UPGRADED DISINFECTION: PROVIDING FOUR-LOG VIRUS TREATMENT OF A FINISHED WATER SUPPLY FOR A CONSECUTIVE WATER SYSTEM

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Background

The Broward County Water and Wastewater Services (BCWWS) District 3A service area obtains its treated water supply from the City of Hollywood through a bulk purchase agreement between Broward County and the City of Hollywood. The BCWWS District 3A service area, which includes the Fort Lauderdale-Hollywood International Airport, is depicted in **Figure 1.**

The water supply from the City of Hollywood is delivered to the District 3A service area though a single, dedicated 20-inch diameter transmission main that is used to fill a 2.0 million gallon (MG) ground storage tank on the BCWWS Pump Station 3A site. The treated water delivered to the 3A facility contains a total combined chloramine residual averaging approximately 2.8 mg/L. Downstream of the storage tank, the water is pumped to distribution in the District 3A service area using the BCWWS Pump Station 3A high service pumping system. The 3A facility also includes sodium hypochlorite and ammonia storage and feed systems to boost the chloramine residual prior to distribution. **Figure 2** shows a site plan of the 3A pump station facility with the proposed four-log virus treatment system.

The City of Hollywood water treatment plant has not yet demonstrated four-log virus treatment of the finished water as defined under the Federal Ground Water Rule (GWR) and Chapter 62-550.828, Florida Administrative Code (FAC). Consequently, The City must conduct regular "assessment" microbial monitoring of their groundwater sources (production wells) and is subject to "triggered" monitoring of their groundwater sources as a result of any positive total coliform or fecal indicator results from distribution system monitoring. Because District 3A is a consecutive system with the City, if any assessment monitoring sample collected by Hollywood tests positive for fecal coliform, BCWWS must issue a Tier 1 Public Notice within 24 hours. If the offending well cannot be taken off line, a precautionary boil water notice must be included.

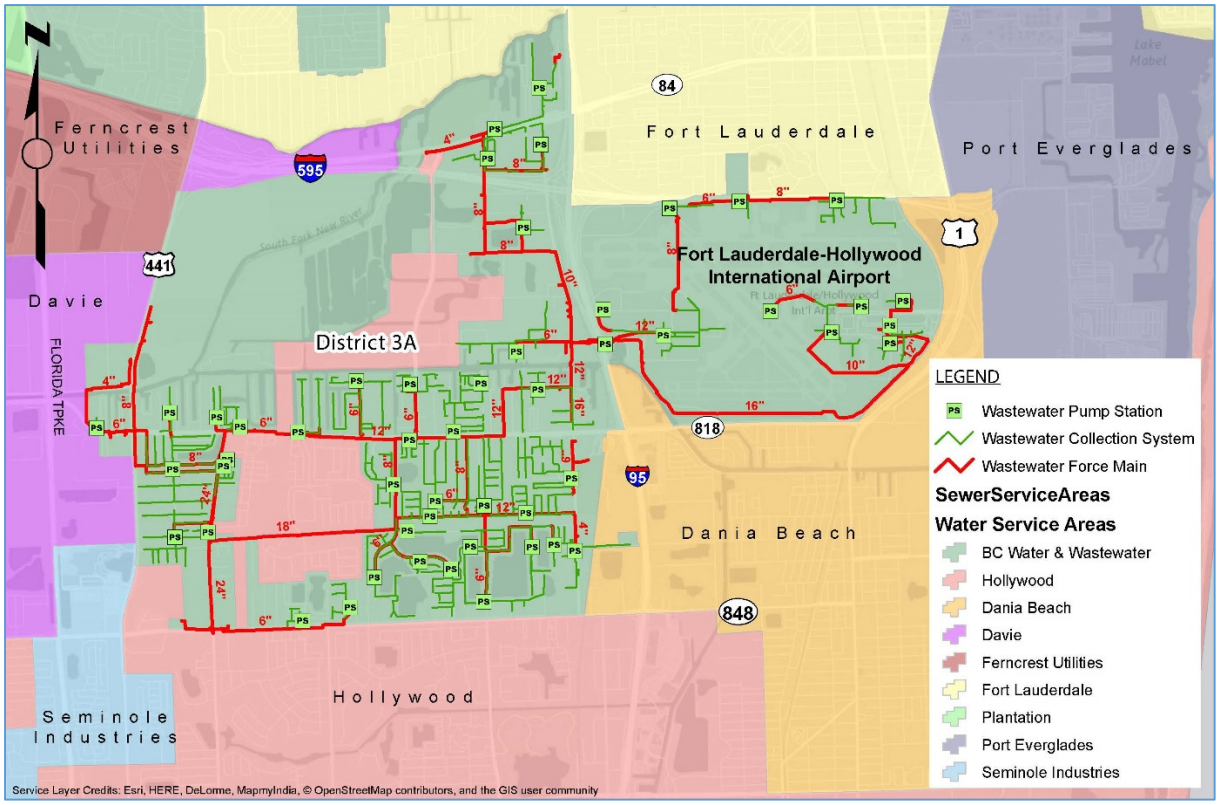

Figure 1 – Broward County Water and Wastewater Services District 3A Service Area

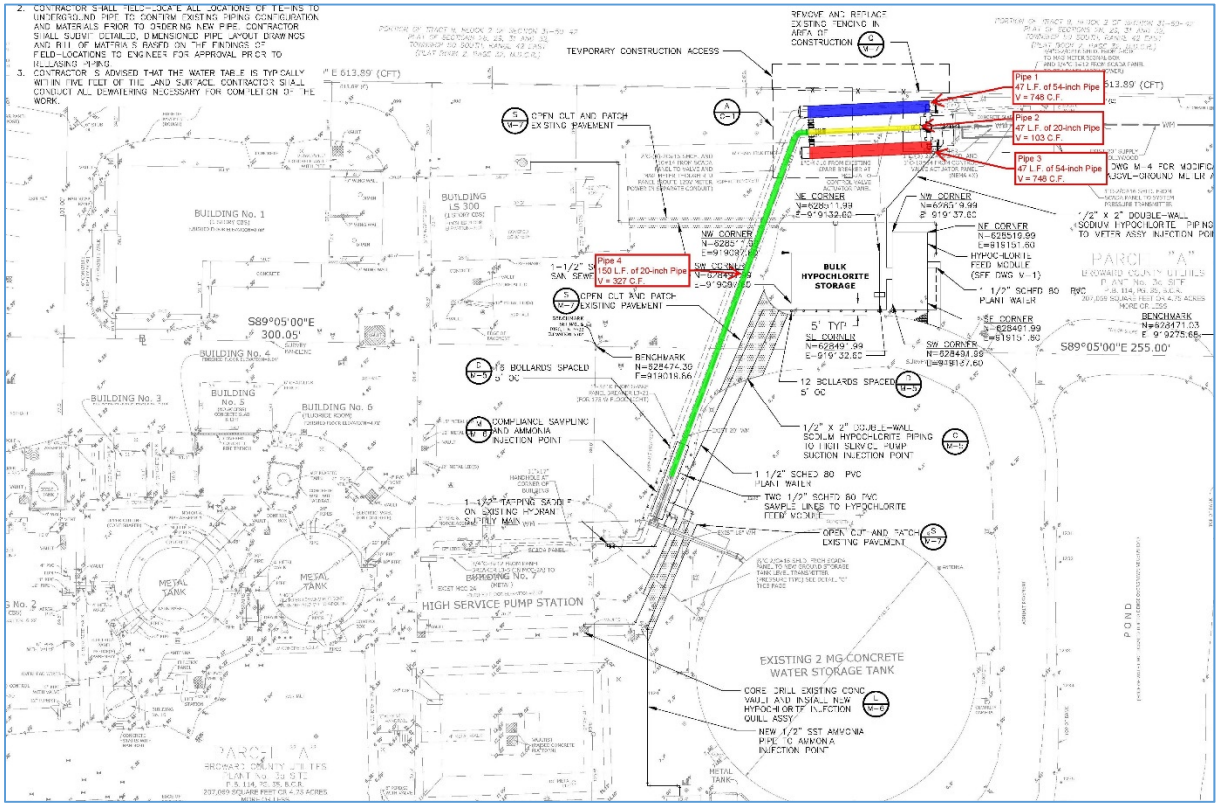

Figure 2 – BCWWS Pump Station 3A Site Plan Showing Four-Log Virus Treatment System

Due to the critical importance of maintaining uninterrupted, reliable service to the users in the District 3A service area, including the Fort Lauderdale-Hollywood International Airport, BCWWS intends to provide a higher level of disinfection for the water supply by providing four-log virus treatment at the BCWWS 3A facility, prior to distribution to BCWWS customers in the service area. Four-log virus treatment "certification" of the District 3A water supply will enable BCWWS to avoid the Tier 1 public notice and potential boil water notice requirements resulting from any positive fecal coliform test results in Hollywood's assessment monitoring program.

Development of the Strategy for Four-Log Virus Treatment

Four-log virus treatment can be provided using various treatment technologies, including physical removal of pathogens (e.g., through membrane treatment, conventional filtration, etc.), ultraviolet (UV) disinfection, and/or chemical disinfection (e.g., free chlorination, chloramination, etc.). The regulatory criteria for determining that a facility is capable of providing four-log virus treatment vary depending on the treatment technology, or combination of treatment technologies, and other factors such as process flow, water temperature, pH, etc.[i] Due to site constraints and cost considerations, BCWWS elected to evaluate chemical disinfection with free chlorine at the 3A facility.

For chemical disinfection, virus removal credits are based on the calculated "CT" value for the selected disinfectant at prevailing conditions in the treatment process, relative to the applicable "CT" table included in the *Guidelines* (see references), which are based on tables published by the EPA. "CT" is obtained by multiplying the target residual disinfectant concentration (C), in milligrams per liter (mg/L) measured before or at the first customer, by the corresponding disinfectant contact time (T), in minutes.[ii] Under the Federal Surface Water Treatment Rule, the contact time (T) for a vessel is the time when 10 percent of the water entering the inlet has passed through the outlet. This theoretical time is called T_{10} and is estimated by multiplying the vessels hydraulic detention time (vessel volume divided by the flow rate) by a baffling factor, which is based on flow characteristics within the disinfectant contact zone.[iii]

To demonstrate four-log virus treatment with chemical disinfection, a minimum target disinfectant residual must be determined based on the following assumptions:

- Peak (maximum) flow through the disinfectant contact vessel(s)
- Minimum contact vessel volume
- Minimum temperature observed based on historical data
- pH range based on process historical data
- Applicable and approved baffle factor(s) for the disinfectant contact vessel(s)

As noted above, under non-emergency conditions, the only source of water for the District 3A service area is the City of Hollywood bulk supply which is delivered solely through the single dedicated transmission main that is used to fill the 2 MG ground storage tank on the 3A facility site. Therefore, four-log virus treatment can be effectively implemented within this transmission main without risk of short circuiting or "contamination" of the treated water from non-four-log virus-treated water.

The strategy for providing four-log virus treatment for the 3A facility consists of chemical disinfection through the application of sodium hypochlorite solution (hypochlorite) to the delivered Hollywood water supply at a dosage rate sufficient to develop a free chlorine residual in excess of the minimum required to meet the appropriate "CT" criterion, within a dedicated free chlorine contact zone in the downstream piping, prior to discharge to the storage tank.

Because the Hollywood supply contains a combined chloramine residual, and potentially some level of free ammonia, BCWWS established the following objectives in the scope of the project:

- To characterize the levels of free ammonia in the "raw" water supply (treated water from the City of Hollywood) to be treated for four-log disinfection with free chlorine.

- To develop a representative chlorine breakpoint curve for the Hollywood water supply to estimate the required chlorine dose necessary to meet the target free chlorine residual to provide four-log virus treatment, and to meet the BCWWS goal for total residual chloramine in the finished water delivered to the District 3A service area.

- To confirm that the four-log virus treatment protocol will not compromise the BCWWS's continued compliance with the Disinfectants/Disinfection By-Product (D/DBP) Rule (i.e., result in a significant increase in current levels of total trihalomethanes (TTHMs) and/or five haloacetic acids (HAA5) in the finished water).

To achieve the above objectives, the scope of the project included the following tasks:

- Detailed development of the four-log virus treatment protocol, including the determination of four-log virus treatment parameters such as process flow, water temperature, contact vessel volume(s), baffle factor(s) and contact times, CT requirements, and free chlorine residual requirements.

- Field and laboratory investigations for characterization of the "raw" water supply, development of chlorine breakpoint curve(s) for estimating chlorine dosing requirements, and characterization of DBP formation resulting from the proposed four-log virus treatment protocol.

- Preparation of a *Demonstration of Four-Log Virus Treatment of Groundwater* package for submittal to the Florida Department of Health in Broward County (FDHBC).

- Design of a sodium hypochlorite storage and feed system, piping and process modifications, and four-log virus treatment compliance monitoring system for the 3A facility based on the proposed treatment protocol.

Four-Log Virus Treatment Process Parameters and Treatment Protocol

Process Flow

Prior to initiation of this project, the 3A facility did not have a defined "treatment capacity," because the facility effectively acted only as a storage and re-pump facility. Based on service area demand projections developed in 2014, BCWWS established a design maximum day demand of 5.0 million gallons per day (mgd) for the project. Because the Hollywood supply can be delivered to the site at a constant rate (with the 3A facility high service pumping system meeting instantaneous peaks in excess of the daily demand), the "process" flow through the disinfection contact zone is equal to the daily demand (5.0 mgd maximum).

Contact Volume and Baffle Factor

Various options for providing the disinfectant contact volume were evaluated, ranging from providing all free chlorine contact within the existing 20-inch transmission piping to the installation of sections of new large-diameter (up to 54-inch diameter piping). Assuming other parameters (e.g., baffle factor) remain constant, the required free chlorine residual for four-log virus treatment is inversely proportional to the disinfectant contact volume. Increasing the contact volume results in a proportional increase in the contact time (T_{10}) and corresponding reduction in the required free chlorine residual necessary to meet the appropriate CT criterion.

Considering the pH conditions (discussed below), and to provide maximum operational flexibility, redundancy, and operating safety margin, BCWWS ultimately elected to install two new parallel 47-foot-long, 54-inch diameter, above-grade pipe sections downstream of the free chlorine injection point. As discussed below, the chorine contact pipe sections can be operated in parallel (under normal operation), or either section can be isolated for maintenance or repairs while still providing four-log virus treatment under "alternate" operating conditions. This is discussed in greater detail below. Because the chlorine contact is taking place entirely in the tank-fill piping, the Demonstration calculations were prepared using a baffle factor of 1.0 (plug flow, pipeline).

Water Temperature

BCWWS had sufficient temperature data (in excess of 12 consecutive months) indicating a minimum water temperature of 21.9^{o} C. A minimum temperature of 21° C was selected for determination of the appropriate CT requirements.

pH

Historical water quality data analyzed under the field/laboratory study phase of the project indicated that the pH of the treated Hollywood supply ranged between 8.0 and 9.3. Between February 2014 and May 2015, the pH of the water delivered to the 3A facility was between 9.0 and 9.3 approximately 26 percent of the time. This fact is critical with respect to the proposed treatment protocol because the CT value required for four-log virus treatment increases significantly when the pH exceeds 9.0. Because BCWWS has no effective control of the "incoming" pH, they elected to request two pH conditions for the demonstration of four-log virus treatment. Based on Table B-1 of the *Guidelines* (and a water temperature of 21° C), two pH conditions were used in the determination of the CT requirements for four-log virus treatment with free chlorine: 6.0 to 9.0 and 9.1 to 9.5.

Summary

Figure 3 presents a schematic of the four-log virus treatment protocol, showing the sodium hypochlorite injection points, free chlorine contact zones, and compliance monitoring location. As noted above, the proposed 54-inch pipe sections can be operated in parallel (under normal conditions) or with one section isolated for maintenance or repairs, while still providing four-log treatment. Also, BCWWS developed and requested two pH conditions under which four-log virus treatment may be provided. These combined alternatives result in the four-log virus treatment compliance conditions summarized in **Table 1.**

After a thorough review of the *Demonstration* package reflecting the above-described treatment and compliance protocols, the FDHBC issued a Conceptual Determination of Four-Log Virus Treatment of Groundwater letter for the 3A facility on December 16, 2015. This Determination is contingent on satisfactory completion of construction and commissioning of the proposed improvements.

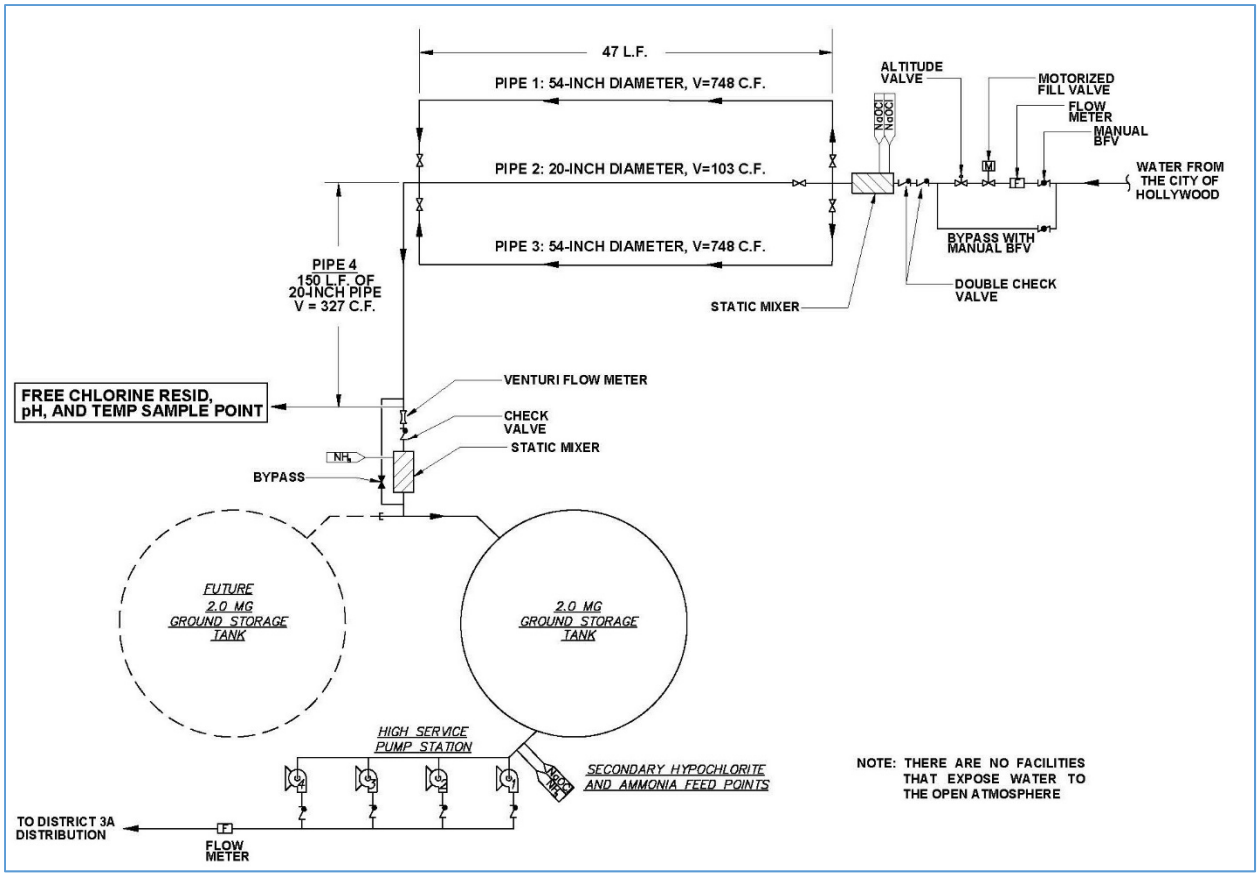

Figure 3 – Schematic of Four-Log Virus Treatment System

Table 1

Summary of Four-Log Virus Treatment Compliance Conditions

	pH range 6.0 to 9.0		**pH range 9.0 to 9.5**	
Operating Scenario	Reqd CT (mg-min/L)	Cl Resid (mg/L)	Reqd CT (mg-min/L)	Cl Resid (mg/L)
Normal Operation - All Piping in Service	2.8	**0.68**	5.7	**1.38**
Alternate - Single 54-Inch Section in Service	2.8	**1.21**	5.7	**2.47**

Field and Laboratory Investigations

As noted above, the field and laboratory investigations were aimed at characterizing the quality of the "raw" water supply to be treated, and quantifying the chlorine and ammonia dosing requirements necessary to achieve four-log virus treatment. Additionally, this investigation was intended to address the treatment protocol necessary to meet the BCWWS's goal for combined chloramine residual in the finished water supply and to confirm that the proposed four-log virus treatment protocol will not compromise compliance with other applicable water quality regulations (i.e., D/DBP Rule).

With the exception of a single sample of pure Hollywood lime softened water (not blended with membrane permeate) that was collected for the DBP investigations, all "raw" water samples were collected from an

existing PVC sampling tap. The location of the tap is immediately upstream of the proposed disinfectant contact zone. Therefore, this sample location provides samples that are representative of the raw water supply to be disinfected with the proposed four-log treatment system. Analyses for temperature and pH were measured using an YSI pH10A handheld device. Free chlorine and total chlorine were analyzed using a Hach Model 58700-00 Cl_2 Pocket Colorimeter II handheld device. This unit utilizes the EPA-approved Standard Method 4500-Cl G. Ammonia was measured using a Hach Model 5870026 Pocket Colorimeter II (Chloramine, Mono and Free Ammonia) handheld device.

In addition to the water quality data collected during the field investigations, previous historical data (February 2014 through May 2015) collected by BCWWS staff were compiled.

Estimation of Chlorine Dosing Rates

A representative chlorine breakpoint curve for the Hollywood water supply was developed by applying varying dosing rates to water samples and analyzing them for free and total chlorine, and pH after a selected incubation time. The sample incubation time was selected to represent the hydraulic detention time (HDT) in the proposed four-log virus treatment disinfectant contact zone at the projected minimum flow rate for the 3A facility (1.0 mgd), which corresponds to the projected maximum HDT. The chlorine breakpoint curve was prepared by plotting total and free chlorine residual (mg/L) on the y-axis versus applied hypochlorite dose (mg/L) on the x-axis. **Figure 4** presents the plot of the chlorine breakpoint curve at a 21-minute incubation time.

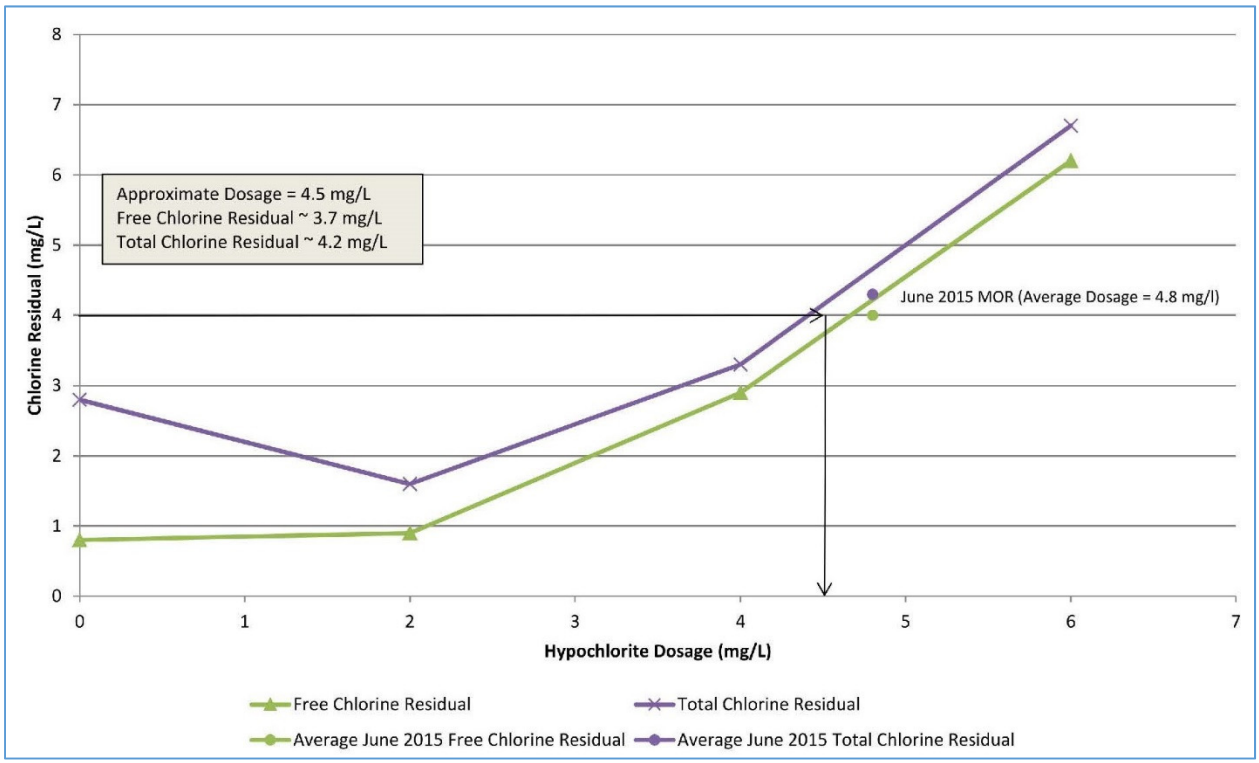

Figure 4 – Free and Total Chlorine Residual vs. Applied Hypochlorite Dose

Referring to Figure 4, the fact that increasing doses of hypochlorite result in a direct increase in the free chlorine residual beyond an applied dose of approximately 2 mg/L indicates that this portion is beyond the "breakpoint," or in Zone 3 of the theoretical breakpoint curve. In this zone, the proportion of free chlorine to total chlorine is roughly constant throughout the plot. The portion of the total chlorine residual other than

free chlorine (approximately 0.4 to 0.7 mg/L) is termed "nuisance residuals" and consists of monochloramine, dichloramine, and trichloramine or nitrogen trichloride.[iv]

With respect to the BCWWS's four-log virus treatment strategy at the 3A facility, the significance of the nuisance residual is that it places an upper limit on the free chlorine residual that may be achieved before exceeding the maximum total combined chloramine residual goal of 4.0 to 4.2 mg/L. For example, if there is a nuisance residual of 0.7 mg/L, BCWWS may apply a hypochlorite dose to achieve a free residual of approximately 3.3 mg/L before reaching a total chlorine residual of 4 mg/L. Therefore, the target free chlorine residual for four-log virus treatment must be less than 3.3 mg/L (in practice, a reasonable operating safety margin must also be considered), or else the total finished combined residual (after combining with ammonia downstream) will exceed the regulatory maximum residual disinfectant level (MRDL) of 4 mg/L.

Figure 4 indicates that a dosing rate of approximately 4.5 mg/L hypochlorite will result in a total chlorine residual of approximately 4.2 mg/L and a free chlorine residual of approximately 3.7 mg/L under the conditions prevailing at the time of the study. These residual values meet the BCWWS's treatment objectives.

For a point of comparison to the desk-top laboratory analysis, full-scale operating data for the 3A facility were reviewed from a recent month during which BCWWS was conducting a "free chlorine burn" while Hollywood was under normal chloramine residual maintenance (June 2015 Monthly Operating Report (MOR) for the 3A facility). With respect to the objective of estimating the required hypochlorite dose necessary to achieve the target free chlorine residual, this operating scenario is representative of BCWWS's proposed four-log virus treatment protocol. The June 2015 MOR data indicate that, on average, an applied hypochlorite dose of approximately 4.8 mg/L produced a free chlorine residual of approximately 4.0 mg/L during that time period. These data points are plotted on Figure 4 for reference. Considering the limited duration of the field sampling encompassed in the study and the potential variability in the Hollywood water supply, these data are consistent with the findings of the desk-top study.

Estimation of Ammonia Dose

To achieve the BCWWS's goal of a combined chloramine residual of approximately 4 mg/L, the "free" portion of the total chlorine residual at the end of the disinfection contact zone must be combined with ammonia, ideally leaving a free ammonia of less than 0.05 mg/L. The theoretical weight ratio (chlorine:ammonia) necessary to convert all free chlorine to chloramine with no excess free ammonia is 5:1. In practice, however, the ratio can vary significantly. To estimate the appropriate ratio (and ammonia dose rate) for the 3A system, samples of water treated with the appropriate hypochlorite dose were then dosed with varying concentrations of ammonia, and then analyzed for free chlorine, total chlorine, and free ammonia.

Samples were prepared by first determining the hypochlorite dose necessary to produce a total combined residual of approximately 4.0 to 4.2 mg/L. This dose was estimated to be approximately 2.1 mg/L. (Note that the sampling for the ammonia investigation was conducted at a different time than the chlorine breakpoint sampling, illustrating the potential variability in the Hollywood supply.) Six 200 mL volumes of the same sample were then each treated with a 2.1 mg/L hypochlorite dose, and allowed to incubate for 12 minutes. The six treated volumes were then dosed with ammonium sulfate doses ranging from 0.4 mg/L to 1.4 mg/L and allowed to incubate for approximately 2.5 minutes. The samples were then analyzed for free and total chlorine and free ammonia,

The reactions between free chlorine and free ammonia are highly dependent on pH, temperature, contact time, the initial chlorine-to-ammonia ratio, and initial concentrations of chlorine and ammonia.[v] The data collected during the ammonia investigation showed that both free chlorine residual and free ammonia reached a minimum between ammonia dosing rates of 0.6 to 0.8 mg/L, although a free chlorine residual

was still present in the prepared sample. Based on the observed results, it is likely that the reactions were not complete at the time of analyses. However, the ammonia dosing rate of 0.6 to 0.8 mg/L correlates to an ammonia-to-chlorine ratio between 5:1 to 6.7:1, which is consistent with typical operational experience.

Disinfection By-Product Formation

Following estimation of the design sodium hypochlorite and ammonia dosing rates, samples were prepared for analysis for DBPs. Samples were dosed at the "design" hypochlorite dosing rates, incubated for 21 minutes (representing the longest projected HDT), and then dosed with a slight excess of ammonia to "quench" the DBP formation reactions. These samples were sent to a local certified commercial water quality laboratory for analysis for total trihalomethanes (TTHMs) and five haloacetic acids (HAA5).

In addition to analyzing the sample of the treated "typical" water supply to the 3A facility from the City of Hollywood (membrane permeate and lime softened blend), a sample of pure lime softened water (no blend from the City's membrane treatment processes) from the City of Hollywood Water Treatment Plant was prepared for analyses of DBP formation potential under the proposed four-log virus treatment conditions. This sample represents the potential worst-case condition with respect to the formation of DBPs under the proposed disinfection protocol. Because the membrane permeate should have a much lower level of DBP precursors than the lime softened water, the worst-case scenario with respect to DBP formation would be the Hollywood membrane treatment process is off line, and the water supply to the 3A facility is pure lime softened water.

Table 2 summarizes the results of the DBP formation investigation. The regulatory maximum contaminant levels (MCLs) for TTHM and HAA5 are 80 µg/L and 60 µg/L, respectively. Laboratory results for the normal (blended) water supply to the 3A facility from Hollywood indicate that the proposed four-log virus treatment protocol should result in TTHM and HAA5 levels that do not exceed the respective MCLs. Similarly, the laboratory results for the lime softened water from the City of Hollywood water treatment plant indicate that the proposed four-log virus treatment protocol should result in TTHM and HAA5 levels that do not exceed the respective MCLs.

Table 2
Disinfection By-Product Formation Laboratory Results

No.	Description	HOCl Dose (mg/L)	NH_3 Dose (mg/L)	TTHM (µg/L)	HAA5 (µg/L)
1.	Normal Hollywood supply - Sample 1	4.11	1.26	23.1	25.9
2.	Normal Hollywood supply - Sample 2	4.11	1.26	23.5	25.4
3.	Lime Softened Water	2.60	1.00	24.1	21.3

Design and Implementation

Concurrently with the field and laboratory investigations and preparation of the Demonstration submittal, BCWWS initiated final design of the improvements to the 3A facility necessary to implement four-log virus treatment. The proposed improvements include the following:

1. A sodium hypochlorite storage and feed system for injecting hypochlorite solution upstream of the free chlorine contact disinfection zone.

2. Modifications to the existing above-ground flow meter and valve assembly and 20-inch diameter transfer piping from the City of Hollywood. These modifications will include the addition of a double check valve backflow preventer, dual sodium hypochlorite injection points, a static mixer downstream of the hypochlorite injection points, sample points at the end of the free chlorine contact zone for collection of free chlorine residual, pH, and temperature data, and dual ammonia injection points downstream of the compliance sampling points.
3. Instrumentation, controls, and supervisory controls and data acquisition (SCADA) system improvements to collect and log the data necessary to demonstrate compliance with the proposed treatment protocol and subject regulatory requirements.
4. Miscellaneous civil, structural, and electrical improvements associated with the four-log disinfection system.

The FDHBC issued a Water Treatment Plant Construction Permit for the proposed improvements on April 11, 2016. BCWWS received bids for the project in June 2016, with a low bid of $1,593,000. Construction is expected to commence in the fourth quarter of 2016, and the system is expected to be placed in operation in the first quarter of 2018.

Conclusion

Based on the information presented above, it is feasible to provide four-log virus treatment of the Hollywood water supply to the 3A facility by applying a hypochlorite dose necessary to develop a free chlorine residual in excess of minimum required for four-log virus treatment compliance and provide a combined finished water chloramine residual of approximately 4 mg/L. The average required hypochlorite dosing rate necessary to provide four-log virus treatment should fall in the range of 2.0 to 5.0 mg/L. The ammonia-to-chlorine ratio necessary to develop a total combined finished water chloramine residual should be in the range of 5:1 to 6.7:1. The actual hypochlorite and ammonia dosing rate can be determined based on operational experience. Furthermore, the implementation of the proposed four-log virus treatment protocol should not compromise continued compliance with the D/DBPR (i.e., result in exceedances of the applicable TTHM and HAA5 MCLs). When completed, the proposed improvements will provide an elevated level disinfection reliability for the water supply to the District 3A service area by achieving four-log virus treatment while complying with the GWR, D/DBPR, and Chapter 62-550.828 FAC.

References

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[i] *Guidelines for Four-Log Virus Treatment of Groundwater, Drinking Water Section*, Florida Department of Environmental Protection, October 2009 (*Guidelines)*.

[ii] *Guidelines,* p. 2-7.

[iii] *Compliance Manual for Subpart H Systems,* Florida Department of Environmental Protection, June 2004, p. F.1.-3.

[iv] *Handbook of Chlorination, Second Edition*, George Clifford White, Van Nostrand Reinhold Company, New York, 1986, p. 162-202.

[v] *Handbook of Chlorination*, Second Edition, George Clifford White, Van Nostrand Reinhold Company, New York, 1986, p. 163.