated to exceed $1,000,000. Therefore, the following recommendations have been put together for the County of Maui DWS's consideration:

1. Since the GAC encompasses over 80% of the projected cumulative annual O&M cost, minimizing the frequency of carbon change outs per year can produce significant cost savings. Carbon change outs occur once the carbon bed is exhausted, and the exhaustion rate is based on the loading. The GAC system seems to be over-used given that HAA_5 levels in the Lower Kula system meet EPA's MCL and have been at or below DWS's MCLG. The addition of variable frequency drive (VFD) pumps can help reduce the loading on the carbon vessels, thus extending the life and reducing the annual O&M costs for the system.
2. The main electrical cost for the GridBee® is from the operation of the blowers, whose main purpose is to increase the air exchange rate. The possibility of running just the aerators during low TOC levels could significantly reduce GridBee® O&M costs.
3. As shown on Table 21, new TOC-based operating scenarios have been proposed with cost savings in mind.

Table 21: Predicted TOC-Based Treatment Scenarios with Possible Cost Saving Options

Pi'iholo Filter Effluent TOC Range (ppm)	Treatment	Possible Cost Saving Treatment Option
< 0.75	No GAC | No GridBee®	No GAC | No GridBee®
0.75 - 1.0	No GAC | 1 Blower	No GAC | Aerators Only
1.0 – 1.2	No GAC | 2 Blower	No GAC | 1 Blower
1.2 - 1.5	GAC | 2 Blower	Low Flow GAC | 1 Blower
> 1.5	GAC | 2 Blowers	Medium Flow GAC | 2 Blowers

4. Pifer & Fairey (2013) found that UV_{254} produced a higher R^2 than TOC for DBP prediction. Furthermore, the Pi'iholo WTP is currently transitioning from TOC to UV_{254} monitoring of its GAC system. Therefore, it is recommended that the TTHM and HAA_5 models be based on UV_{254} values. Consequently, it will be required that UV_{254} be collected as the control parameter for the operation of the Pi'iholo DBP control technologies.

APPENDIX A: WATER QUALITY METHODS

Table 22: Water Quality Analysis Summary

Test	Method Reference Number & Instrument	Method Reporting Level (MRL)	Accuracy	Precision	Holding Time (HT)	Sample Volume (SV)	Container Type (CT)	Preservative
pH	SM 45000-H^+ B; pHTestr 30	0.0010 units	± 0.1 pH	± 0.13 pH	Analyze immediately	250 mL	Plastic	None
Temperature	SM 2550B; pHTestr 30	0.1 °C	± 0.1 °C	NIST approved	Analyze immediately	250 mL	Plastic	None
UV_{254}	HACH Method 10054; DR 6000	0.005 cm^{-1}	N/A	< 20 % RPD	2 days	125 mL	Amber borosilicate glass with teflon lined cap	Cool, 4°C
TOC	SM 5310C; TOC Analyzer	0.5 mg/L	80-120 % Recovery	< 20 % RPD	2 days	40 mL	Amber borosilicate glass with teflon lined cap	Cool, 4°C
Free Cl_2	HACH Method 8021	0.02 mg/L	80-120 % Recovery	< 20 % RPD	Analyze immediately	125 mL	Amber borosilicate glass with TFE lined cap	None
TTHMs	SM 6232B; Gas chromatograph	8 µg/L	80-120 % Recovery	< 20 % RPD	14 days	60 mL	Amber borosilicate glass with TFE lined cap	Cool, 4°C; add 1 mL of 50 g/L Na_2SO_3
HAA_5	EPA Method 552.3; Gas chromatograph	10 µg/L	70-130 % Recovery	<3 0 % RPD	14 days	250 mL	Amber borosilicate glass with TFE lined cap	Cool, 4°C; add 1 mL of 50 g/L NH_4Cl

APPENDIX B: LOWER KULA DATA LOG SHEET EXAMPLE

Table 23: Lower Kula Distribution System Sampling Data Sheet (Example)

Lower Kula Distribution System Data Sheet

Date:

Brooks Tank Data

Influent Flow

Effluent Flow

Water Level, ft

Sample	Collection Time	pH	Temp	TOC (mg/L)	Cl2 Conc. (mg/L)	THM Quench Time	HAA Quench Time	Observations
Vault B								
(2) Vault D								
(3) Brooks influent								
(4) Brooks effluent								
(5) 247-SM #1								
(6) 247-902								
(6) 247-902 D								
(7) 247-905								
(8) 247-906								
(9) 247-907								
(9D) 247-907 D								
(10) 247-SM#2								

	DWS	Site		DWS	Site
LEGEND	247-SM #1	Ehu Rd SP 52	**LEGEND**	247-906	Naalae Rd SP 320
	247-902	Piliwale SP 335		247-907	Pueo Dr Hyd 515
	247-905	Kula Kai Hyd 89		247-SM #2	Pueo Dr Hyd 512

APPENDIX C: PRECISION AND ACCURACY CONTROL CHARTS

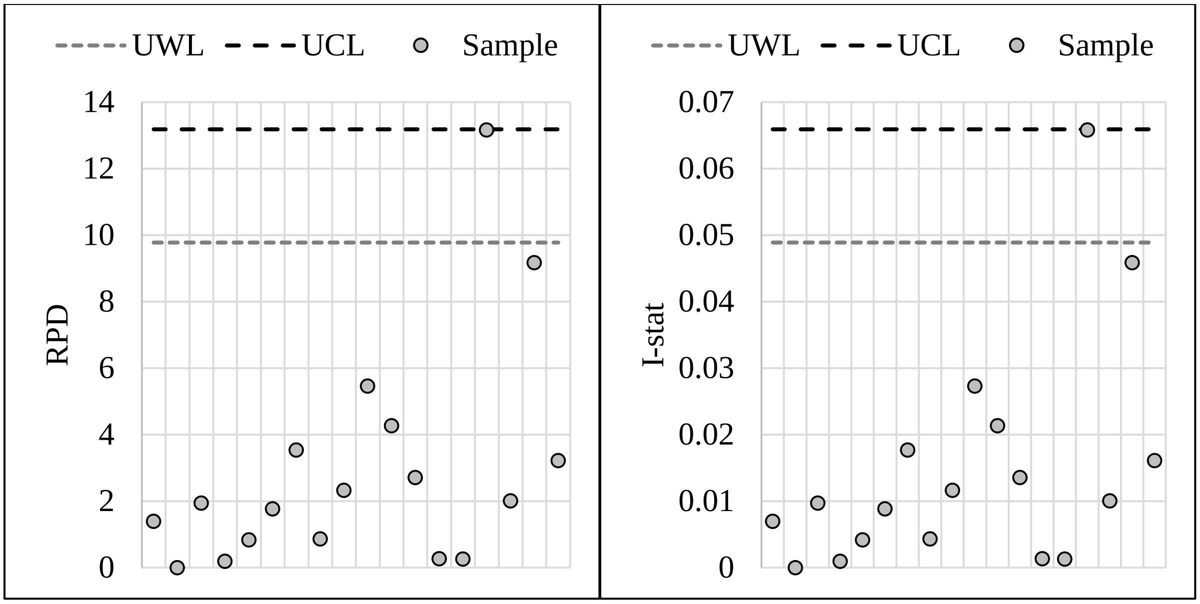

Figure 17: TOC Field Sampling Precision Control Chart

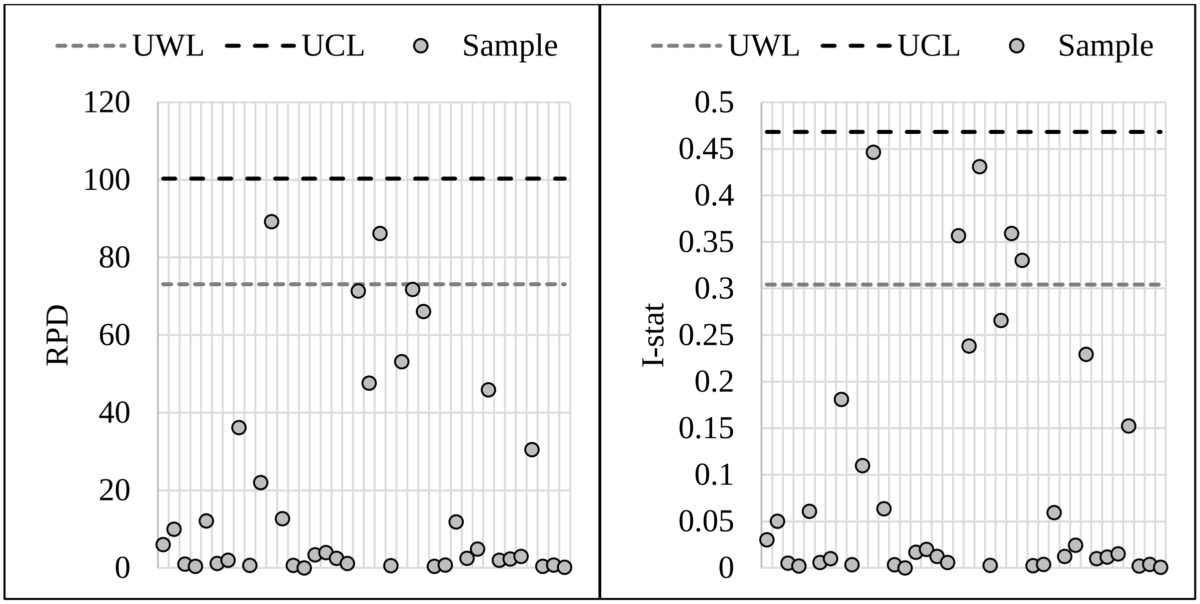

Figure 18: TTHM Field Sampling Precision Control Chart

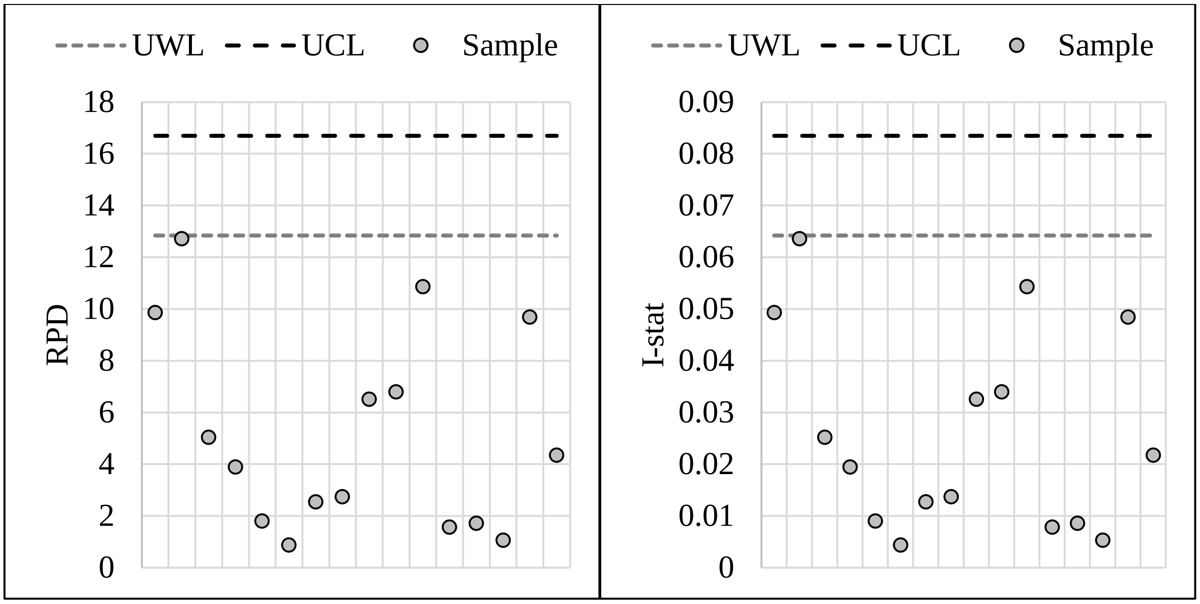

Figure 19: HAA_5 Field Sampling Precision Control Chart

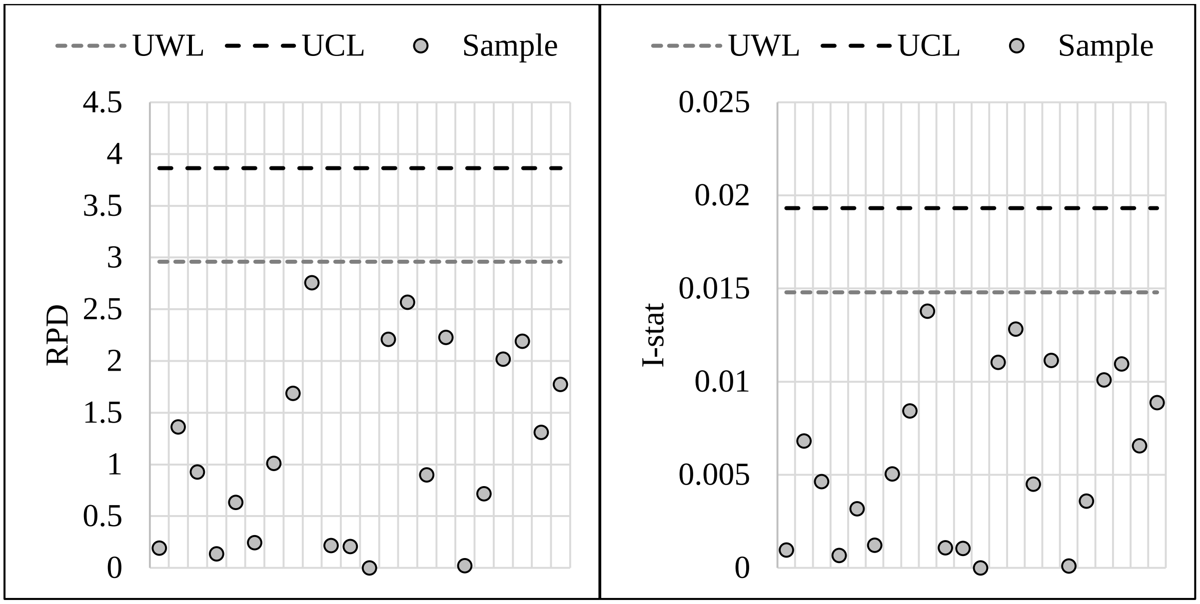

Figure 20: TTHM Lab Analysis Precision Control Chart

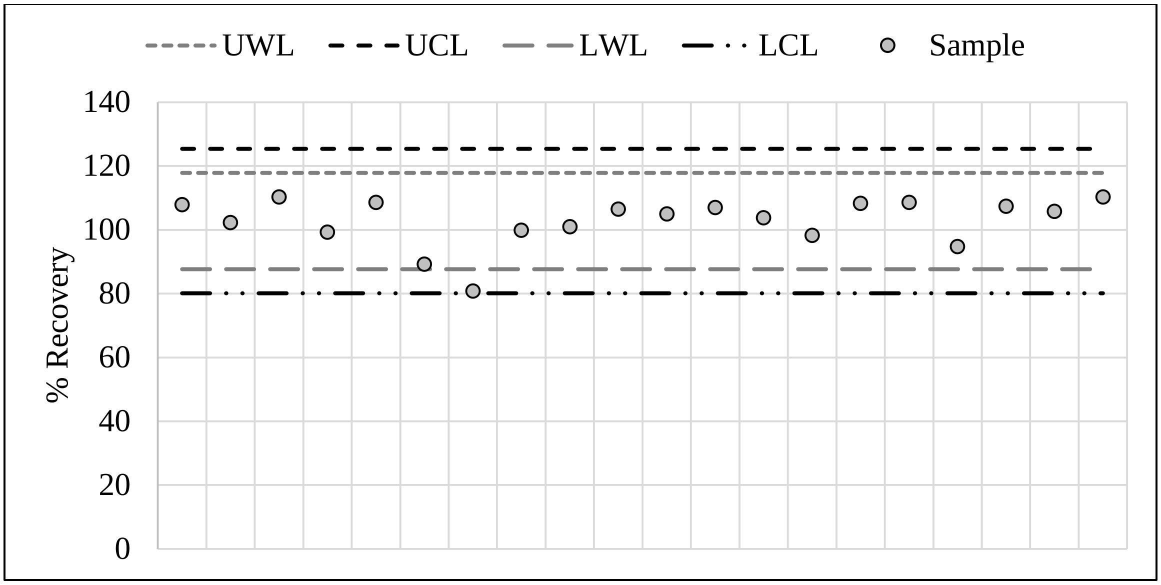

Figure 21: TTHM Lab Analysis Accuracy Control Chart

APPENDIX D: DBP CONTROL TECHNOLOGIES RAW DATA SETS

Table 24: TTHM Raw Data Sets

Historical			GridBee® at half capacity			GridBee® at half capacity with GAC			GridBee® at full capacity with GAC		
Sampling Date	**Data Origin**	**TTHM LRAA (µg/L)**	**Sampling Date**	**Data Origin**	**TTHM LRAA (µg/L)**	**Sampling Date**	**Data Origin**	**TTHM LRAA (µg/L)**	**Sampling Date**	**Data Origin**	**TTHM LRAA (µg/L)**
8/17/2011	DWS	99.0	2/20/2013	UCF	55.6	3/12/2015	UCF	76.2	3/2/2016	DWS	37.1
8/30/2011	DWS	115	3/8/2013	DWS	50.7	4/17/2015	DWS	70.4	3/6/2016	UCF	33.8
9/15/2011	DWS	125	4/15/2013	UCF	45.9	5/17/2015	UCF	63.7	6/12/2016	UCF	33.5
9/20/2011	DWS	123	4/19/2013	UCF	45.5	7/2/2015	DWS	73.1	7/8/2016	DWS	35.5
11/23/2011	DWS	108	4/23/2013	DWS	42.8	7/30/2015	DWS	78.2	7/15/2016	DWS	40.0
12/6/2011	DWS	91.0	5/3/2013	UCF	41.5	8/6/2015	DWS	75.5	7/29/2016	DWS	43.4
2/9/2012	DWS	69.0	7/22/2013	DWS	46.2	8/14/2015	DWS	78.7	8/14/2016	UCF	46.3
6/20/2012	DWS	58.5	8/27/2013	DWS	58.0	8/19/2015	DWS	68.3			
9/14/2012	DWS	80.5	10/26/2013	UCF	67.5	8/26/2015	DWS	62.3			
9/24/2012	UCF	90.7	11/14/2013	DWS	74.5	9/4/2015	DWS	61.5			
10/22/2012	DWS	106	2/14/2014	DWS	69.0	9/11/2015	DWS	59.8			
12/20/2012	UCF	83.4	5/11/2014	UCF	59.5	9/18/2015	DWS	60.8			
1/23/2013	DWS	64.5	7/8/2014	DWS	56.0	9/25/2015	DWS	57.0			
1/30/2013	UCF	59.9	8/4/2014	DWS	59.0	10/2/2015	DWS	55.8			
			8/18/2014	DWS	61.6	10/9/2015	DWS	53.5			
			10/19/2014	UCF	71.7	10/18/2015	UCF	42.1			
			11/14/2014	DWS	75.4	10/29/2015	DWS	39.6			
			1/15/2015	DWS	71.9	11/6/2015	DWS	36.1			
						11/13/2015	DWS	35.1			
						12/18/2015	DWS	41.3			

Table 25: HAA_5 Raw Data Sets

Historical			GridBee® at half capacity			GridBee® at half capacity with GAC			GridBee® at full capacity with GAC		
Sampling Date	**Data Origin**	**HAA_5 LRAA (μg/L)**	**Sampling Date**	**Data Origin**	**HAA_5 LRAA (μg/L)**	**Sampling Date**	**Data Origin**	**HAA_5 LRAA (μg/L)**	**Sampling Date**	**Data Origin**	**HAA_5 LRAA (μg/L)**
8/17/2011	DWS	38.0	2/20/2013	UCF	50.5	3/12/2015	UCF	45.7	3/2/2016	DWS	24.1
8/30/2011	DWS	44	3/8/2013	DWS	49.3	4/17/2015	DWS	40.2	3/6/2016	UCF	22.9
9/15/2011	DWS	48	4/15/2013	UCF	51.6	5/17/2015	UCF	33.7	6/12/2016	UCF	22.2
9/20/2011	DWS	52	4/19/2013	UCF	53.0	7/2/2015	DWS	34.3	7/8/2016	DWS	20.5
11/23/2011	DWS	45	4/23/2013	DWS	41.3	7/30/2015	DWS	33.1	7/15/2016	DWS	17.1
12/6/2011	DWS	37.5	5/3/2013	UCF	34.7	8/6/2015	DWS	33.1	7/29/2016	DWS	17.9
2/9/2012	DWS	26.7	7/22/2013	DWS	31.7	8/14/2015	DWS	31.1	8/14/2016	UCF	19.1
6/20/2012	DWS	21.2	8/27/2013	DWS	33.3	8/19/2015	DWS	28.8			
9/14/2012	DWS	28.7	10/26/2013	UCF	38.3	8/26/2015	DWS	25.8			
9/24/2012	UCF	37.9	11/14/2013	DWS	37.8	9/4/2015	DWS	25.5			
10/22/2012	DWS	47	2/14/2014	DWS	37.8	9/11/2015	DWS	25.8			
12/20/2012	UCF	47.8	5/11/2014	UCF	46.2	9/18/2015	DWS	26.0			
1/23/2013	DWS	39.2	7/8/2014	DWS	48.6	9/25/2015	DWS	27.3			
1/30/2013	UCF	41.2	8/4/2014	DWS	52.4	10/2/2015	DWS	28.5			
			8/18/2014	DWS	51.2	10/9/2015	DWS	28.0			
			10/19/2014	UCF	46.6	10/18/2015	UCF	28.2			
			11/14/2014	DWS	46.4	10/29/2015	DWS	26.7			
			1/15/2015	DWS	43.3	11/6/2015	DWS	23.0			
						11/13/2015	DWS	22.5			
						12/18/2015	DWS	21.8			

APPENDIX E: DBP INDICATOR PARAMETER MODEL RAW DATA

Table 26: Filter TOC vs LRAA DBP Model Raw Data

Data Set	Date	TTHM (µg/L)	HAA_5 (µg/L)	Filter TOC (ppm)	Treatment Scenario	Waikamoi Intake 1
Training	8/6/2015	64.0	31.0	1.70	GridBee® at half capacity with GAC	Closed
	8/14/2015	65.0	26.0	2.00	GridBee® at half capacity with GAC	Closed
	8/19/2015	53.0	24.0	1.50	GridBee® at half capacity with GAC	Closed
	8/26/2015	67.0	22.0	1.80	GridBee® at half capacity with GAC	Closed
	9/4/2015	61.0	30.0	1.71	GridBee® at half capacity with GAC	Closed
	9/11/2015	58.0	27.0	1.59	GridBee® at half capacity with GAC	Closed
	9/18/2015	57.0	25.0	1.44	GridBee® at half capacity with GAC	Closed
	9/25/2015	52.0	27.0	1.55	GridBee® at half capacity with GAC	Closed
	10/2/2015	56.0	35.0	1.48	GridBee® at half capacity with GAC	Closed
	10/9/2015	49.0	25.0	1.18	GridBee® at half capacity with GAC	Closed
	10/29/2015	42.0	21.0	1.03	GridBee® at half capacity with GAC	Closed
	11/6/2015	42.0	20.0	1.15	GridBee® at half capacity with GAC	Closed
	11/13/2015	45.0	23.0	1.37	GridBee® at half capacity with GAC	Closed
	12/18/2015	36.0	23.0	1.00	GridBee® at half capacity with GAC	Closed
	3/2/2016	25.3	30.4	0.691	GridBee® at half capacity with GAC	Closed
	3/6/2016	28.8	15.2	0.742	GridBee® at half capacity with GAC	Closed
Validation	6/12/2016	43.8	20.5	1.21	GridBee® at full capacity with GAC	Closed
	7/8/2016	44.1	15.8	1.03	GridBee® at full capacity with GAC	Closed
	7/15/2016	43.5	16.8	1.09	GridBee® at full capacity with GAC	Closed
	7/29/2016	42.4	18.6	0.91	GridBee® at full capacity with GAC	Closed
	8/14/2016	55.4	25.1	1.46	GridBee® at full capacity with GAC	Closed

APPENDIX F: TABULATED LITERATURE REVIEW HIGHLIGHTS

Table 27: Tabulated Literature Review Highlights

Reference Type / Year	Highlights	Citation
Article / 1984	• Henry's law constants **not** affected by presence of other THMs or water composition • Independent of concentration between 10-1000µg/L (zero order) • Henry's law constant for THMs approximately doubles with each 10°C increase • Table with H values for THM species	Nicholson, et al., 1984
Article / 1990	• DBPFP from colored raw waters similar to DBPFP observed for aquatic humic and fulvic acids • Alum coagulation of moderately colored surface water yielded 50-90% removal of precursors tested	Reckhow & Singer, 1990
Article / 1994	• DBP control least expensive options: 1. move disinfection point, 2. use alternative disinfectant • DBP control least desirable option: remove DBPs after they are formed • DBP control most effective option: remove DBP precursors • Choice of option is site specific, not cure-all answer. • Distribution system design (another DBP control measure) is expected to raise the cost of water • THM formation favored in alkaline pH while HAA favored in acidic pH • Table with henry's coefficient for THMs (dimensionless)	Clark, et al., 1994
Article / 2002	• DBPFP highest at pH 7 and with increased reaction time • DBPs classified by USEPA as probable or possible human carcinogens • THM vs HAA formation preference is dependent not just on pH but also on the type of organic matter in the water	Kim, et al., 2002
Article / 2004	• THMFP influenced by: Cl2 dose, concentration and type of NOM, time, pH, temperature, and Br • Disinfection level must balance microbial risk with DBP risk	Sadiq & Rodriguez, 2004
Article / 2007	• 85 DBPs reviewed, 11 regulated by EPA, 74 considered emerging DBPs • Emerging DBP concentrations are increased with use of alternative disinfectants such as ozone and chloramines • In several occasions, emerging DBPs are more genotoxic than the regulated DBPs • Generally brominated DBPs are more genotoxic/carcinogenic than chlorinated, and iodinated more toxic than brominated	Richardson, et al., 2007

Reference Type / Year	Highlights	Citation
Article / 2008	• Rapid sand filter bed retrofitted into a GAC filter bed for a high ammonia/DOC raw water • Overall removal efficiency of DOC and DBPs (pre-formed due to pre-chlorination) was higher for GAC compared to sand filter • THM breakthrough occurred after 3 months of operations, then removal decreased to <10% • HAA removal by GAC first through adsorption, then through biodegradation (heavily influenced by water temperature) • Similar turbidity removal, but better manganese removal in sand filter as opposed to GAC	Kim & Kang, 2008
Article / 2010	• 11 different finished waters from water treatment plants tested (prior to disinfection) • SUVA values for the sampled water ranged from 1.5 to 5.4 m-1Lmg-1C and avg Br of 105µg/L • Chloramine use reduced HAAs production by ~77% and THM by 92% • Genotoxicity and cytotoxicity higher for nitrogen-containing compounds than THMs and HAAs	Bougeard, et al., 2010
Article / 2010	• Homogenous surface diffusion model (HSDM) produced best correlation between predicted and experimental values • Recommended for predicting NOM adsorption from raw surface water by GAC	Sulaymon, et al., 2010
Article / 2010	• Linear regression techniques used to model TOC breakthrough in bituminous GAC • Model variables include mesh size, EBCT, [TOC], and pH • Model better than previous empirical models, but not advisable to use for design of full scale GAC	Zachman & Summers, 2010
Article / 2011	• Diffused aeration inside a water tank or chlorine contact basin exhibited removal efficiencies between 9 and >99.5% • Diffused aeration efficiency depended on air-to-water ratio, water temperature, and THM species • Spray aeration efficiency was between 20 and >99.5% • Spray aeration efficiency was dependent on droplet diameter, droplet travel distance, water temperature, and THM species • Droplet diameter can be controlled by pressure and nozzle characteristics • Droplet travel distance showed greater influence on THM removals • Free chlorine seems to not be reduced by aeration because only a small part is amenable to removal in closed-system environments • THM mass transfer appears to be influenced by both gas and liquid film resistance	Brooke & Collins, 2011
Article / 2012	• Using pre-ozonation/enhanced coagulation/activated carbon filtration treatment train was most effective method for controlling DBP precursors in WTP	Badawy, et al., 2012

Reference Type / Year	Highlights	Citation
Article / 2013	• Best correlating parameter found for TTHMFP, with R2 of 0.89, was UV254 • Fluorescence excitation/emission wavelength pair 240/562 produced R2 of 0.81 • Maximum fluorescence intensities of components from parallel factor analysis had R2 of 0.78 • DOC produced an R2 of 0.75 • 44 different waters tested; at various pHs, with raw and alum-coagulated waters in the mix	Pifer & Fairey, 2013
Article / 2014	• Influence of various parameters on spray aeration effectiveness evaluated using mass balance approach and sensitivity analysis • The most influential parameters for spray aeration efficiency were found to be: droplet size, travel distance, spray pattern, and % recycle • Least influential factors: temperature, spray angle, and THM species • Study predicted good removal efficiencies for brominated THM species using spray aeration	Cecchetti, et al., 2014

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