Sequential Chlorination and Chloramination: Cost-Effective Disinfection Methods for Reclaimed Water Aquifer Recharge

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The Kanapaha Water Reclamation Facility (KWRF) is a 14.9-mil-gal-per-day (mgd) annual-average-daily-flow (AADF) advanced domestic wastewater treatment facility located in Gainesville, and is owned and operated by Gainesville Regional Utilities (GRU). Major treatment processes of the KWRF include pretreatment, a Modified Ludzack-Ettinger (MLE), and Eimco DenitIR® carrousel-activated sludge for nitrogen removal, clarification, deep-bed filtration, and high-level disinfection.

The GRU is permitted to beneficially recharge 10-mgd AADF into the Lower Floridan aquifer when the effluent meets primary and secondary drinking water standards. Reclaimed water from the KWRF is used for irrigation at residences, commercial areas, parks, and golf courses, as well as for aesthetic water features and wetland demonstration projects. Meeting the disinfection byproducts (DBPs) standards for total trihalomethanes (TTHMs) and haloacetic acids (HAA5) presented significant challenges at the KWRF, which used sodium hypochlorite for free-chlorine, high-level disinfection. Free chlorine reacts with organic matter in secondary or tertiary effluents to produce TTHMs and HAA5.

The KWRF operating permit requires the effluent to meet 75 percent nondetectable fecal coliform counts and annual average effluent concentrations of 80 µg/L TTHMs and 60 µg/L HAA5. Figures 1 and 2 show that the KWRF final effluent consistently met the 80 µg/L TTHM limit, but did not consistently meet the 60 µg/L HAA5 limit using the free-chlorine disinfection method.

The GRU investigated a number of alternative disinfection methods and completed several studies to reduce HAA5, including covering the chlorine contact basins (CCBs) to reduce ultraviolet (UV) degradation and lower chlorine feed rates, peracetic acid addition in lieu of chlorine addition, and DBPs precursors removal using alum and polyaluminum chloride/polymer before filtration. The polyaluminum chloride study showed reduced HAA5 formation, but created unacceptable effluent turbidity levels. An ozone system, followed by an UV system, could reliably meet the strict KWRF effluent DBPs and disinfection limits, but these two systems required a large capital expenditure and a significant increase in the annual operations and maintenance (O&M) costs. Jones Edmunds proposed the sequential chlorination and chloramination disinfection methods to control DBP formation, meet the fecal coliform requirements, and significantly reduce capital, operation, and maintenance costs at the KWRF.

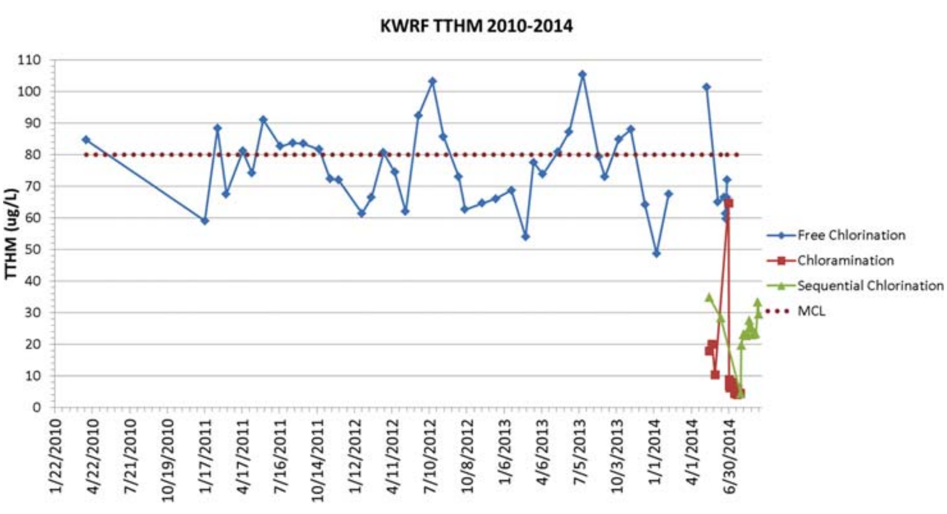

Figure 1. Effluent Total Trihalomethane Concentrations, 2010-2014

Sequential Chlorination Disinfection

As Figure 3 shows, sequential chlorination disinfection involves free chlorination, followed by chloramination. A sequential chlorination system allowed substantial capital and O&M cost savings by using the existing chlorine contact basin and chlorine storage and feed system. This disinfection method only required the addition of an ammonia storage and feed system.

Chloramine disinfection processes generally form much fewer TTHMs and HAA5 than free chlorine (Hua and Reckhow, 2008). Chloramine disinfection, commonly referred to as chloramination, has been identified as a cost-effective technology to reduce wastewater DBP formation (Bober, 2007; Brandes et al, 2008; Erdal et al, 2008; Hua and Yeats, 2010; Maguin et al, 2009). Chloramines are weaker disinfectants than free chlorine; however, chloramines are more stable than free chlorine and will provide a longer-lasting disinfectant residual. Many full-scale studies have shown that chloramination is an effective method to disinfect treated domestic wastewater (Erdal et al, 2008; Maguin et al, 2009). Wastewater chloramination may produce some emerging byproducts, such as N-Nitrosodimethylamine (NDMA) and cyanogens. As a result, sequential chlorination disinfection was developed to reduce NDMA formation in wastewater. Sequential chlorination is a two-step process and consists of a free-chlorine disinfection step, followed by a chloramination step. In the first step, free chlorine is added to a fully nitrified effluent to inactivate pathogens and oxidize inorganic and organic compounds. Ammonia is added in the second step to form chloramines, which stops the formation of DBPs and provides chloramine disinfection. Full-scale applications of sequential chlorination have shown

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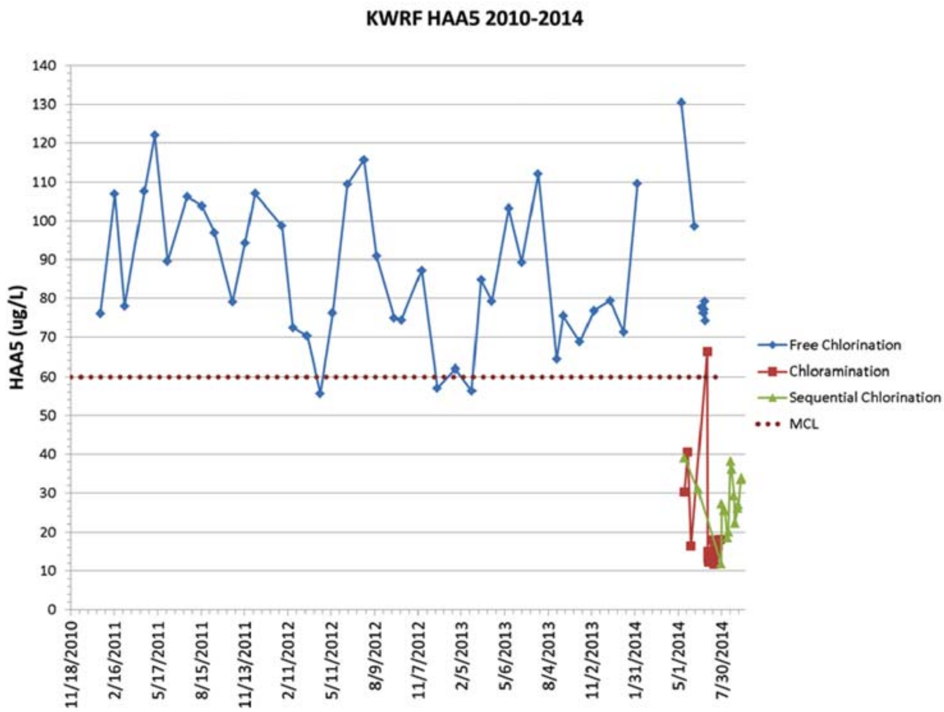

Figure 2. Effluent Haloacetic Acids Concentrations, 2010-2014

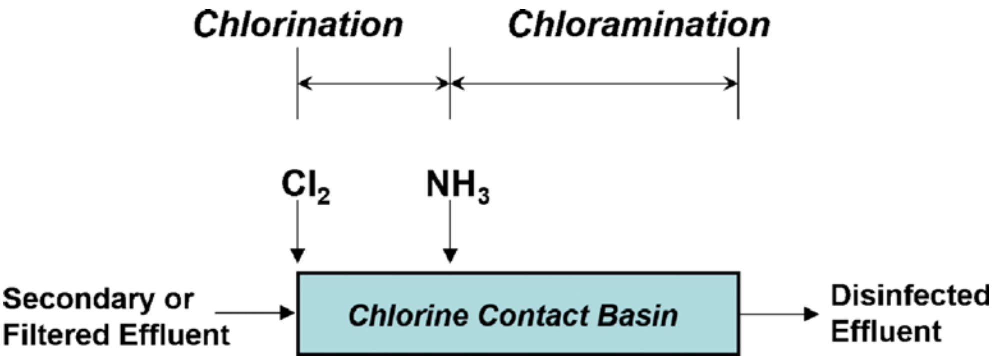

Figure 3. Sequential Chlorination Disinfection

Table 1. Chemical Properties of Ammonium

Specific Gravity	1.2
% $(NH_4)_2SO_4$ by Weight in Solution	40
Density lb/gal	10.0
lb $(NH_4)_2SO_4$/gal Solution	4.0
lb N/gal	0.85
pH	4.0 to 5.0

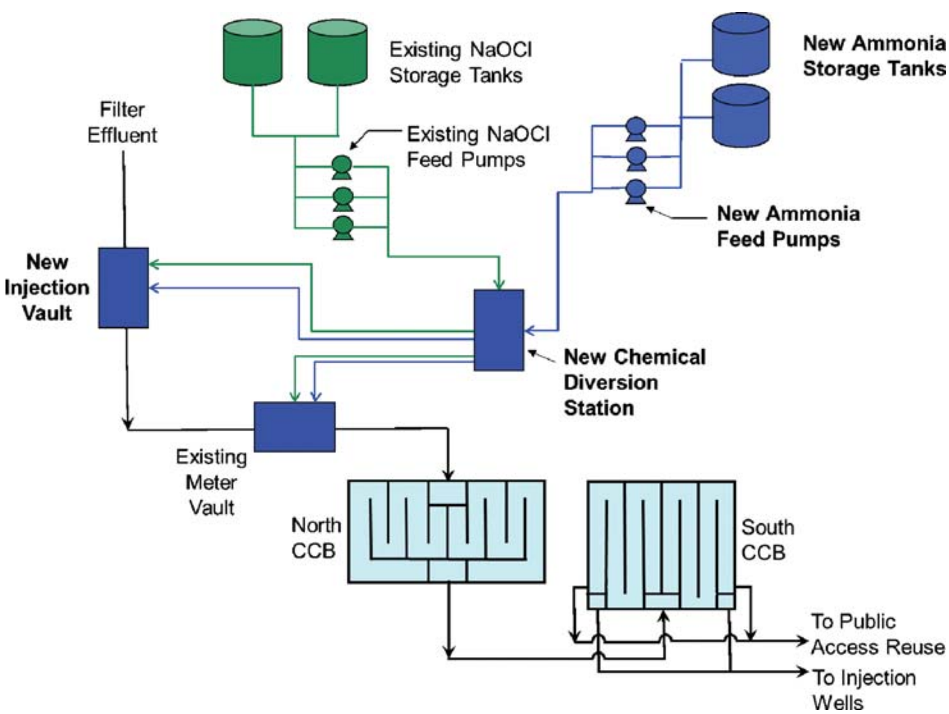

Figure 4. Kanapaha Water Reclamation Facility Disinfection System Improvements Schematic

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that the prechlorination step can effectively oxidize precursors for some nitrogenous DBPs, such as NDMA and cyanogens (Maguin et al, 2009). Full-scale studies have shown that sequential chlorination exhibits excellent inactivation of coliform bacteria and viruses in filtered wastewater (Maguin et al, 2009). Full-scale implementations of chloramination and sequential chlorination disinfection at wastewater treatment plants owned and operated by the Sanitation Districts of Los Angeles County, Calif.; the Somerset Raritan Valley Sewerage Authority, Bridgewater, N.J.; and the Mountain View Wastewater Treatment Facility, Wayne Township, N.J., have shown that these alternative chlorine disinfection methods effectively achieve high levels of disinfection (low fecal coliform counts) and low DBP limits.

Pilot Study

Jones Edmunds performed a bench scale and a three-month pilot study at the KWRF to evaluate the performance of the sequential chlorination and chloramination disinfection methods (Hua et al, 2010). The results of the pilot studies showed that sequential chlorination with a short free-chlorine contact time (0.5 to 9 minutes) and a total contact time of 100 minutes of completely inactivated fecal and total coliforms. The average TTHM concentrations of the pilot-scale tests ranged from 5 to 40 µg/L, and the average HAA5 concentrations ranged from 12 to 37 µg/L. The TTHM and HAA5 pilot results were well below the compliance limits of 80 and 60 µg/L, respectively. Based on the results of the pilot testing, GRU retained Jones Edmunds to design the sequential chlorination and chloramination improvements at KWRF.

Ammonia Source Selection

The sequential chlorination and chloramination systems required the construction of a new ammonia storage and feed system. Commercially available forms of ammonia include anhydrous ammonia, ammonium hydroxide, and ammonium sulfate. The GRU evaluated the three ammonia sources and decided to use ammonium sulfate as the ammonia source. Although ammonium sulfate is typically more expensive than other ammonia sources, GRU selected ammonium sulfate based on the following operational advantages:

- Reduced safety concerns and risk for operators and the community
- Reduced O&M

- Self-contained breathing apparatus not required
- Class A spill response suits/personnel not required
- Maintenance of ammonia sensors (sensors not needed)
- Nonscale forming at points of addition
- Odorless and nonvolatile (minimal off-gassing)
- Stable and easy to handle
- Less hazardous if contacted
- Has less expensive storage facilities and does not require stainless steel pressurized storage tanks, ammonia off-gas sensors, air-conditioned storage building with scrubbers, and stainless steel/corrosion resistant piping/pumps as required by the other ammonia sources.

Table 1 presents the typical chemical properties of ammonium sulfate solution (40 percent) supplied to the KWRF by Dumont in Oviedo.

Implementation

Jones Edmunds designed the disinfection system improvements to have the flexibility of operating in three modes: (1) free chlorination, (2) sequential chlorination, and (3) chloramination. The disinfection system improvements included the following:

- Ammonia storage and feed buildings
- Ammonia and sodium hypochlorite feed piping and chemical diversion station
- Chemical injection vaults and injection points
- Ammonia and chlorine analyzers and building
- Plant supervisory control and data acquisition (SCADA) system additions and modifications

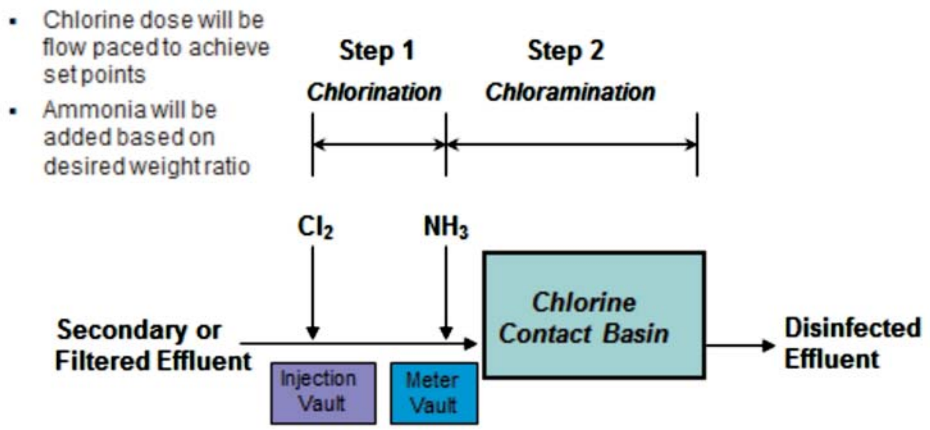

Figure 5. Sequential Chlorination Disinfection Process

Figure 4 is a schematic showing the improvements to the disinfection system.

Sequential Chlorination Mode

In the sequential chlorination mode, the existing sodium hypochlorite feed system will add free chlorine to the filtered effluent at the new chemical injection vault immediately downstream of the postfilter basin (filter clearwell). The new ammonium sulfate feed system will add ammonia to the chlorinated effluent at the existing meter vault downstream of the postfilter basin. Free-chlorine residual will be continuously monitored at the point upstream of the ammonia addition. Figure 5 is a basic schematic of the sequential chlorination process.

The ammonium sulfate dosage is based on the flow, chlorine residual, and the design chlorine-to-ammonia ratio (refer to Table 2). Figure 6 shows that if the Cl_2-to-NH_3-N ratio is kept in the 3:1 to 5:1 range, the desired stable monochloramine (NH_2Cl) is formed. The primary benefits for the initial free chlorination step in the sequential chlorination mode are greater disinfection efficiency (greater initial pathogen kill) and color removal by quick oxidation reactions. The primary benefits of the chloramination step following free chlorination are reduced DBPs formation, effective disinfection, and a longer-lasting total chlorine residual.

Chloramination Mode

In the chloramination disinfection mode, an ammonia analyzer at the postfilter basin continuously monitors the ammonia concentration in the filter effluent. The ammonium sulfate feed system adds ammonia to the new chemical injection vault immediately downstream of the postfilter basin, as shown in Figure 7. The sodium hypochlorite feed system adds chlorine in response to the measured

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Chlorine Dose	5 to 10 mg/L
Ammonia Dose	1 to 2 mg/L as N
Cl_2 to NH_3-N Mass Ratio	4 to 5
Chlorine Injection Point (New)	Chemical Injection Vault
Ammonia Injection Point (New)	Effluent Flow Meter Vault

Table 2. Sequential Chlorination Operating Mode

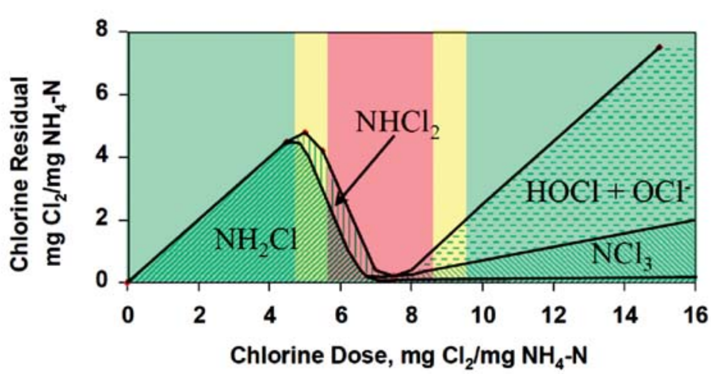

Figure 6. Theoretical Breakpoint Curve

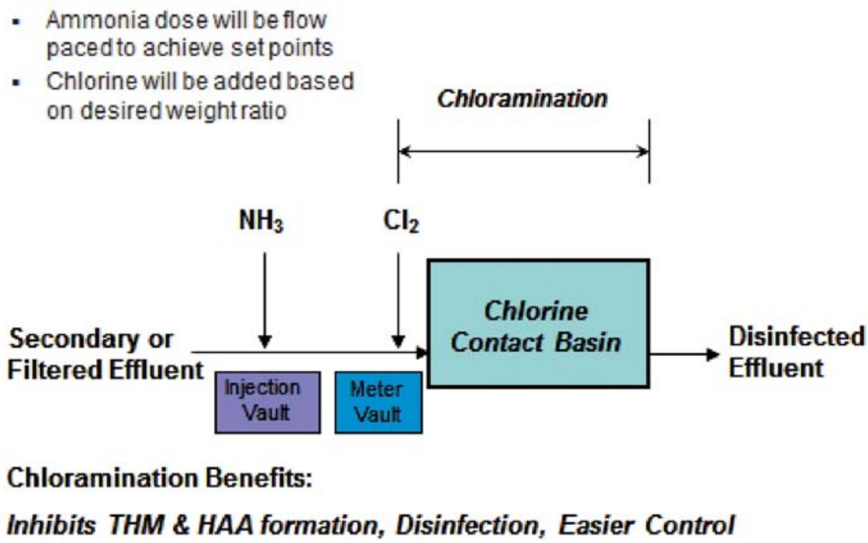

Figure 7. Chloramination Disinfection Process

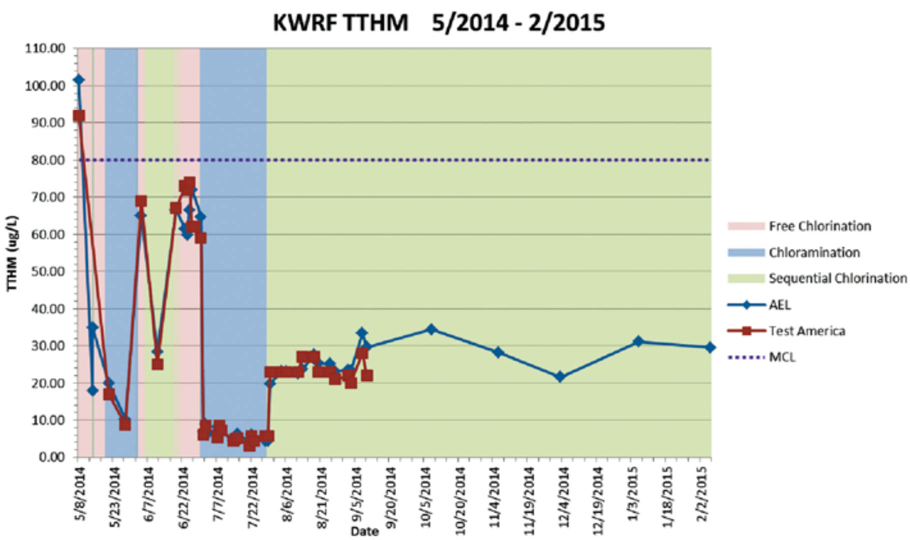

Figure 8. Trihalomethane Final Effluent Concentrations During Startup, Testing, and to the Present

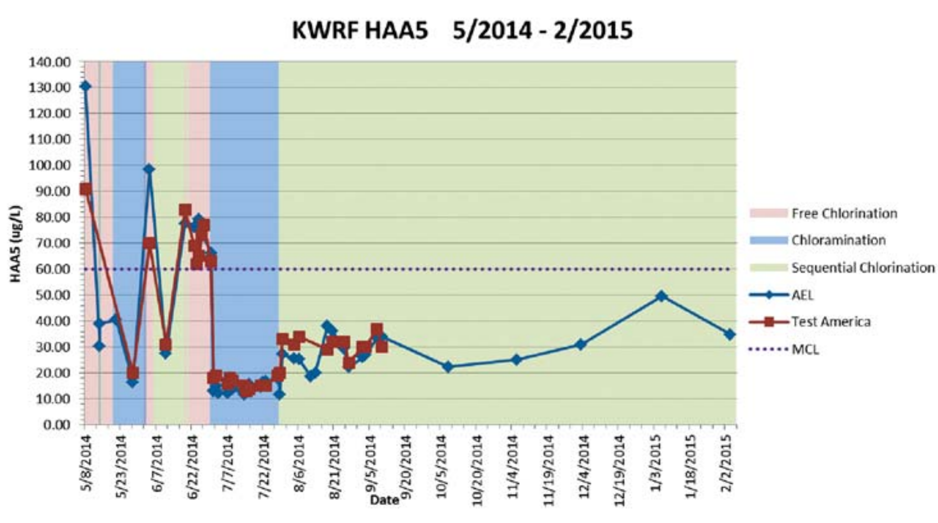

Figure 9. Haloacetic Acids Final Effluent Concentrations During Startup, Testing, and to the Present

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ammonia at the meter vault downstream of the ammonia addition point. The chlorine dosage will be based on the flow, ammonia concentration, and target chlorine-to-ammonia mass ratio.

Operators control the modes of disinfection (free, sequential, chloramination) through the KWRF's SCADA system. The operators set chemical dosages, alternate chemical feed pump operations, and meter chemical usage at the operations center control room.

Results

The GRU required a 60-day reliability and performance acceptance testing period at the conclusion of the construction of the system to verify that consistent operations and a compliant effluent were achieved. After the system was tested and accepted, and system training was completed, GRU's KWRF operating staff fine-tuned the controls and set points, and improved the performance of the system in free chlorination, chloramination, and sequential chlorination disinfection modes. Figures 8 and 9 show the system's ability to meet the DBP standards for the three modes of operation. Samples were sent to two certified laboratories to verify the effectiveness of the new disinfection system. Both sequential chlorination and chloramination disinfection modes have been demonstrated to be very effective at reducing final effluent TTHM and HAA5 concentrations below the regulatory limits of 80 µg/L and 60 µg/L, respectively, and meet all fecal coliform disinfection requirements.

Conclusion

The KWRF has been in full compliance with the TTHMs and HAA5 since the completion and testing of the full-scale sequential chlorination and chloramination systems in July 2014. Implementation of the sequential chlorination and chloramination systems avoided a complex transition to an alternative disinfection system. These systems have saved GRU an estimated $8.5 million in new capital expenditures by avoiding a more complex UV and ozone disinfection system. The final design and construction cost of the sequential chlorination and chloramination systems was $2.5 million, and the ammonium sulfate chemical cost is estimated to be about $80,000 per year (FY2015). Future efforts at the KWRF will evaluate the potential chemical cost savings associated with operating in chloramination disinfection mode by optimizing chlorine and ammonia feed and control systems and using a partially nitrified filter effluent as an ammonia source.

Acknowlegments

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