

## Article

# Transforming Water Supplies in the Midwest: Two CBAT Pilots Demonstrate the Potential for Water Reuse

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## Abstract

Population growth, increasing water demands for data centers, and the need for more sustainable water practices are prompting advancement of next-generation water resource management strategies including water reuse. In the Midwestern United States (U.S.), where non-traditional approaches to augmenting water supply, including water reuse, are relatively new, full advanced water treatment (AWT), which includes microfiltration/ultrafiltration (MF/UF) and reverse osmosis (RO), produces a concentrate stream that is expensive to address (i.e., brine disposal). Carbon-based advanced treatment (CBAT), which combines ozonation, biofiltration, and granular activated carbon, has been shown to be a viable alternative with select advantages over the traditional RO approach, including the lack of brine generation. Two novel pilots were conducted in the Midwestern U.S., one at a large (>100 MGD) and one at a small (~10 MGD) wastewater reclamation facility (WRF), to provide proof of concept that CBAT could meet distinct regional needs. While additional demonstration data are ultimately needed for future regulatory approvals, results from the pilots showed that water quality objectives were met with treated water quality of <0.5 mg/L total Kjeldal nitrogen (TKN), <2 mg/L total organic carbon (TOC), and substantial reduction in constituents of emerging concern (CECs). If nitrate removal is required to meet drinking water standards (10 mg/L), additional treatment optimization at the source WRFs would be required. Areas for further research identified by this effort include mitigating the potential for ozonation to contribute to the formation of disinfection byproducts such as bromate and N-nitrosodimethylamine (NDMA). Along with the treatment performance demonstrated at these pilots, the study provided an opportunity to engage with key stakeholders to build trust in the AWT approach, which is critically important for regulatory and public acceptance. Based on two field-scale pilot studies in the U.S. Midwest, this paper analyzes CBAT application advantages and challenges in municipal water reuse and identifies research directions for the industry.



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**Keywords:** reuse; advanced water treatment; carbon-based advanced treatment; Midwest; disinfection by-products; ozone, biofiltration, granular activated carbon

## 1. Introduction

Due to a number of emerging factors, including population growth, increased water demands for data centers, and an emphasis on more sustainable water practices, water reuse is gaining acceptance as an option in a diversified portfolio of water supply options [1]. Importantly, these trends are driving growth in water demands in specific geographies,

including the Midwestern United States (U.S.), where non-traditional approaches to augmenting water supply are relatively new. The concept of addressing these water supply needs through water reuse has prompted the formation of new WaterReuse Association chapters in states including Ohio, Illinois, and Kansas. In the context of this move toward considering water reuse in integrated water supply planning, utilities are exploring advanced water treatment (AWT) for non-potable and potable reuse applications [2]. Due to the lack of previous experience with water reuse in the U.S. Midwest, there is a gap in identifying potential treatment options for augmenting water supplies. While it will be important to develop a body of evidence for this practice at additional locations and for a longer period, initial pilot testing can be a supporting mechanism for developing this regional experience.

To identify options for these inland facilities, it is important to consider that AWT for water reuse is built around multi-barrier “treatment trains” that combine physical, chemical, and biological processes to achieve required levels of pathogen and contaminant removal. The most established configuration of AWT for high-quality applications, including potable reuse, is microfiltration/ultrafiltration (MF/UF) → reverse osmosis (RO) → advanced oxidation process (with ultraviolet light and hydrogen peroxide, UV/H<sub>2</sub>O<sub>2</sub>), which provides high removal of pathogens, salts, and trace organics. While this treatment train has traditionally been considered as a regulatory benchmark in many regions [3], challenges do exist with this approach. Capital and operating costs, energy, and brine management challenges of this treatment train have driven growing adoption of non-RO based potable reuse approaches, especially at inland sites. Key examples of these include the F. Wayne Hill Water Resources Center, owned and operated by the Gwinnett County Department of Water Resources, GA, and the Upper Occoquan Service Authority (UOSA), VA [4].

One promising AWT approach that addresses the issues associated with RO concentrate is carbon-based advanced treatment (CBAT), which integrates ozone, biofiltration, and granular activated carbon (GAC) in a multi-barrier process to convert treated wastewater effluent into high-quality reclaimed water. This configuration is an efficient option for addressing a wide spectrum of water quality parameters (microorganisms, organic contaminants, and emerging contaminants) for a variety of reuse applications, including potable, non-potable, and industrial applications. The Hampton Roads Sanitation District (HRSD), VA’s Sustainable Water Initiative for Tomorrow (SWIFT), is another excellent example of a utility leveraging this non-RO based approach to augment drinking water supplies [5], and communities like Franklin, TN that have piloted a CBAT plan to incorporate CBAT as an AWT scheme into their integrated portfolio of water-supply treatment options [6]. Additionally, CBAT may offer economic advantages for inland utilities and has been shown to be less than half the cost of a comparable traditional Full Advanced Treatment (FAT) process when certain brine disposal options are considered [7]. Table 1 presents a general comparison of membrane-based advanced treatment trains and CBAT for potable reuse.

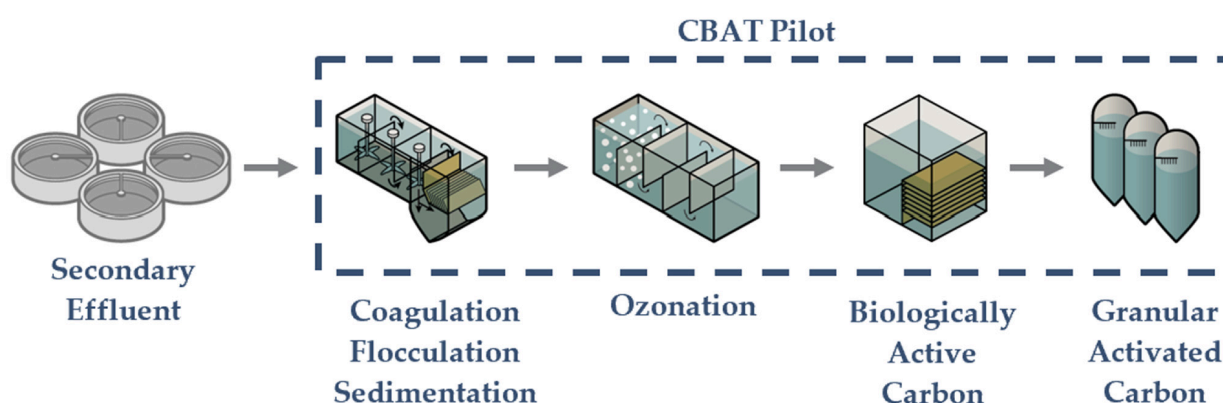
Two pilot studies were conducted as a novel approach to demonstrating a proof of concept regarding the feasibility and versatility of CBAT in the Midwest, where no regulatory framework for water reuse exists. The pilot treatment train included chemical pretreatment with coagulation, flocculation, and sedimentation (CFS), followed by ozone, two biologically activated carbon (BAC) filters in series, and two GAC filters in series. A process flow diagram is shown in Figure 1.

Additionally, pilot testing of CBAT in the Midwest is a novel approach to stakeholder engagement, where proof of concept for reducing uncertainty and establishing a credible technical foundation for water reuse can be demonstrated. This is critically important in a region where both treatment experience and regulatory structure are still emerging. With only a few full-scale CBAT systems implemented in the U.S., these pilots conducted at

both large (>100 MGD) and small (10 MGD) utilities serve as critical early demonstrations of performance to inform feasibility. These pilots aimed to show how CBAT (Figure 1) performed under Midwest-specific conditions, including geographically unique water quality characteristics influenced by the land use and development of the region, which features a mix of rapid residential growth, legacy industrial use, modern high-technology investments, and large-scale agriculture. By generating high-quality, region-specific data, these efforts will help regulators, utilities, and engineers better understand treatment performance, operational complexity, and design requirements in a context that differs from regions where high-quality reuse applications are well-established [8]. For comparison with other utilities operating CBAT for water reuse, Table 2 summarizes key qualitative characteristics evaluated as part of this study, along with those of other CBAT systems used for inland potable reuse applications.

**Table 1.** Comparison of carbon-based and membrane-based advanced treatment for potable reuse.

|                                        | Carbon-Based Advanced Treatment                                                       | Membrane-Based Advanced Treatment                                                                       |
|----------------------------------------|---------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------|
| Core Treatment Processes               | Ozonation, Biofiltration, GAC, UV (advanced oxidation either accompanies ozone or UV) | MF/UF, NF/RO, UV/H <sub>2</sub> O <sub>2</sub>                                                          |
| Multiple Chemical Contaminant Barriers | Yes                                                                                   | Yes                                                                                                     |
| Multiple Pathogen Treatment Barriers   | Yes                                                                                   | Yes                                                                                                     |
| Dissolved Solids Removal               | No                                                                                    | Yes                                                                                                     |
| Water Quality Considerations           | Suitability of treatment processes to influent water quality                          | Chemical compatibility of treated water quality with receiving waters (aquifers or distribution system) |
| Operational Complexity                 | Less complex processes, generally requiring greater operator intervention             | Highly complex but generally more automated processes                                                   |
| Capital and Operating Costs            | Generally Lower                                                                       | Generally Higher                                                                                        |
| Waste Stream Management Considerations | Spent filter/contactor media handling                                                 | Concentrate/brine handling                                                                              |
| Regulatory Considerations              | Less commonly regulated                                                               | More commonly regulated, considered benchmark technology                                                |



**Figure 1.** Process flow diagram of CBAT.

Equally important to demonstrating treatment performance, these pilots are supporting the broader institutional and social groundwork needed for the adoption of water reuse as a strategic water supply option [9]. In the absence of an established Midwest regulatory framework, these novel pilot studies provide the technical evidence required to inform discussions around future guidance and policy development. They create a shared basis of understanding among utilities, regulators, and public stakeholders, helping to build trust in CBAT as a viable alternative to more conventional approaches based on RO. By demonstrating feasibility at different scales and transparently evaluating performance, these projects support

long-term operations planning and considerations for workforce readiness. Ultimately, the motivation extends beyond technology validation to enabling a diversified portfolio of options in integrated water supply strategies, positioning reuse as a locally appropriate solution to meet water demands as resource pressures continue to grow in the Midwest.

**Table 2.** Comparison of select CBAT systems for water reuse in the U.S.

| Utility                                   | Two Undisclosed<br>(This Study)                                                 | Gwinnett County, GA                                             | HRSD, VA                                                                   | Franklin, TN                                                                        |
|-------------------------------------------|---------------------------------------------------------------------------------|-----------------------------------------------------------------|----------------------------------------------------------------------------|-------------------------------------------------------------------------------------|
| Geographical Location                     | U.S. Midwest                                                                    | U.S. Southeast                                                  | U.S. Mid-Atlantic                                                          | U.S. Upper South                                                                    |
| Nearby Ocean for Potential Brine Disposal | No                                                                              | No                                                              | Potentially                                                                | No                                                                                  |
| Upstream Wastewater Treatment             | Secondary effluent from a conventional activated sludge facility                | Tertiary effluent from a conventional activated sludge facility | Secondary effluent from conventional activated sludge facility             | Tertiary effluent from a conventional activated sludge facility                     |
| Operational Status                        | Pilot scale completed                                                           | Full-scale in operation                                         | Demonstration facility (1 MGD) in operation, full-scale under construction | Pilot scale completed, full-scale in design                                         |
| Core Operational Features                 | Potential non-potable reuse and indirect potable reuse via groundwater recharge | Surface water augmentation for indirect potable reuse           | Aquifer recharge for indirect potable reuse                                | Planned non-potable reuse and surface water augmentation for indirect potable reuse |
| State-Level Reuse Regulations             | Not yet established                                                             | Guidance only                                                   | Established approach                                                       | Under development                                                                   |

## 2. Materials and Methods

The AWT pilot was constructed by Intuitech, Inc. (Salt Lake City, UT, USA) and consisted of three treatment skids inside a modified shipping container. The unit treatment processes included: coagulation-flocculation-sedimentation (CFS) (Intuitech S300), ozone (Intuitech Z400), biofiltration and granular activated carbon (Intuitech F1200). Dedicated feed pumps for each skid were installed with overflows strategically placed between the treatment processes to allow for flexibility in modifying flow rates and treatment configurations. The flow rates through the pilot were approximately 5 gallons per minute (gpm) through the CFS skid, 2.5 gpm through the ozone skid, and 1 gpm through the filter skid. A programmable logic controller (PLC)-based SCADA system and human-machine interface (HMI) screens on each skid enabled both local operator control at the pilot trailer and remote access for adjustment of key operational parameters and alarm diagnostics.

The pilot operated in multiple phases at each site, with different objectives described in the following sections. Water temperatures in the pilot influent ranged from an average of approximately 55 to 65 °F (approximately 13 to 18 °C) from February to June in Pilot Study 1 and from an average of approximately 68 to 73 °F (approximately 20 to 23 °C) from July to August in Pilot Study 2. Each pilot study operated with all unit processes in service except where otherwise noted.

At each of the two facilities where pilot testing was conducted, secondary clarifier effluent was pumped to the pilot trailer and conveyed through the AWT train. Both studies included coagulation-flocculation-sedimentation as the first treatment step, with the goal of lowering turbidity and reducing particle loading onto the downstream filters. The coagulant selected for each pilot study was dosed into the rapid mix basin on the CFS skid. Pilot Study 1 used ferric chloride at a dose of 50 mg/L and Pilot Study 2 used aluminum chlorohydrate (ACH) at a dose varying between 35 and 40 mg/L. The water then passed through a flocculation basin with 60 min of retention time followed by a sedimentation basin with 45 min of retention time. The sedimentation basin included plate settlers to increase the effective settling area in the small footprint of the pilot trailer.

Clarified water was pumped to the ozone skid, which had two ozone contact basins available with over-under baffles and a fine bubble diffuser. One basin was actively used during each study, providing a retention time of 50 min. Because 50 min was greater than the time required for ozone concentrations to decay to zero residual, the second contactor was not needed. Ozone is a strong chemical oxidant and disinfectant that improves the biodegradability of organic compounds [10]. When combined with downstream biofiltration, ozone improves the removal of organic compounds through the filters and can strengthen the performance of BAC filters and GAC contactors; accordingly, ozone-biofiltration is a viable and commonly utilized advanced water treatment technology [11]. The ozone dosing strategy was based on targeted ozone to total organic carbon (ozone/TOC) ratios at certain project phases and experiments, such as an ozone/TOC ratio of approximately 0.5 for transforming bulk organic matter and trace organic contaminants, and higher ratios at or above an ozone/TOC ratio of approximately 1.0 that is on the scale of that used for disinfection where a substantial ozone residual persists in the contactor. These targets have been informed by potable reuse regulations in other states [12] as well as recent research [13]. The applied ozone dose was recorded, and online measurements of ozone off-gas were used to calculate the real-time transferred ozone dose that was achieved. Additionally, ozone residual measurements were collected at 10 min contact time.

Ozonated water was pumped to the filtration skid, first passing through two BAC filter columns in series. BAC filters are typically paired immediately downstream of ozonation for polishing of organic matter, nutrients, and certain emerging contaminants by the bacterial communities present on the biofilm of the filter media [14,15]. A total of 10 to 15 min of contact time was provided in each of the two BAC filters for over 20 min of overall empty bed contact time (EBCT). Acclimated BAC media was collected from a full-scale drinking water facility running BAC as part of its normal treatment process. The donor facility used Norit GAC 816 (Norit Activated Carbon, Horsham, PA, USA) that was installed in approximately 2015. The BAC media from Pilot Study 1 was reused in Pilot Study 2. Upon optimization of the filtration process as described in the subsequent sections, the typical backwashing frequency for the BAC filter columns was every 48 to 72 h.

Following the second BAC filter, water passed through two GAC contactor columns in series. GAC media provides removal of organic compounds and emerging contaminants, such as per- and polyfluoroalkyl substances (PFAS), through the mechanism of adsorption to pores on the surface of the media [16,17]. A total of 10 to 15 min of contact time was provided in each of the two GAC contactors for over 20 min of overall EBCT. Virgin GAC (Filtrisorb 300<sup>®</sup>, Calgon Carbon Corporation, Moon Township, PA, USA) was used in Pilot Study 1, with the same media reused in Pilot Study 2. Typical backwashing frequency of the GAC contactor columns was once per month. Table 3 summarizes the physical characteristics of the BAC and GAC media used for both pilots.

Throughout the duration of each pilot, comprehensive water quality monitoring was conducted across the AWT train. In addition to the robust set of conventional parameters that were monitored, disinfection byproducts (DBPs), pharmaceuticals and personal care products (PPCPs), and other organic and inorganic contaminants were also measured. Each week, over 20 water quality parameters were tested across the treatment train (Appendix A, Table A1). Ultimately, over two hundred unique water quality parameters were sampled and analyzed (Appendix A, Table A2). Most of the weekly testing was conducted by the pilot operations team, while some samples were sent to a local laboratory for analysis. A larger suite of analytes was tested two to three times at each location. These samples were sent out for analysis to both the local laboratory, Alloway Environmental Company (now Eurofins Scientific), and to Eurofins Scientific. Both laboratories are accredited by the National Environmental Laboratory Accreditation Program (NELAP). Information regarding chains of custody, accreditation, and

quality control practices can be found at each institute's respective website. Each pilot study included additional testing unique to the site.

**Table 3.** BAC and GAC media characteristics.

| Parameter                             | BAC Filter Media      | GAC Contactor Media    |
|---------------------------------------|-----------------------|------------------------|
| Iodine Number (mg/g)                  | 900 (min)             | 900 (min)              |
| Moisture by Weight                    | 2% (max)              | 2% (max)               |
| Effective Size (mm)                   | 1.3–1.5               | 0.8–1.0                |
| Uniformity Coefficient                | 1.4 (max)             | 2.1 (max)              |
| Abrasion Number                       | 75 (min)              | 78 (min)               |
| Mesh Size                             |                       |                        |
| Greater than:                         | 8 mesh (2.36 mm): 15% | 8 mesh (2.36 mm): 15%  |
| Less than:                            | 16 mesh (1.18 mm): 4% | 30 mesh (0.595 mm): 4% |
| Apparent Density (g/cm <sup>3</sup> ) | 0.51                  | 0.56                   |

Statistical analyses were performed for various water quality parameters in RStudio (2026.01.0) using R version 4.5.1 [18]. Any sample replicates (a particular parameter sampled at the same location and time) were averaged before analysis. Unless otherwise specified, statistical tests were performed using the base R statistics package stats. Excel data were imported into R with the readxl package and formatted using the tidyverse package [19,20]. For each parameter, distributional assumptions were evaluated for each sample location group using the Shapiro-Wilk test for normality, supplemented by visual inspection via quantile-quantile (Q-Q) plots, and equal variance assumptions were evaluated using both Bartlett's and Levene's tests. Levene's test was performed using the car package [21]. Because violations of normality were observed across all parameters, nonparametric statistical methods were applied. Specifically, differences between sample locations were evaluated using the Kruskal-Wallis rank-sum test, followed by Dunn's test for post hoc pairwise comparisons. Dunn's Test was performed using the FSA package [22], with *p*-values adjusted using the Holm-Bonferroni method to control the family-wise error rate.

### 2.1. Pilot Study 1 Description

Pilot Study 1 was conducted using the secondary effluent water (the AWT feed, or feed water) of a conventional activated sludge (CAS) treatment facility with a permitted average design flow of 10 MGD. The pilot was conducted with the objective of assessing whether sufficient water quality could be met to augment drinking water supplies without producing a concentrated stream. The service area contributing flow to the facility consists primarily of residential wastewater inputs. At this pilot, ferric chloride was used as the coagulant and was added to a rapid mix chamber. Jar tests were performed to obtain a starting ferric chloride dose. Soda ash was used for alkalinity and pH adjustment necessitated by using ferric chloride (which lowers pH) as well as for maintaining an optimal pH for BAC. Soda ash was applied immediately before the ozone contactor. Additional water quality testing at this pilot study location included PFAS (persistent, man-made "forever chemicals" used in industrial and consumer products and that are resistant to natural degradation and treatment), microplastics (University of Missouri, manuscript in preparation), nitrogenous DBPs (N-DBPs, currently unregulated DBPs that form when organic nitrogen precursors are present and are of concern due to their higher toxicity than regulated DBPs, manuscript in preparation), and pathogens (manuscript in preparation). Table 4 shows the operational phases performed during the duration of Pilot Study 1.

**Table 4.** Operational phases in Pilot Study 1.

| Phase                         | Description                                                                                                                                                                                                                                                                                                                                                                                              | Duration |
|-------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------|
| Phase 1:<br>CFS Optimization  | CFS optimization included varying the coagulant (ferric chloride) dose, rapid mixing and flocculation speeds, and sedimentation blowdown intervals to optimize floc formation and particle removal.                                                                                                                                                                                                      | 1 month  |
| Phase 2:<br>BAC Optimization  | Air and water backwash rates and intervals were varied to optimize filter runtimes, along with pH adjustment with soda ash for biofiltration optimization.                                                                                                                                                                                                                                               | 2 weeks  |
| Phase 3:<br>Steady State      | The pilot was run with minimal changes to operating conditions. Flow rates and chemical doses were generally constant, and 21 min of EBCT were provided through BAC (10 min in BAC column 1 followed by 11 min in BAC column 2) and 28 min through GAC (13 min in GAC column 1 followed by 15 min in GAC column 2). Ozone doses were varied based on a transferred ozone/TOC ratio between 0.75 and 1.0. | 3 weeks  |
| Phase 4:<br>Challenge Testing | This phase included testing the performance of the ozone-biofiltration processes by varying the transferred ozone/TOC ratio between 0.5 and 1.2 while reducing BAC EBCT to a total of 10 min (by using one BAC column only).                                                                                                                                                                             | 1 month  |

## 2.2. Pilot Study 2 Description

The second pilot was conducted using the secondary effluent water of a major conventional activated sludge WRF that receives residential and industrial waste streams and flow from combined sewers, with a permitted average design flow of 114 MGD and a peak hydraulic capacity of 330 MGD. The objective of the pilot was to determine whether the system could provide water quality suitable for industrial reuse as well as potentially groundwater recharge for indirect potable reuse. Table 5 shows the breakdown of the operational phases of Pilot Study 2.

**Table 5.** Operational phases in Pilot Study 2.

| Phase                                        | Description                                                                                                                                                                                                                                                                                                                                                                                                                        | Duration |
|----------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------|
| Phase 1:<br>Startup and Commissioning        | Startup and commissioning involved maintenance, troubleshooting, and jar testing of various coagulants. This phase also included external process and power connections.                                                                                                                                                                                                                                                           | 1 week   |
| Phase 2:<br>BAC Optimization and Maintenance | Air and water backwash rates and intervals were varied to optimize filter runtimes and establish ideal conditions for biofiltration. During this period, a failure of the ozone mass flow controllers resulted in the ozone skid being offline for approximately two weeks while a manual bypass was prepared.                                                                                                                     | 3 weeks  |
| Phase 3:<br>CFS Optimization                 | CFS optimization included varying the coagulant (ACH) dose, rapid mixing and flocculation speeds, and sedimentation blowdown interval to optimize floc formation and particle removal. During this period, there was a failure of the air conditioning system for the pilot enclosure, resulting in the pilot being offline for one week. Ozone, BAC, and GAC skids were shut down during this time, leaving only the CFS running. | 2 weeks  |
| Phase 4: Challenge Testing                   | Challenge testing involved assessing the limits and performance of the treatment processes by changing coagulant dose and varying the transferred ozone/TOC ratio between 0.5 and 1.0 while maintaining a constant EBCT through BAC and GAC. The same EBCTs were used as in Pilot Study 1, a total of 21 min through BAC and a total of 28 min through GAC.                                                                        | 3 weeks  |

Jar tests were performed with ferric chloride, polyaluminum chloride (PACL), and ACH to determine the optimal coagulant for the water source. Ultimately, ACH was selected as it showed strong settleability and did not necessitate pH adjustment downstream.

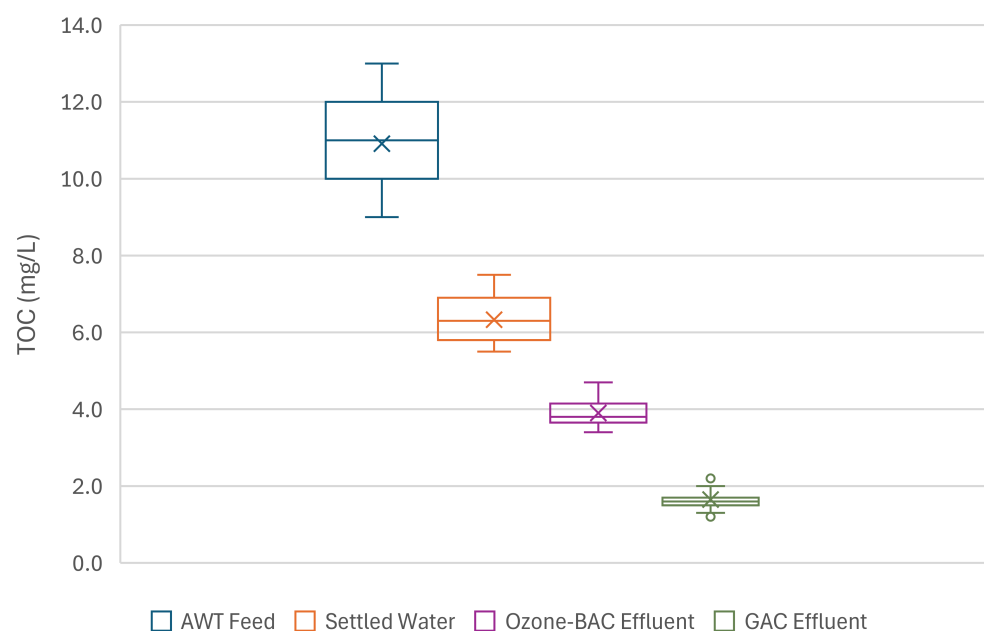
Additional parameters tested at Pilot Study 2 included microplastics (University of Missouri, manuscript in preparation), toxicity bioassays (INDIGO Biosciences, manuscript in preparation), and pathogen analysis (H<sub>2</sub>O Molecular, manuscript in preparation). Due to the relatively high total dissolved solids (TDS) encountered at this facility, with expectations for increased TDS in the future due to new industry discharges, bench-scale hollow-fiber nanofiltration (HFNF) was investigated as an auxiliary treatment process option for selective ion removal to lower TDS. Bench-scale HFNF testing was performed using an NX Filtration Mexplorer Pilot Unit with a MP025-PVC dNF80 (800 Dalton cutoff) membrane module (NX Filtration, Enschede, The Netherlands). HFNF can potentially offer important advantages over RO for some inland water reuse applications. The HFNF membrane configuration provides exceptionally high packing densities (~500–3000 m<sup>2</sup>/m<sup>3</sup>), yielding substantially greater membrane surface area per unit volume than spiral-wound membranes and enabling higher throughput with a smaller footprint. HFNF membranes exhibit superior fouling resistance and support routine hydraulic backwashing, allowing effective performance recovery and improved tolerance to variable and high-foulant feed waters, capabilities that are not available in spiral-wound NF or RO systems. In addition, HFNF can achieve high water-recovery rates (>95% in certain applications), significantly reducing the volume of concentrate produced. Compared with RO, HFNF typically requires lower energy input for applications targeting selective TDS reduction (e.g., divalent ion removal), while emerging membrane materials also offer enhanced chemical stability for more aggressive cleaning. Collectively, these attributes make HFNF a compact, energy-efficient, and operationally robust alternative to traditional RO and NF membranes, especially in inland reuse settings where concentrate management is a key constraint.

Settled water and BAC effluent samples were tested at an effective 80% recovery (achieved by concentrating the influent water to 20% of its original volume using the dNF80 with a recirculating concentrate line and the permeate line to waste) in order to mimic the recovery of typical full-scale systems. The crossflow velocity was approximately 0.3 m/s with a membrane flux ranging from 44 to 50 L/m<sup>2</sup>-h (LMH). Projection models were also run to compare bench-scale versus modeled HFNF and to compare HFNF to other TDS removal membranes. This modeling included an NX Filtration dNF80 membrane (like used at bench-scale), an NX Filtration dNF40 membrane (400 Dalton cutoff), a DuPont NF270 spiral wound membrane (DuPont, Edina, MN, USA), and a DuPont BW30 RO membrane (DuPont, Edina, MN, USA). Modeling was performed using NX Filtration's projection tool (NX Filtration, Hengelo, The Netherlands) and DuPont's WAVE, projection tool, v1.83, Database 63 (DuPont, Wilmington, DE, USA).

### 3. Results

#### 3.1. Pilot Study 1

Comprehensive water quality monitoring for Pilot Study 1 was conducted across the advanced treatment train, including conventional water quality parameters, organic contaminants, inorganic contaminants, and emerging contaminants. Results of the water quality monitoring demonstrated substantial removal of key constituents. This was exemplified in Figure 2, which shows a consistent trend in TOC reduction across the treatment train. Overall, there was a substantial reduction in TOC (85%) from approximately 11 mg/L to 1.7 mg/L, which is on the order of typical drinking water concentrations.

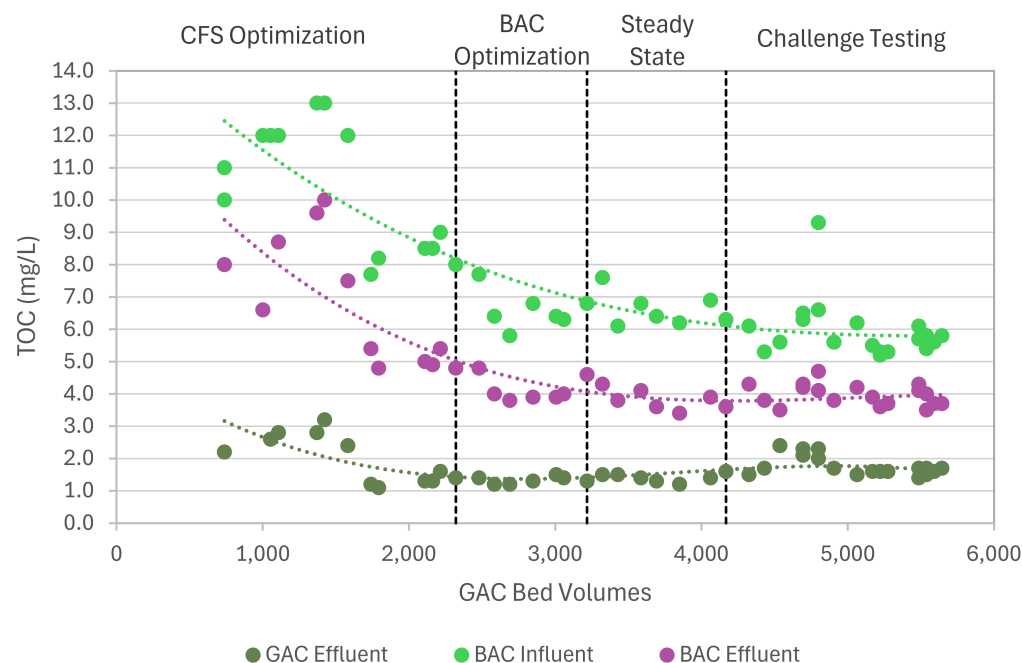


**Figure 2.** Substantial TOC removal occurred across the Pilot Study 1 treatment train. Data includes samples collected during steady state and challenge testing, following CFS and BAC optimization.

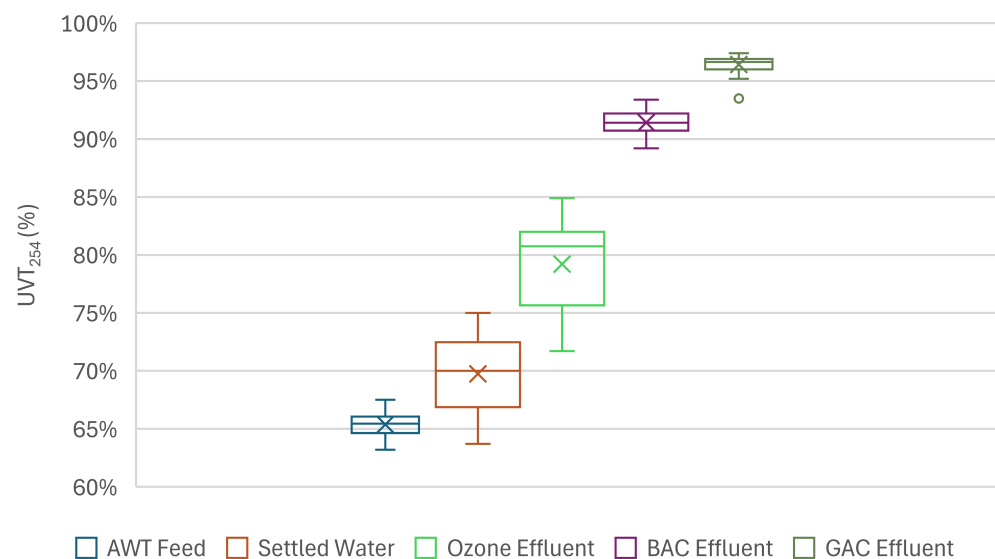
The boxes in Figure 2, as with subsequent box plots in other figures throughout this manuscript, encompass the interquartile range (IQR, 25th to 75th percentiles), with the central horizontal line indicating the median and “x” denoting the average. Whiskers extend to the furthest data within 1.5 times the IQR of the quartiles; points beyond the whiskers represent outliers. The Kruskal-Wallis test indicated a significant difference in TOC concentrations across the treatment train ( $\chi^2 = 91.03$ ,  $df = 3$ ,  $p < 0.0001$ ). Post hoc pairwise analysis using Dunn’s Test with a Holm adjustment confirmed that every treatment stage achieved a statistically significant reduction in TOC from the preceding stage ( $p < 0.05$ ). Lowercase letters in parentheses indicate statistically unique groups based on pairwise comparisons; treatment stages sharing no common letters are significantly different ( $p < 0.05$ ; AWT Feed = a; Settled Water = b; Ozone-BAC Effluent = c; GAC Effluent = d).

Notably, the acclimated BAC demonstrated biomass stabilization between 2000 and 3000 bed volumes, following CFS optimization, when BAC effluent TOC concentrations were maintained at  $<4$  mg/L. Similarly, GAC columns showed substantial initial adsorption capacity during CFS optimization with TOC stabilizing to under 2 mg/L during steady state (Figure 3).

UV Transmittance (UVT, specifically UVT<sub>254</sub>), another surrogate for tracking natural organic matter (NOM), also showed substantial improvement throughout treatment from approximately 65% in the AWT feed, to 79% after ozone, and to 96% after GAC (Figure 4). The boxes shown in the figure encompass the IQR, with the central horizontal line indicating the median and “x” denoting the average. Whiskers extend to the furthest data within 1.5 times the IQR of the quartiles; points beyond the whiskers represent outliers. The Kruskal-Wallis test indicated a significant difference in UVT concentrations across the treatment train ( $\chi^2 = 148.63$ ,  $df = 4$ ,  $p < 0.0001$ ). Post hoc pairwise analysis using Dunn’s Test with a Holm adjustment confirmed that every treatment stage achieved a statistically significant increase in UVT from the preceding stage ( $p < 0.05$ ). Lowercase letters in parentheses indicate statistically unique groups based on pairwise comparisons; treatment stages sharing no common letters are significantly different ( $p < 0.05$ ; AWT Feed = a; Settled Water = b; Ozone Effluent = c; BAC effluent = d, GAC Effluent = e).



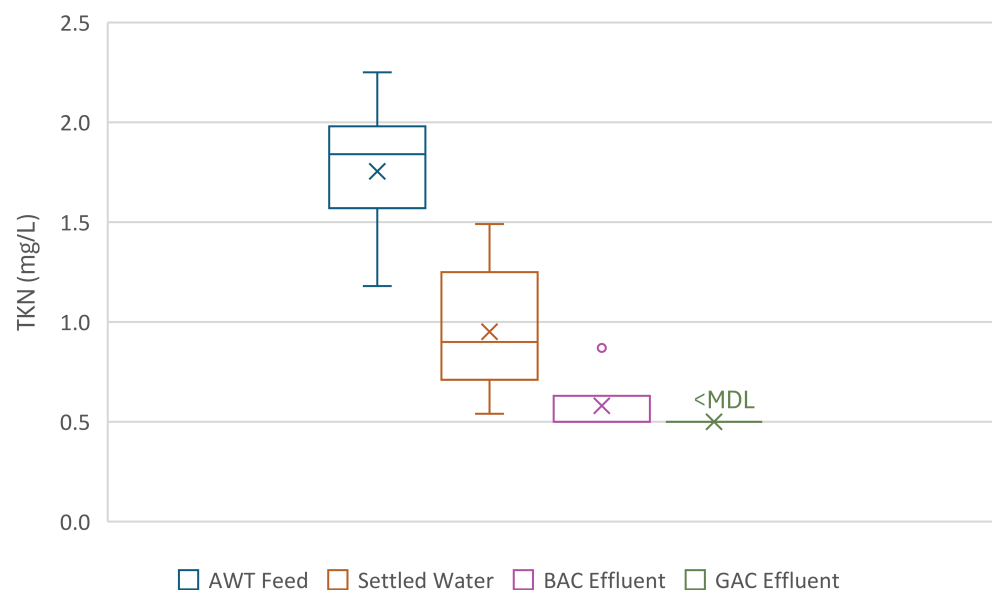
**Figure 3.** TOC versus GAC Bed Volumes for BAC influent, BAC effluent (which is the GAC influent), and GAC effluent. Trendlines are shown as third-order polynomials for visual reference only.



**Figure 4.** UV<sub>T</sub> increased substantially across the Pilot Study 1 treatment train. Data includes samples collected during steady state and challenge testing, following CFS and BAC optimization.

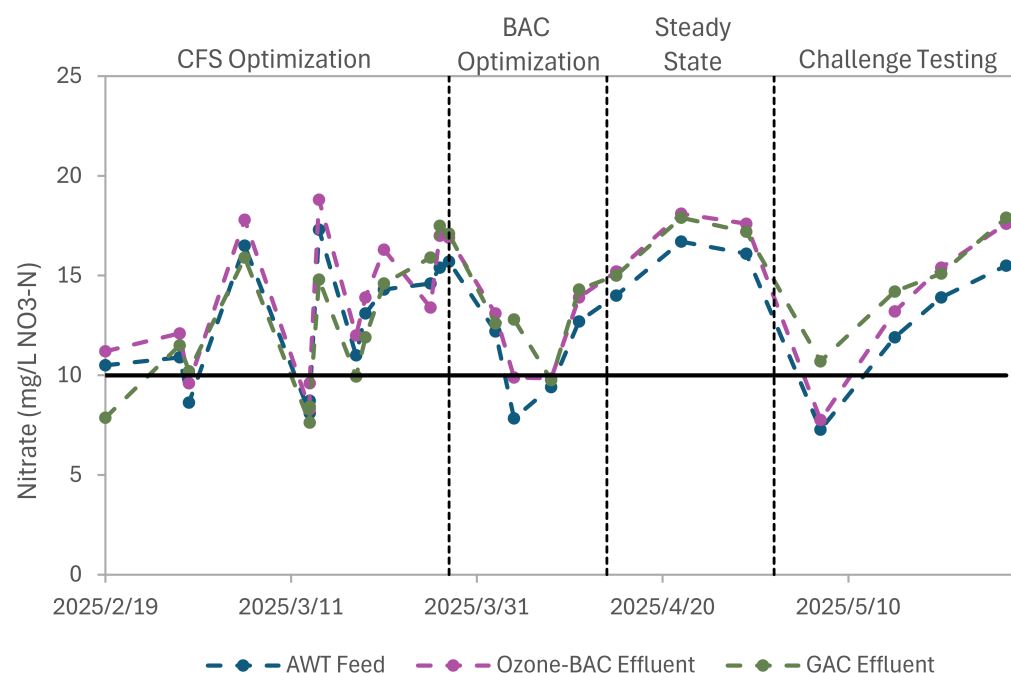
Total Kjeldahl Nitrogen (TKN), which is the sum of organic nitrogen and ammonia, is well removed through ozone-biofiltration, where ozone increases biodegradability and the biofilter biologically degrades bioavailable nitrogen. The TKN concentrations (Figure 5) were reduced from just under 2 mg/L in the pilot feed to below the MDL of 0.5 mg/L, indicating high rates of treatment. The boxes shown in the figure encompass the IQR, with the central horizontal line indicating the median and “x” denoting the average. Whiskers extend to the furthest data within 1.5 times the IQR of the quartiles; points beyond the whiskers represent outliers. The Kruskal-Wallis test indicated a significant difference in TKN concentrations across the treatment train ( $\chi^2 = 23.00$ ,  $df = 3$ ,  $p < 0.0001$ ). Post hoc pairwise analysis using Dunn’s Test with a Holm adjustment was used to evaluate TKN changes between stages ( $p < 0.05$ ). Lowercase letters in parentheses indicate statistically unique groups based on pairwise comparisons; treatment stages sharing no common

letters are significantly different ( $p < 0.05$ ; AWT Feed = a; Settled Water = ab; Ozone-BAC Effluent = b; GAC Effluent = b).



**Figure 5.** Effective TKN removal occurred across the treatment train for Pilot Study 1. Data includes samples collected during steady state and challenge testing, following CFS and BAC optimization.

Except for nitrate, all GAC effluent parameters measured during Pilot Study 1 were below their respective U.S. Environmental Protection Agency (EPA) Drinking Water Maximum Contaminant Levels (MCLs). Nitrate through the pilot with time is shown in Figure 6, with an average concentration of 13.6 mg/L over the duration of the study, compared to the MCL of 10 mg/L.



**Figure 6.** Nitrate (as NO<sub>3</sub>-N) over time across Pilot Study 1. The horizontal line at 10 mg/L represents the EPA drinking water MCL.

The average pilot feed and GAC effluent concentrations for conventional water quality parameters, along with percent change in the concentrations, for Pilot Study 1 are presented in Table 6. Data include occasional replicate sampling that was conducted (sampling at the same location and time for a particular parameter). Results equal to the MDL are reported as the MDL in this table.

**Table 6.** Pilot Study 1 conventional water quality parameters and percent change. Data include samples collected during steady state and challenge testing, following CFS and BAC optimization.

| Parameter                   | Units                  | Average AWT Feed Value | Standard Deviation (Sample) | Average GAC Effluent Value | Standard Deviation (Sample) | % Change |
|-----------------------------|------------------------|------------------------|-----------------------------|----------------------------|-----------------------------|----------|
| Conductivity                | mS/cm                  | 0.87                   | 0.05                        | 1.00                       | 0.05                        | +16%     |
| Turbidity                   | NTU                    | 2.71                   | 0.86                        | 0.15                       | 0.05                        | −94%     |
| UVT-254                     | %                      | 65                     | 0.01                        | 97                         | 0.01                        | +47%     |
| DO                          | mg/L                   | 7.26                   | 0.39                        | 11.53                      | 1.39                        | +59%     |
| pH                          | N/A                    | 6.58                   | 0.14                        | 6.70                       | 0.12                        | −2%      |
| Total Alkalinity            | mg/L-CaCO <sub>3</sub> | 101                    | 24.90                       | 107.7                      | 14.89                       | +7%      |
| Nitrate                     | mg/L-N                 | 13.9                   | 3.06                        | 15.7                       | 2.53                        | +14%     |
| Nitrite                     | mg/L-N                 | 0.547                  | 0.05                        | 0.012                      | 0.01                        | −98%     |
| Ammonia                     | mg/L-N                 | 0.109                  | 0.05                        | 0.015                      | 0.00                        | −86%     |
| Total Phosphorus            | mg/L-P                 | 0.24                   | 0.05                        | 0.01                       | 0.02                        | −94%     |
| Soluble Reactive Phosphorus | mg/L-PO <sub>4</sub>   | 0.21                   | 0.15                        | <MDL                       | 0.00                        | −100%    |
| Total COD                   | mg/L                   | 38.3                   | 3.22                        | 4.57                       | 2.18                        | −88%     |
| TDS                         | mg/L                   | 540                    | 15.0                        | 581                        | 26.2                        | +8%      |
| TSS                         | mg/L                   | 5.88                   | 1.91                        | 0.80                       | 0.75                        | −86%     |
| CBOD                        | mg/L                   | 4.37                   | 0.88                        | 2.00                       | 0.00                        | −54%     |
| TKN                         | mg/L                   | 1.75                   | 0.34                        | 0.5                        | 0.00                        | −71%     |
| DOC                         | mg/L                   | 10.1                   | 0.95                        | 2.1                        | 0.72                        | −80%     |
| TOC                         | mg/L                   | 10.9                   | 1.10                        | 1.7                        | 0.31                        | −85%     |

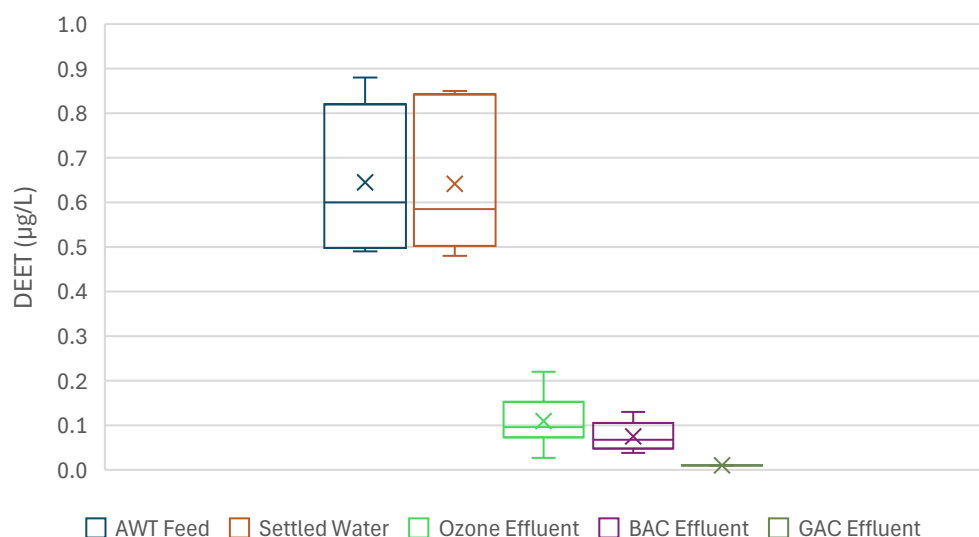
In addition to conventional parameters, 212 unique constituents were evaluated in Pilot Study 1, including DBPs, PPCPs, PFAS, and other organic and inorganic constituents. Of these, 174 parameters were not detected (were less than the method detection limit, MDL) in the AWT feed water throughout sampling. The non-detected AWT feed water constituents included all tested polychlorobiphenyls (PCBs, a group of legacy chemicals used for their thermal resistance that, while banned, are persistent in the environment), volatile organic compounds (VOCs), and microcystins (a group of toxic cyanotoxins produced by certain blue-green algae). Of the measured constituents, 38 were detected above their MDLs, including certain halogenated DBPs, synthetic organic compounds (SOCs), pesticides, PFAS, PPCPs, and N-DBPs.

Table 7 summarizes the average, standard deviation, and number of samples for constituent detections in AWT feed water. Following treatment, 13 parameters were detected in the final GAC effluent:

- Low levels of 1,4-dioxane were detected in the effluent near the MDL of 0.07 ug/L, reduced from an average of 0.083 ug/L in the AWT feed water. 1,4-dioxane is a synthetic industrial chemical primarily used as a solvent and a stabilizer for chlorinated solvents. It is used as a treatment indicator in water reuse because it is exceptionally difficult to remove using standard treatment methods.
- Low levels of tris(2-chloroethyl) phosphate (TCEP) were detected in the effluent near the MDL of 0.01 ug/L, reduced from an average of 0.064 ug/L in the AWT feed water. TCEP is a flame retardant and plasticizer frequently assessed in water reuse because it is ubiquitous and highly persistent in the environment.
- Low concentrations of N,N-Diethyl-meta-toluamide (DEET), at less than 1 ug/L, were detected in the AWT feed water well under the Minnesota guidance value of 200 ug/L [23]. DEET is an active ingredient in personal insect repellents, and an indicator of human impact in water reuse. DEET was mostly removed by ozone and

was typically under the MDL of 0.01  $\mu\text{g/L}$  after GAC, as shown in Figure 7. The boxes shown in the figure encompass the IQR, with the central horizontal line indicating the median and “x” denoting the average. Whiskers extend to the furthest data within 1.5 times the IQR of the quartiles; points beyond the whiskers represent outliers. The Kruskal-Wallis test indicated a significant difference in DEET concentrations across the treatment train ( $\chi^2 = 25.47$ ,  $\text{df} = 4$ ,  $p < 0.0001$ ). Post hoc pairwise analysis using Dunn’s Test with a Holm adjustment was used to evaluate DEET changes between stages ( $p < 0.05$ ). Lowercase letters in parentheses indicate statistically unique groups based on pairwise comparisons; treatment stages sharing no common letters are significantly different ( $p < 0.05$ ; AWT Feed = a; Settled Water = a; Ozone Effluent = ab; BAC effluent = ab; GAC Effluent = b).

- Three shorter chain PFAS compounds were detected in the final GAC effluent, each at increasing concentrations as the pilot testing continued. Perfluorobutanoic acid (PFBA) was detected at a maximum concentration of 7.55  $\text{ng/L}$ , Perfluorohexanoic acid (PFHxA) at a maximum concentration of 8.40  $\text{ng/L}$ , and Perfluoropentanoic acid (PFPeA) at a maximum concentration of 9.90  $\text{ng/L}$ .
- Detections of four PPCP compounds were observed throughout the pilot, including primidone at an average of 0.0087  $\mu\text{g/L}$ , caffeine at an average of 0.0117  $\mu\text{g/L}$ , metformin at an average of 1.66  $\mu\text{g/L}$ , and cotinine at an average of 0.0056  $\mu\text{g/L}$ . These compounds do not have federal or state guidelines and are not included on the proposed Contaminant Candidate List 6 (CCL 6) [24].
- Two N-DBPs were detected in the final effluent. N-nitrosodiphenylamine (NDPA) was detected on one occasion at 23  $\text{ng/L}$ , and N-nitrosomorpholine (NMOR) was detected several times near the MDL of 2.00  $\text{ng/L}$ . These nitrosamines are not currently regulated compounds; they may form during ozonation in the presence of certain precursors and are important in potable reuse because many are potent carcinogens.
- Gross Beta particles were detected in the effluent once at 10  $\text{pCi/L}$ , which is below the EPA screening trigger level of 50  $\text{pCi/L}$  [25].



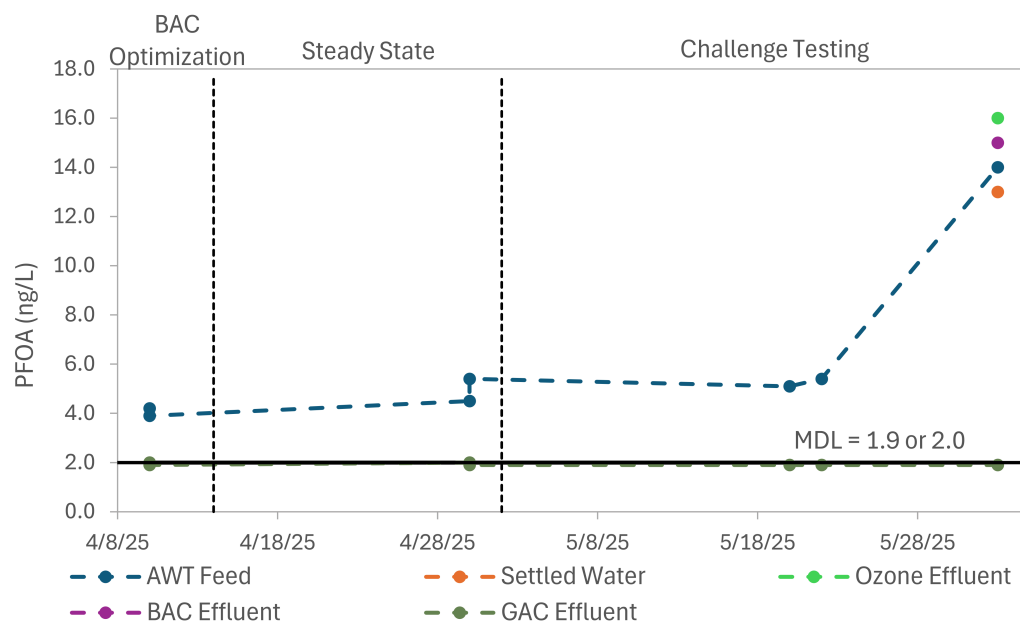
**Figure 7.** Low AWT feed water levels of DEET in Pilot Study 1. Data includes samples collected during steady state and challenge testing, following CFS and BAC optimization.

**Table 7.** Constituent detections above their MDLs in the AWT feed of Pilot Study 1, excluding conventional parameters. Note that some MDL values varied for samples taken at different sampling periods due to the contract laboratory calibration protocols.

| Detected in AWT Feed | Category     | Average Result | Standard Deviation (Sample) | Units | No. of Samples | MDL                  |
|----------------------|--------------|----------------|-----------------------------|-------|----------------|----------------------|
| 1,4-Dioxane          | SOCs         | 0.083          | 0.010                       | ug/L  | 7              | 0.07                 |
| Androstenedione      | PPCPs        | 0.005          | 0.000                       | ug/L  | 7              | 0.01                 |
| Atenolol             | PPCPs        | 0.202          | 0.101                       | ug/L  | 7              | 0.01                 |
| Atrazine             | Pesticides   | 0.093          | 0.041                       | ug/L  | 3              | 0.07                 |
| Azithromycin         | PPCPs        | 0.700          | 0.383                       | ug/L  | 7              | 0.01 or 0.10         |
| Caffeine             | PPCPs        | 0.023          | 0.0159                      | ug/L  | 7              | 0.01                 |
| Carbamazepine        | PPCPs        | 0.103          | 0.047                       | ug/L  | 7              | 0.01                 |
| Chloroform           | DBPs         | 0.583          | 0.098                       | ug/L  | 6              | 0.50                 |
| Cimetidine           | PPCPs        | 0.067          | 0.032                       | ug/L  | 7              | 0.01                 |
| Codeine              | PPCPs        | 0.019          | 0.008                       | ug/L  | 7              | 0.01                 |
| Cotinine             | PPCPs        | 0.021          | 0.005                       | ug/L  | 7              | 0.01                 |
| DCAA                 | DBPs         | 1.033          | 0.058                       | ug/L  | 3              | 1.00                 |
| DEET                 | Pesticides   | 0.567          | 0.254                       | ug/L  | 7              | 0.01                 |
| Diltiazem            | PPCPs        | 0.114          | 0.049                       | ug/L  | 7              | 0.01                 |
| Diphenhydramine      | PPCPs        | 0.335          | 0.203                       | ug/L  | 7              | 0.01 or 0.05         |
| Erythromycin         | PPCPs        | 0.023          | 0.005                       | ug/L  | 7              | 0.02                 |
| Fluoxetine           | PPCPs        | 0.104          | 0.046                       | ug/L  | 7              | 0.01                 |
| Gross Beta           | Radiological | 11.220         | 12.134                      | pCi/L | 2              | 4.00                 |
| Meprobamate          | PPCPs        | 0.015          | 0.007                       | ug/L  | 7              | 0.01                 |
| Metformin            | PPCPs        | 2.543          | 0.637                       | ug/L  | 7              | 0.02 or 0.20         |
| Metolachlor          | Pesticides   | 0.250          | 0.087                       | ug/L  | 3              | 0.20 or 0.19         |
| NDMA                 | N-DBPs       | 2.471          | 0.544                       | ng/L  | 7              | 2.00                 |
| NMOR                 | N-DBPs       | 7.871          | 1.555                       | ng/L  | 7              | 2.00                 |
| Paraxanthine         | PPCPs        | 0.040          | 0.026                       | ug/L  | 7              | 0.02                 |
| PFBA                 | PFAS         | 5.825          | 0.699                       | ng/L  | 4              | 2.00 or 1.90         |
| PFBS                 | PFAS         | 3.850          | 0.887                       | ng/L  | 6              | 2.00 or 1.90         |
| PFHxA                | PFAS         | 12.417         | 4.348                       | ng/L  | 6              | 1.90 or 2.00         |
| PFOA                 | PFAS         | 6.071          | 3.545                       | ng/L  | 7              | 2.00 or 1.90 or 2.10 |
| PFOS                 | PFAS         | 1.971          | 0.076                       | ng/L  | 7              | 2.00 or 1.90 or 2.10 |
| PFPeA                | PFAS         | 11.825         | 2.862                       | ng/L  | 4              | 2.00 or 1.90         |
| Primidone            | PPCPs        | 0.243          | 0.089                       | ug/L  | 7              | 0.01                 |
| SMX                  | PPCPs        | 0.167          | 0.080                       | ug/L  | 7              | 0.01                 |
| Sulfasalazine        | PPCPs        | 0.062          | 0.023                       | ug/L  | 7              | 0.05                 |
| TCAA                 | DBPs         | 1.033          | 0.058                       | ug/L  | 3              | 1.00                 |
| TCEP                 | SOCs         | 0.064          | 0.028                       | ug/L  | 7              | 0.01                 |
| TCPP                 | SOCs         | 0.570          | 0.171                       | ug/L  | 7              | 0.40                 |
| Trimethoprim         | PPCPs        | 0.249          | 0.119                       | ug/L  | 7              | 0.01                 |
| Tylosin              | PPCPs        | 0.006          | 0.001                       | ug/L  | 7              | 0.01                 |

The low perfluorooctanesulfonic acid (PFOS) concentrations (<MDL) in the AWT feed water remained below their EPA drinking water MCLs throughout the treatment train. The detected perfluorooctanoic acid (PFOA) concentrations in the AWT feed water were relatively low, except for a brief period where there may have been an industrial contribution that passed through the plant into the effluent, but this was effectively removed through the BAC and GAC (Figure 8). While PFOA was measured in the pilot influent, it was effectively reduced through the treatment train even during the PFOA spike that occurred during testing (Figure 8). The Kruskal-Wallis test indicated a statistically significant difference in PFOA concentration between the AWT Feed and GAC effluent ( $p = 0.008$ ). Since the figure includes limited sampling for settled water, ozone effluent, and BAC effluent (number of samples,  $n = 1$  at each location), statistical analysis was performed for the AWT feed and

GAC groups only. Lowercase letters in parentheses indicate statistically unique groups ( $p < 0.05$ ; AWT Feed = a; GAC Effluent = b).



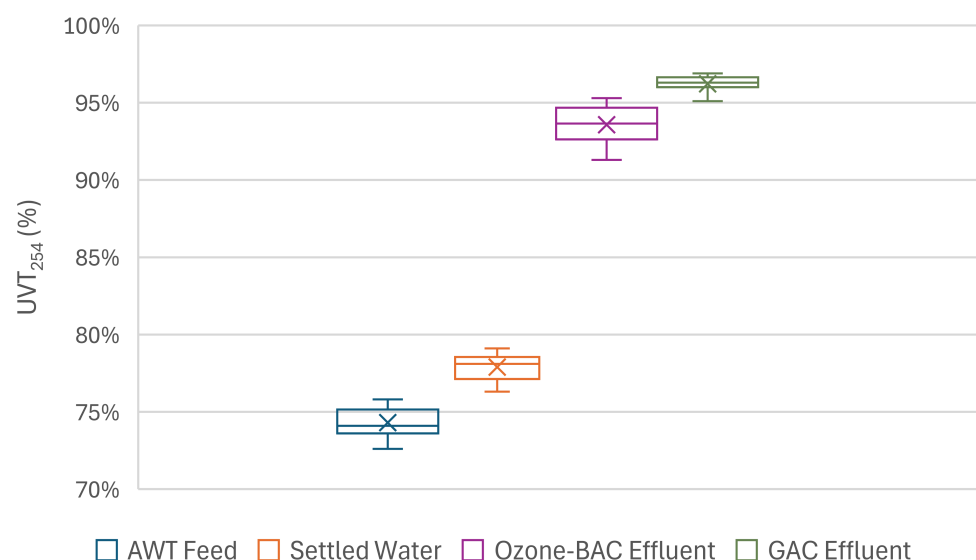
**Figure 8.** PFOA over time during Pilot Study 1, the method detection limit is shown as a horizontal black line, and varied from 1.9–2.0 ng/L.

### 3.2. Pilot Study 2

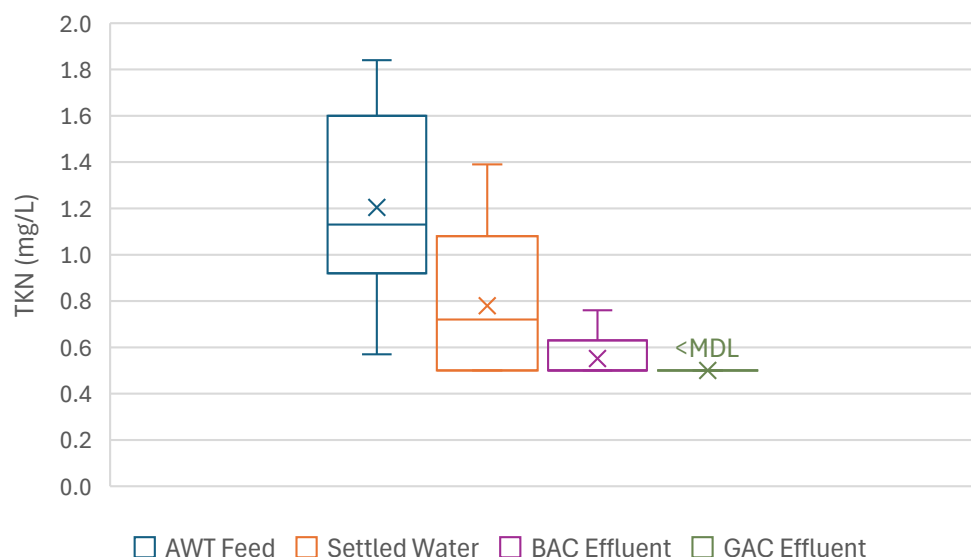
Similar comprehensive water quality monitoring was conducted for Pilot Study 2. Additional testing for Pilot Study 2 included microplastics, toxicity bioassays, pathogen analysis, and bench-scale HFNF. The results showed similar treatment performance to Pilot Study 1 for TOC, UVT, TKN, and nitrate (Figures 9–12, respectively), with unique insights from Pilot Study 2 for TDS management using HFNF and other membrane projections.



**Figure 9.** Substantial TOC removal occurred across the Pilot Study 2 treatment train. Data includes samples collected during challenge testing, following CFS and BAC optimization.

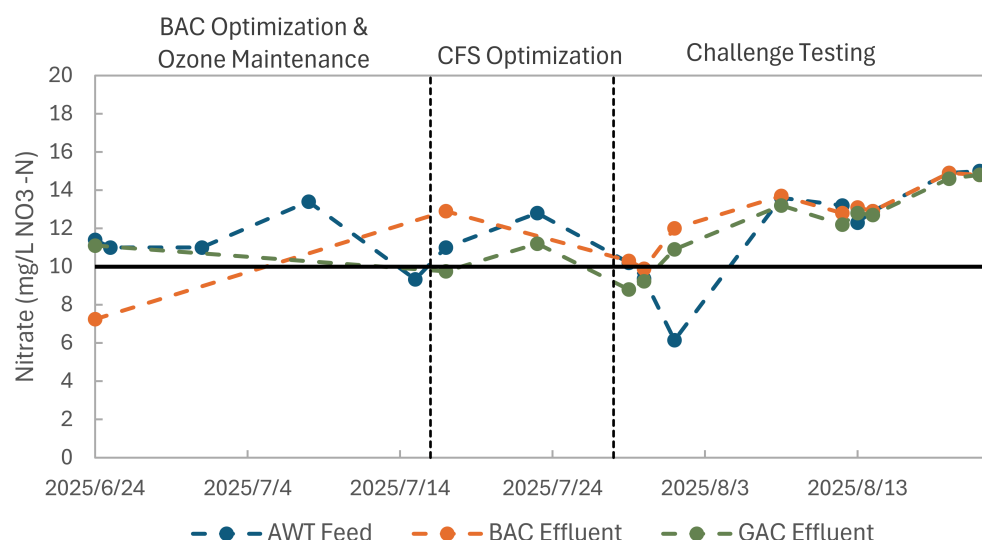


**Figure 10.** UVT increased substantially across the Pilot Study 2 treatment train. Data includes samples collected during challenge testing, following CFS and BAC optimization.



**Figure 11.** Effective TKN removal occurred across the treatment train for Pilot Study 2. Data include samples collected during challenge testing, following CFS and BAC optimization.

TOC was reduced substantially by 72% across the pilot train to approximately 1.8 mg/L, as shown in Figure 9, with the largest reduction occurring through ozone-BAC. The boxes shown in the figure encompass the IQR, with the central horizontal line indicating the median and “x” denoting the average. Whiskers extend to the furthest data within 1.5 times the IQR of the quartiles; points beyond the whiskers represent outliers. The Kruskal-Wallis test indicated a significant difference in TOC concentrations across the treatment train ( $\chi^2 = 60.44$ ,  $df = 3$ ,  $p < 0.0001$ ). Post hoc pairwise analysis using Dunn’s Test with a Holm adjustment confirmed that every treatment stage achieved a statistically significant reduction in TOC from the preceding stage ( $p < 0.05$ ). Lowercase letters in parentheses indicate statistically unique groups based on pairwise comparisons; treatment stages sharing no common letters are significantly different ( $p < 0.05$ ; AWT Feed = a; Settled Water = b; Ozone-BAC Effluent = c; GAC Effluent = d).



**Figure 12.** Nitrate (as NO<sub>3</sub>-N) over time across Pilot Study 2; the horizontal line at 10 mg/L represents the EPA drinking water MCL.

UVT also improved, as shown in Figure 10, which shows an increase from approximately 74% in the AWT feed water to 94% after ozone and BAC and to 96% in the final effluent. The boxes shown in the figure encompass the IQR, with the central horizontal line indicating the median and “x” denoting the average. Whiskers extend to the furthest data within 1.5 times the IQR of the quartiles; points beyond the whiskers represent outliers. The Kruskal-Wallis test indicated a significant difference in UVT concentrations across the treatment train ( $\chi^2 = 73.60$ ,  $df = 3$ ,  $p < 0.0001$ ). Post hoc pairwise analysis using Dunn’s Test with a Holm adjustment confirmed that every treatment stage achieved a statistically significant increase in UVT from the preceding stage ( $p < 0.05$ ). Lowercase letters in parentheses indicate statistically unique groups based on pairwise comparisons; treatment stages sharing no common letters are significantly different ( $p < 0.05$ ; AWT Feed = a; Settled Water = b; Ozone Effluent = c; BAC effluent = d, GAC Effluent = e).

TKN was reduced to the MDL of 0.5 mg/L in the GAC contactor effluent, with CFS and ozone-biofiltration both being major drivers behind TKN removal. The box encompasses the IQR, with the central horizontal line indicating the median and “x” denoting the average. Whiskers extend to the furthest data within 1.5 times the IQR of the quartiles; points beyond the whiskers represent outliers. The Kruskal-Wallis test indicated a significant difference in TKN concentrations across the treatment train ( $\chi^2 = 13.25$ ,  $df = 3$ ,  $p < 0.0041$ ). Post hoc pairwise analysis using Dunn’s Test with a Holm adjustment was used to evaluate TKN changes between stages ( $p < 0.05$ ). Lowercase letters in parentheses indicate statistically unique groups based on pairwise comparisons; treatment stages sharing no common letters are significantly different ( $p < 0.05$ ; AWT Feed = a; Settled Water = ab; Ozone-BAC Effluent = b; GAC Effluent = b).

As in Pilot Study 1, nitrate (NO<sub>3</sub>-N) removal was insignificant during Pilot Study 2, as expected with CBAT processes, and ranged from 6 to 15 mg/L throughout the pilot, compared to the MCL of 10 mg/L (Figure 12).

The average pilot feed and GAC effluent concentrations for conventional water quality parameters, along with the percent change in the concentrations, for Pilot Study 2 are presented in Table 8. Data include occasional replicate sampling that was conducted (sampling at the same location and time for a particular parameter). Results equal to the MDL are reported as the MDL in this table.

**Table 8.** Pilot Study 2 conventional water quality parameters and percent reductions. Data includes samples collected during challenge testing, following CFS and BAC optimization.

| Parameter                   | Units                  | Average AWT Feed Value | Standard Deviation (Sample) | Average GAC Effluent Value | Standard Deviation (Sample) | % Change |
|-----------------------------|------------------------|------------------------|-----------------------------|----------------------------|-----------------------------|----------|
| Conductivity                | mS/cm                  | 0.925                  | 0.03                        | 0.918                      | 0.03                        | −1%      |
| Turbidity                   | NTU                    | 0.86                   | 0.31                        | 0.09                       | 0.01                        | −90%     |
| UVI-254                     | %                      | 74                     | 0.01                        | 96                         | 0.01                        | +30%     |
| DO                          | mg/L                   | 5.64                   | 1.16                        | 12.92                      | 2.30                        | +129%    |
| pH                          | N/A                    | 7.02                   | 0.08                        | 6.89                       | 0.14                        | −2%      |
| Total Alkalinity            | mg/L-CaCO <sub>3</sub> | 130                    | 11.53                       | 127                        | 15.54                       | −2%      |
| Nitrate                     | mg/L-N                 | 12.0                   | 2.89                        | 12.1                       | 2.13                        | +1%      |
| Nitrite                     | mg/L-N                 | 0.054                  | 0.02                        | 0.000                      | 0.00                        | −100%    |
| Ammonia                     | mg/L-N                 | 0.100                  | 0.05                        | 0.015                      | 0.00                        | −85%     |
| Total Phosphorus            | mg/L-PO <sub>4</sub>   | 0.801                  | 0.20                        | 0.183                      | 0.06                        | −77%     |
| Soluble Reactive Phosphorus | mg/L-PO <sub>4</sub>   | 0.541                  | 0.21                        | 0.193                      | 0.06                        | −64%     |
| Total COD                   | mg/L                   | 20.3                   | 2.50                        | 5.8                        | 1.79                        | −72%     |
| TDS                         | mg/L                   | 565                    | 48.6                        | 554                        | 41.7                        | −2%      |
| TSS                         | mg/L                   | 4.0                    | 0.00                        | 4.0                        | 0.00                        | 0%       |
| CBOD                        | mg/L                   | 2.3                    | 0.55                        | 2.0                        | 0.00                        | −12%     |
| TKN                         | mg/L                   | 1.20                   | 0.34                        | 0.5                        | 0.00                        | −58%     |
| DOC                         | mg/L                   | 6.0                    | 0.40                        | 1.9                        | 0.18                        | −69%     |
| TOC                         | mg/L                   | 6.3                    | 0.38                        | 1.8                        | 0.18                        | −72%     |

In addition to conventional parameters, 192 unique constituents were screened in Pilot Study 2 to assess whether the treatment performance was similar to Pilot Study 1, and the testing included a similar list of parameters to those in Pilot Study 1. Throughout testing and sampling, 169 of the measured parameters were not detected (<MDL) in the AWT feed water. The non-detected contaminants included all tested total PCBs, VOCs, and microcystins, as with Pilot Study 1. Of the measured parameters, 23 were above their MDLs in the AWT feed water and included certain SOCs, PPCPs, halogenated DBPs, N-DBPs, radiological particles, and pesticides and herbicides.

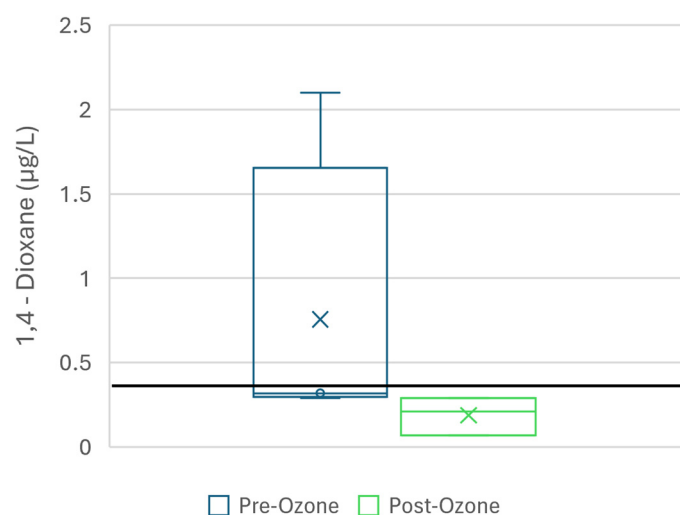
Table 9 includes the average, standard deviation, and numbers of samples for each of the AWT feed detections. Notably, statistical analyses could not be performed on the parameters where only a small number of samples (<3) were collected in this screening evaluation. Eight parameters were detected in the final treated water, including the following:

- Halogenated DBPs: Bromate (detailed later) and very low levels of chloroform (CHCl<sub>3</sub>).
- SOCs: Low levels of 1,4-dioxane that were mostly removed by ozone.
- PPCPs: Acetaminophen and trimethoprim were found near their MDL values, and metformin was also detected.
- N-DBPs: NMOR was detected in the final effluent at approximately 7 mg/L.
- Radiological: Gross Beta particles were detected once at 7 pCi/L, under the EPA screening trigger level of 50 pCi/L.

The CBAT pilot results from the screening study in Pilot Study 2 indicated similar treatment performance to Pilot Study 1 with effective removal of various compounds, including low levels of 1,4-dioxane, a commonly monitored constituent in AWT trains. 1,4-dioxane detected in the AWT feed water was reduced by ozone to below the EPA health advisory level of 0.35 ug/L [26], as shown in Figure 13.

**Table 9.** Constituent detections above their MDLs in the screening study for the AWT Feed of Pilot Study 2, excluding conventional parameters. Note that some MDL values varied for samples taken at different time points due to outside laboratory calibration protocols.

| Detections in AWT Feed Water | Category                  | Average Result | Units | No. of Samples | MDL          |
|------------------------------|---------------------------|----------------|-------|----------------|--------------|
| 1,4-Dioxane                  | SOCs                      | 1.210          | ug/L  | 2              | 0.07         |
| Atenolol                     | PPCPs                     | 0.070          | ug/L  | 2              | 0.01         |
| Atrazine                     | Pesticides and Herbicides | 0.405          | ug/L  | 2              | 0.07         |
| Azithromycin                 | PPCPs                     | 0.365          | ug/L  | 2              | 0.01         |
| Carbamazepine                | PPCPs                     | 0.114          | ug/L  | 2              | 0.01         |
| Chloroform                   | Halogenated DBPs          | 0.665          | ug/L  | 4              | 0.50         |
| Cimetidine                   | PPCPs                     | 0.093          | ug/L  | 2              | 0.01         |
| Diltiazem                    | PPCPs                     | 0.092          | ug/L  | 2              | 0.01         |
| Diphenhydramine              | PPCPs                     | 0.089          | ug/L  | 2              | 0.01         |
| Erythromycin                 | PPCPs                     | 0.029          | ug/L  | 2              | 0.02         |
| Fluoxetine                   | PPCPs                     | 0.067          | ug/L  | 2              | 0.01         |
| Gross Beta                   | Radiological              | 11.220         | pCi/L | 2              | 4.00         |
| Meprobamate                  | PPCPs                     | 0.022          | ug/L  | 2              | 0.01         |
| Metformin                    | PPCPs                     | 0.138          | ug/L  | 2              | 0.02         |
| Metolachlor                  | Pesticides and Herbicides | 0.315          | ug/L  | 2              | 0.20 or 0.19 |
| NDMA                         | N-DBPs                    | 6.725          | ng/L  | 4              | 2.00         |
| NMOR                         | N-DBPs                    | 9.500          | ng/L  | 4              | 2.00         |
| Primidone                    | PPCPs                     | 0.195          | ug/L  | 2              | 0.01         |
| Simazine                     | Pesticides and Herbicides | 0.054          | ug/L  | 2              | 0.05         |
| Sulfamethoxazole             | PPCPs                     | 0.440          | ug/L  | 2              | 0.01         |
| TCEP                         | SOCs                      | 0.073          | ug/L  | 2              | 0.01         |
| TCPP                         | SOCs                      | 0.880          | ug/L  | 2              | 0.40         |
| Trimethoprim                 | PPCPs                     | 0.190          | ug/L  | 2              | 0.01         |

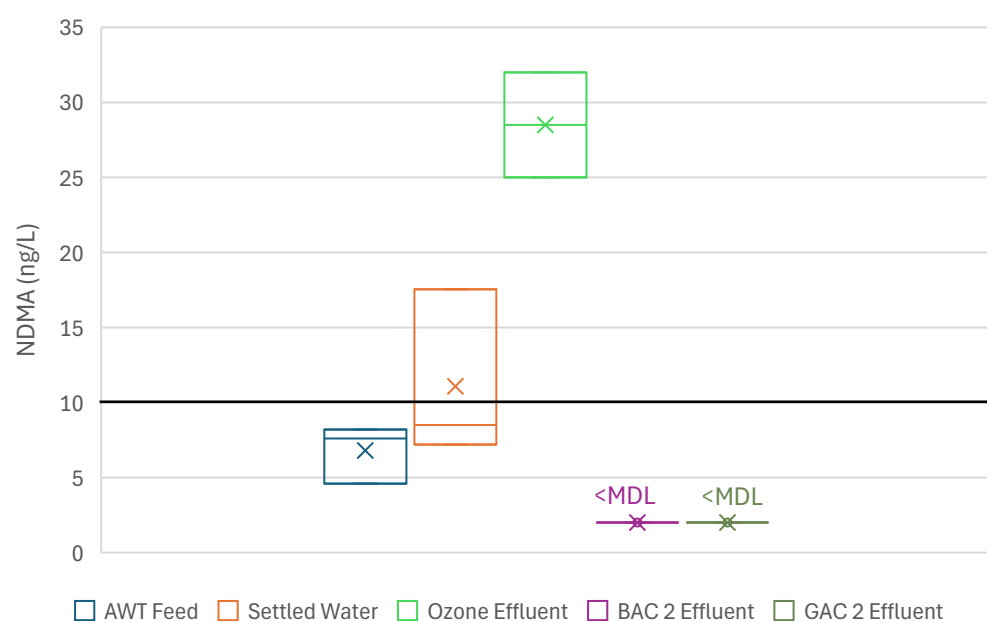


**Figure 13.** 1,4-dioxane removal by ozone. Data includes all samples collected throughout the pilot and the solid horizontal line represents the EPA health advisory level of 0.35 ug/L.

Data shown in Figure 13 compares pre-ozone sampling (AWT feed water or settled water,  $n = 4$ ) with post-ozone sampling (ozone effluent,  $n = 3$ ) for the duration of the pilot, with the transferred ozone/TOC ratio ranging from 0.5 to 1.2. The boxes shown in the

figure encompass the IQR, with the central horizontal line indicating the median and “x” denoting the average. Whiskers extend to the furthest data within 1.5 times the IQR of the quartiles. The Kruskal-Wallis test indicated no statistically significant difference in 1,4-dioxane concentrations from pre-ozone to post-ozone ( $p = 0.074$ ). While a substantial physical reduction was observed following ozone treatment, the small sample size ( $n = 3$  paired dates) limited the statistical power of the analysis.

Additionally, N-nitrosodimethylamine (NDMA), a N-DBP relevant in water reuse applications, was found to increase after ozone to an average of 29 ng/L, then was effectively reduced by BAC to below the MDL and below the California notification level of 10.0 ng/L and the California Public Health Goal of 3.0 ng/L [27], as shown in Figure 14. Data shown in Figure 14 are for the duration of the pilot, with the transferred ozone/TOC ratio ranging from 0.5 to 1.2. The boxes shown in the figure encompass the IQR, with the central horizontal line indicating the median and “x” denoting the average. Whiskers extend to the furthest data within 1.5 times the IQR of the quartiles. The Kruskal-Wallis test indicated a statistically significant difference in NDMA concentrations across the treatment train ( $\chi^2 = 12.14$ ;  $df = 4$ ;  $p = 0.016$ ). However, individual pairwise comparisons could not be distinguished ( $p > 0.05$ ) due to the conservative nature of the Holm correction factor. This lack of distinct grouping is likely due to a low sample size, as unadjusted comparisons indicated a significant drop in the NDMA concentration following ozone treatment ( $p = 0.0064$ ).

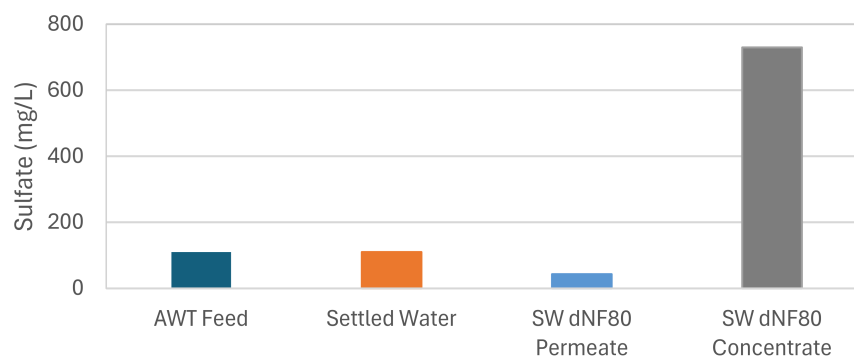


**Figure 14.** NDMA across Pilot Study 2. Data includes all samples collected throughout the pilot when ozone was applied and the horizontal black line represents the California NDMA notification level of 10.0 ng/L.

With exception of nitrate and bromate, all parameters during Pilot Study 2 were measured in the GAC effluent below their respective U.S. EPA Drinking Water MCLs. Bromate was formed by ozone above the EPA drinking water MCL to approximately 30 µg/L average, and with a high event of 65 µg/L (manuscript in preparation).

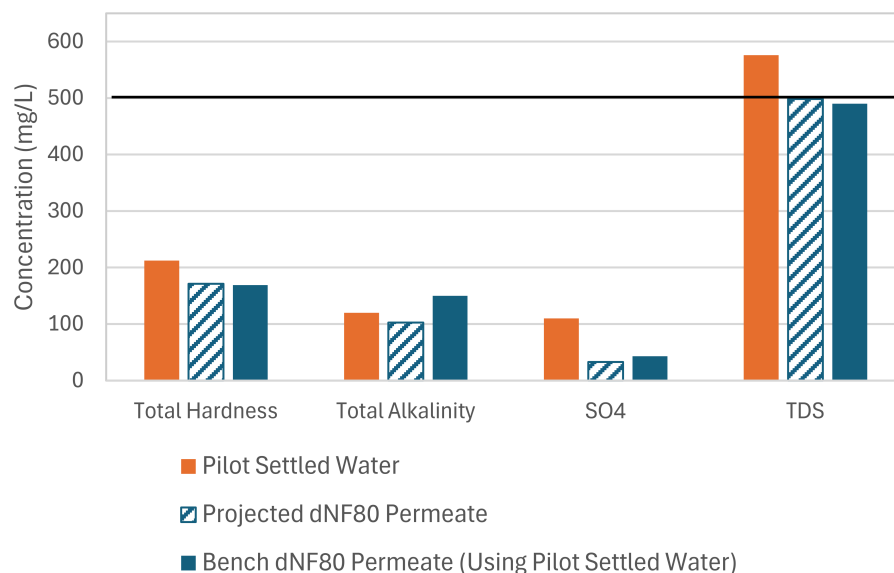
Bench-scale exploratory HFNF experiments were performed to provide insights for TDS management, which may be needed for certain treatment goals or end-uses, including meeting the secondary EPA MCL (SMCL, which is a non-enforceable drinking water guideline for contaminants that mainly affect the aesthetic quality of drinking water rather than direct health impacts) of 500 mg/L. During the pilot, TDS typically ranged from 500 to 650 mg/L throughout testing (manuscript in preparation). The bench-scale HFNF

experiment using the NX Filtration dNF80 was performed with pilot settled water and an effective recovery of 80%. The settled water TDS was reduced from 576 mg/L to 490 mg/L (a 15% reduction) in the effluent permeate. The total hardness was also reduced, as well as various ions that were tested (manuscript in preparation). Sulfate, a larger ion, was reduced from 110 mg/L in the pilot settled water to 43 mg/L after bench-scale HFNF, as shown in Figure 15. The concentrate from the HFNF showed a large increase in ions such as sulfate, as expected.



**Figure 15.** Sulfate in AWT feed water, settled water, and in the permeate and concentrate from bench-scale HFNF using the NX Filtration dNF80 membrane with pilot settled water.

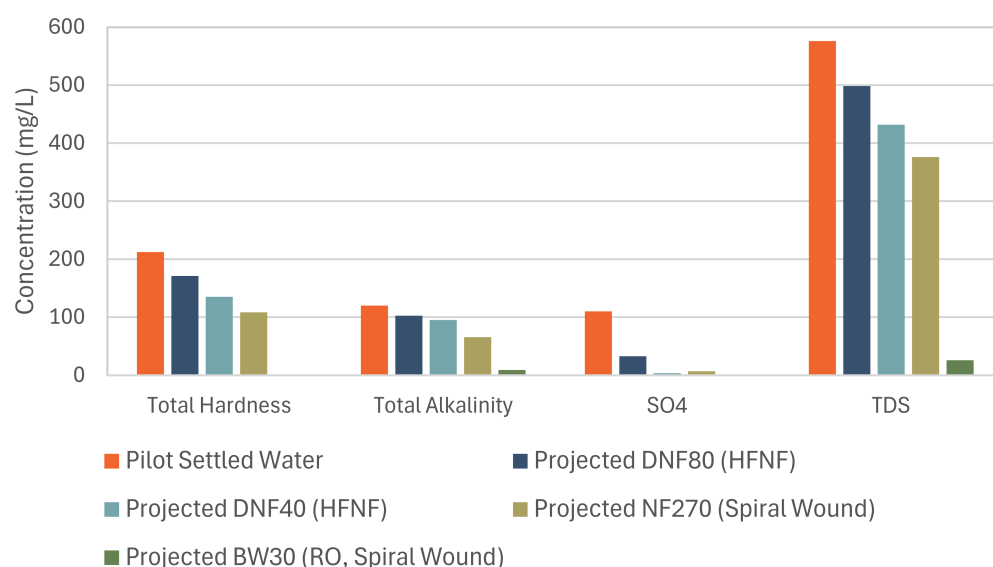
In addition to bench-scale HFNF testing, membrane performance modeling was conducted for three different NF products and one RO product. For the 800 Dalton HFNF (NX filtration dNF80), the bench-scale versus projected results for permeate water values were consistent for TDS, total hardness, and sulfate, as shown in Figure 16. The bench-scale permeate alkalinity value was higher than the influent (pilot settled water) value and the projected value, and additional testing would be warranted to assess full-scale impacts on treated water.



**Figure 16.** Bench scale versus projected HFNF using the NX Filtration dNF80 membrane. The horizontal line at 500 mg/L represents the SMCL for TDS.

Projections to assess the potential performance with other membrane sizes and products (not used during bench-scale testing) showed various reductions in TDS, total hardness, and sulfate, as shown in Figure 17. Projections show greater reduction with tighter membrane sizes, as expected, with higher to lower permeate concentrations occurring in order

from the dNF80, the dNF40 (NX Filtration HFNF with a 400 Dalton cutoff size), NF270 (DuPont NF270 spiral wound membrane), and the BW30 (DuPont RO membrane). While the modeled dNF80 reduced TDS from approximately 576 to 498 mg/L (consistent with bench-scale dNF80 results of 490 mg/L in the permeate), the tighter HFNF membrane, dNF40, projected further TDS reduction to 430 mg/L, which is under the SMCL by a margin of 70 mg/L. The NF270 projected effluent TDS is 380 mg/L. The projections using the BW30 RO membrane showed a very large reduction in TDS, as expected, with an effluent concentration of 26 mg/L. This would notably produce a high concentrate, or brine stream.



**Figure 17.** Pilot settled water versus projected water quality using various membranes.

### 3.3. Stakeholder Engagement

For both pilot studies, multiple site visits were conducted with a broad range of stakeholders including regulators, operators, engineers, and other community members. The pilot served as a mechanism for building trust, transparency, and shared ownership of the project. The site visits included tours led by the project team to establish technical credibility, operational realism, regulatory openness, and a tangible public experience. For these Midwest CBAT pilots especially, the events positioned the pilot as a practical, regionally appropriate solution to water resource challenges, not just a research exercise.

Consistent with other pilot studies, results from the site visits at both pilots were positive with narrative objectives being met. Feedback from stakeholders, while anecdotal, show that the efforts were successful in building regulator confidence, increasing utility leadership support, introducing non-potable and potable reuse concepts to the visitors, demonstrating pilot performance, and building momentum for future funding/permitting outcomes. From a stakeholder perspective, CBAT must demonstrate consistent, reliable removal of contaminants while remaining cost-effective and practical to operate within a robust, multiple-barrier treatment system. Notably, regulators prioritize public health protection and validated performance, while operators focus on operational reliability and lifecycle costs, and the public is primarily concerned with drinking water safety, affordability, and transparency in monitoring that builds confidence in water reuse.

Further, water reuse projects in regulation-deficient areas of the U.S. Midwest are hindered by unclear or lacking regulations, limited funding, aging infrastructure, and public skepticism, all of which increase implementation risk and discourage investment. Regional uptake can be enhanced through state reuse policies, coordinated permitting, financial incentives, pilot demonstration projects, and transparent science communication that

emphasizes water quality, public health protections, and the economic and environmental benefits of reuse.

## 4. Discussion

### 4.1. Operational Performance Analysis of Pilot Studies

Consistent with other studies [13,28,29], results from these pilot studies demonstrated that the secondary effluents from both WRFs are potentially viable source waters for reuse when treated through CBAT. Conducting the pilot studies at WRFs with significant differences in treatment plant capacity and wastewater collection system characteristics was a unique opportunity to demonstrate the flexibility of CBAT for water reuse applications. While both WRFs utilize conventional activated sludge secondary treatment, the WRF in Pilot Study 1 has a permitted average design flow of 10 MGD and a collections system serving primarily residential areas. Conversely, the WRF in Pilot Study 2 has a permitted average design flow of 114 MGD and a peak hydraulic capacity of 330 MGD, with a combined sewer collections system serving both residential and industrial customers.

All parameters during both Pilot Study 1 and 2 were measured in the GAC effluent below their respective U.S. EPA Drinking Water MCLs, except for nitrate, which is discussed further in Section 4.2, and bromate in Pilot Study 2. During Pilot Study 2, bromate formation was higher due to substantial levels of bromide detected, typically 100 to 150 µg/L (manuscript in preparation), as bromate formation during ozonation increases with the bromide concentration [30]. Elevated bromate formation has been observed at bromide concentrations on the order of tens of µg/L in drinking water [31,32].

The similarities in treated GAC contactor effluent water quality between the two pilots underscore the effectiveness of CBAT for potential users with a wide range of community characteristics. In both pilot studies, GAC effluent TOC concentrations were consistently below 2.0 mg/L and GAC effluent UVT averaged 96%. TKN concentrations were effectively reduced to the MDL of 0.5 mg/L in both pilot studies as well. The equipment issues experienced during Pilot Study 2 with the ozone mass flow controllers and air conditioning system may have limited the full performance potential of BAC during Challenge Testing due to the shorter period to acclimate BAC to Pilot Study 2 ozonated water. During the ozone outage, the BAC filters continued operating using settled water as the feed. After the ozone outage, BAC was fed ozonated water for approximately one week during the CFS Optimization phase, prior to the start of the Challenge Testing phase. The treatment effectiveness for most parameters, including TOC, UVT, and TKN, was assessed during the Challenge Testing phase for Pilot Study 2.

On an individual treatment process level, in both pilot studies the CFS step was a significant driver behind the reduction in solids and organic compounds, such as carbonaceous biochemical oxygen demand (cBOD) (manuscript in preparation) and TOC. Ozone-biofiltration was also a significant driver behind the reduction in organic compounds such as TOC, ammonia conversion, and TKN reduction, and certain emerging contaminants including 1,4-dioxane. TKN concentrations in the BAC effluent from these two pilots (averaging 0.55 mg/L for each pilot) were between the BAC effluent TKN concentrations observed at SWIFT (approximately 0.75 mg/L, [29]) and Franklin, TN (approximately 0.15 mg/L, [33]). The GAC process provided further organics removal, as indicated by the increase in UVT between the BAC effluent and the GAC effluent, with an additional focus on reduction in emerging contaminants such as PFAS and PPCPs. TOC concentrations in the GAC effluent from these two pilots were lower than the GAC effluent TOC concentrations observed at SWIFT (approximately 3.0 mg/L, [29]) and Franklin, TN (approximately 3.2 mg/L, [33]), and similar to those observed at Gwinnett County (less than 2.0 mg/L, [34]). Results of PFAS removals through this process in Pilot Study 1 importantly highlight the

potential variability in contaminant loads to the WRF, recognizing that PFAS are not well removed through conventional wastewater treatment processes [35,36]. Regardless, the overall results are similar to those reported in other research indicating that, when GAC is part of a CBAT process, excellent PFAS removal can be achieved [37]. The results of PFAS from pilot testing can be used to project the expected GAC lifetime in a full-scale application with respect to the required media regeneration frequency to meet continuous PFOA and PFOS control [38–41].

In CBAT, as with any other advanced treatment scheme, a single treatment process is not expected to remove every compound; individual treatment processes complement one another to provide a multi-barrier approach combining physical, chemical, and biological processes. The combination of treatment processes operating together demonstrated the ability to remove constituents which the WRFs were not designed to remove, and to further decrease constituent concentrations to levels which would not typically be expected through traditional secondary wastewater treatment. These results support those presented by Liu et al. [42] in exhibiting the ability of ozone followed by BAC to reduce concentrations of emerging contaminants, particularly PPCPs, and Vaidya et al. [29] in confirming the nutrient removal capabilities of CBAT for reuse applications. Utilizing CBAT, the two pilot studies demonstrated that secondary clarifier effluent from both WRFs can be treated to meet water quality objectives for non-potable reuse and indirect potable reuse.

#### *4.2. Engineering Challenges and Future Research*

Notably, NDMA formation following ozone was observed in Pilot Study 2, which is a complex reaction pathway. Ozone can either reduce precursor compounds or transform precursors into more reactive compounds that later form NDMA [43]. Here, NDMA appeared to form with ozonation and was effectively removed by the downstream biofiltration process. It is notable that NDMA itself is difficult to degrade because it is a very small, highly soluble, and relatively biologically recalcitrant compound, although some specialized microorganisms can biodegrade NDMA under certain conditions. However, rates are often slow, and removal can be inconsistent, with treatment performance being sensitive to temperature and acclimation. Because of this, careful consideration regarding the design of biofiltration as a primary NDMA barrier is important for full-scale applications [44]. Specific to Pilot Study 1, two N-DBPs were detected in the GAC contactor effluent: NMOR and NDPA. Future research on management strategies for these compounds to satisfy EPA drinking water MCL goals is warranted if treated water is used for future potable reuse applications.

Specific to Pilot Study 2, bromate was detected in the ozone effluent at concentrations greater than the EPA drinking water MCL of 10 µg/L due to higher bromide levels reacting with ozone, whereas the AWT feed water had bromate concentrations below the EPA drinking water MCL. Future research at this WRF could focus on strategies for limiting bromate formation, such as utilizing side-stream injection, dosing hydrogen peroxide, or operating at a lower pH. Additionally, the duration of operation for Pilot Study 2 did not capture a substantial wet weather event, which would be of particular interest due to the combined sewer collections system which contributes flow to this WRF. The impacts of wet weather flow and upstream treatment at the WRF should be investigated to further understand the secondary effluent water quality and treatment performance of the CBAT train.

Findings from both pilot studies inform areas for future research focus at both WRFs. For example, while ammonia conversion was successful, nitrate was not removed through the CBAT train; thus, this process approach fits best in advanced treatment trains where upstream wastewater treatment provides denitrification to below the EPA drinking water MCL of 10 mg/L as N, or where water is blended with other sources to reduce nitrate [13].

The addition of an internal mixed liquor recycled at the upstream WRFs could reduce the nitrate concentration if determined to be necessary as part of a future reuse scheme. Should a blending approach be utilized, a simple mass balance calculation such as the one demonstrated below can be performed to determine the appropriate ratio of flows from the various sources of water, depending on their respective nitrate concentrations.

$$(Q_1 \times C_1) + (Q_2 \times C_2) = (Q_1 + Q_2) \times C_3$$

where

$Q_1$  = Flow from source 1;

$C_1$  = Concentration in source 1;

$Q_2$  = Flow from source 2;

$C_2$  = Concentration in source 2;

$C_3$  = Concentration in combined flow stream.

Using Pilot Study 2 as an example, let the nitrate concentration in the GAC effluent equal  $C_1$  (12.1 mg/L). Assume a target nitrate concentration of 8 mg/L ( $C_3$ ) in the combined flow stream to provide a buffer below the drinking water MCL of 10 mg/L. Further assume that a source of water for blending has been identified with a nitrate concentration of 2 mg/L. The mass balance equation above can be rearranged to solve for the ratio of flows from the two sources,  $Q_1/Q_2$ , as shown:

$$\frac{Q_1}{Q_2} = \frac{C_3 - C_2}{C_1 - C_3} = \frac{8 - 2}{12.1 - 8} = 1.46$$

TDS is another parameter which saw no significant change in concentration across either pilot, which is to be expected since CBAT does not include a barrier for TDS removal. HFNF, which is generally less costly to operate over time than traditional RO or standard NF for several reasons, was tested at bench-scale with comparative projections as an exploratory effort to address this issue. Notably, HFNF has lower energy requirements due to the slightly larger pore sizes than RO membranes, allowing water to pass through at significantly lower pressures, directly reducing electricity consumption, resulting in 30–50% lower energy compared to standard RO [45]. Pretreatment requirements are lower for HFNF, which only reduces multi-valent ions (like calcium and magnesium) but selectively allows some monovalent ions to pass, resulting in less membrane scaling; this also lowers the need for expensive anti-scalant chemicals [45]. HFNF also has higher water recovery rates—generally in the range of 80–95%, meaning less “reject water” is lost. Finally, HFNF has longer membrane life due to less strain on the membranes from lower operating pressures—combined with reduced chemical scaling—which leads to less frequent membrane fouling and replacement costs over the life of the system. However, the suitability of HFNF depends entirely on the specific water treatment goals, as it does not strip out TDS as completely as RO [45].

The bench scale HFNF test conducted during Pilot Study 2 with a dNF80 membrane demonstrated 15 percent TDS reduction from the AWT feed water, with greater reduction for larger ions such as sulfate (61 percent). These results were supported by follow-up nanofiltration and RO modeling, which also indicated that additional reduction could be achieved with a tighter HFNF membrane. While the results were promising, the extent of the bench-scale testing at one facility is insufficient to establish the operational adaptability of the technology and warrants further research. If greater TDS removal is required to achieve water quality objectives, there are a suite of solutions to remove ions. Various HFNF membranes could be used to lower TDS by selective ion removal; however, if more substantial reductions in TDS are required, it may be necessary to address this through

high pressure membranes such as RO, which has limited concentrate disposal options in the Midwest U.S.

Finally, with the positive outcomes from the stakeholder engagements, both utilities where pilot studies were conducted are moving forward with additional investigations into water reuse. This is critical because population growth, increasing water demands for data centers, and need for more sustainable water practices are driving a clear need for water reuse. This study also demonstrates that it is possible, both technically and from a stakeholder perspective, to leverage this non-traditional CBAT train for water reuse at both large and small WRFs in the U.S. Midwest.

## 5. Conclusions

In conclusion, the two field pilots were successfully operated to demonstrate preliminary data to serve as proof of concept for justification of additional investment in CBAT for water reuse in the Midwestern U.S. While the projects were successful from the perspective of meeting most drinking water MCLs, nitrate is an inherent limitation in the CBAT process which must be addressed outside of the CBAT train through denitrification of the source water or blending with a low nitrate source. Thus, while this preliminary pilot testing was useful as a tool for developing data and for serving as a tool in stakeholder engagement, additional research is needed to fully assess CBAT for application in the U.S. Midwest, including as part of future regulatory efforts. Topics that need additional geographically specific data are centered around several key areas:

- Ozone demand and dose optimization are needed, given the variability of water quality and flows in this region, particularly in combined sewer communities. This includes optimization of reagent dosages, long-term operational safety and operational adaptability, which should be studied in subsequent specialized tests.
- Confirmation of appropriate ozone/TOC ratios for nitrified systems, given that typical ozone/TOC ratios ranging from 0.5 to 1.0 are common starting points.
- Future research should assess whether higher ozone dosing, necessary in wastewater effluent, can be conducted without exceeding bromate standards in the US EPA drinking water regulations. Additionally, shifts in DBPs should be documented, considering that bromate formation has a higher probability in the absence of ammonia in fully nitrified effluents. This should be paired with investigations into low-cost mitigation approaches to ozonation by-products for high-bromide inland water, which should at a minimum include source control, given that industrial discharges are potentially key contributors to bromide in wastewaters.
- Conversely, in wastewater effluent, which can be high in organic nitrogen precursors, ozonation can lead to an increase in NDMA. Therefore, research must determine whether BAC can consistently biodegrade this DBP and investigate the importance of this and other NDBPs in the context of public health risks.
- Additional investigations are needed to assess GAC adsorption cycles and process stability under seasonal water temperature fluctuations.
- Further testing on the HFNF approach to ion removal should be conducted if TDS is a constituent of concern, depending on the ultimate end use of the reclaimed water, to establish the scalability and adaptability of the treatment technology.
- Final disinfection was not evaluated during these pilot studies. However, the effectiveness of UV, ozone and chlorine disinfection is well established for drinking water, wastewater, and water reuse applications, and disinfection would be included in any future full-scale AWT design. Incorporation of disinfection may also enhance demonstration projects that include public stakeholder engagement, such as tasting stations, that are intended to support public outreach and acceptance [46].

- Ongoing research and future demonstration testing should also include opportunities for ongoing stakeholder engagement to help utilities as this innovative approach to water reuse in the U.S. Midwest is increasingly examined as an element in a diversified water supply portfolio.

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## Abbreviations

The following abbreviations are used in this manuscript:

|      |                                        |
|------|----------------------------------------|
| ACH  | Aluminum Chlorohydrate                 |
| AWT  | Advanced Water Treatment               |
| BAC  | Biologically Active Carbon             |
| CAS  | Conventional Activated Sludge          |
| CBAT | Carbon-Based Advanced Treatment        |
| cBOD | Carbonaceous Biochemical Oxygen Demand |
| CCL  | Contaminant Candidate List             |
| CEC  | Constituent of Emerging Concern        |
| CFS  | Coagulation-Flocculation-Sedimentation |
| cm   | Centimeter                             |
| COD  | Chemical Oxygen Demand                 |
| DBPs | Disinfection Byproducts                |
| DEET | N,N-Diethyl-meta-toluamide             |
| EBCT | Empty Bed Contact Time                 |
| g    | Gram                                   |
| GAC  | Granular Activated Carbon              |
| EPA  | Environmental Protection Agency        |
| FAT  | Full Advanced Treatment                |
| gpm  | Gallons per Minute                     |
| HFNF | Hollow Fiber Nanofiltration            |
| HMI  | Human-Machine Interface                |
| hr   | Hour                                   |
| HRSD | Hampton Roads Sanitation District      |

|        |                                            |
|--------|--------------------------------------------|
| IQR    | Interquartile Range                        |
| L      | Liter                                      |
| m      | Meter                                      |
| max    | Maximum                                    |
| MCL    | Maximum Contaminant Level                  |
| MDL    | Method Detection Limit                     |
| MF     | Microfiltration                            |
| mg     | Milligram                                  |
| MGD    | Million Gallons per Day                    |
| min    | Minimum                                    |
| mm     | Millimeter                                 |
| N-DBPs | Nitrogenous Disinfection Byproducts        |
| ng     | Nanogram                                   |
| NDMA   | N-nitrosodimethylamine                     |
| NDPA   | N-nitrosodiphenylamine                     |
| NMOR   | N-nitrosomorpholine                        |
| NOM    | Natural Organic Matter                     |
| PACL   | Polyaluminum Chloride                      |
| PCBs   | Polychlorinated Biphenyls                  |
| pCi    | Picocurie                                  |
| PFAS   | Per- and Polyfluoroalkyl Substances        |
| PFBA   | Perfluorobutanoic acid                     |
| PFHxA  | Perfluorohexanoic acid                     |
| PFOA   | Perfluorooctanoic acid                     |
| PFOS   | Perfluorooctanesulfonic acid               |
| PFPeA  | Perfluoropentanoic acid                    |
| PLC    | Programmable Logic Controller              |
| PPCPs  | Pharmaceuticals and Personal Care Products |
| RO     | Reverse Osmosis                            |
| SMCL   | Secondary Maximum Contaminant Level        |
| SOC    | Synthetic Organic Compounds                |
| SWIFT  | Sustainable Water Initiative for Tomorrow  |
| TCEP   | tris(2-chloroethyl) phosphate              |
| TDS    | Total Dissolved Solids                     |
| TKN    | Total Kjeldahl Nitrogen                    |
| TOC    | Total Organic Carbon                       |
| UF     | Nanofiltration                             |
| ug     | Microgram                                  |
| UOSA   | Upper Occoquan Service Authority           |
| U.S.   | United States                              |
| UVT    | Ultraviolet Transmittance                  |
| VOC    | Volatile Organic Compounds                 |
| WRF    | Water Reclamation Facility                 |

## Appendix A

Tables that include the water quality parameters tested during each pilot.

**Table A1.** Water quality parameters tested weekly at each pilot location.

| Parameter    | Method           | Locations Tested                                                                                        | Frequency |
|--------------|------------------|---------------------------------------------------------------------------------------------------------|-----------|
| Conductivity | EPA Method 10256 | AWT Feed, GAC 2 Effluent                                                                                | 5 x/week  |
| Turbidity    | EPA Method 180.1 | AWT Feed, Settled Water, Ozone Effluent, BAC 1 Effluent, BAC 2 Effluent, GAC 1 Effluent, GAC 2 Effluent | 5 x/week  |

**Table A1.** *Cont.*

| Parameter                                          | Method                                  | Locations Tested                                                                                        | Frequency                                              |
|----------------------------------------------------|-----------------------------------------|---------------------------------------------------------------------------------------------------------|--------------------------------------------------------|
| UVT-254                                            | HACH Method 10243                       | AWT Feed, Settled Water, Ozone Effluent, BAC 1 Effluent, BAC 2 Effluent, GAC 1 Effluent, GAC 2 Effluent | 5 x/week                                               |
| Oxygen, Dissolved                                  | HACH Method 10360                       | AWT Feed, Ozone Effluent, BAC 1 Effluent, BAC 2 Effluent, GAC 1 Effluent, GAC 2 Effluent                | 5 x/week                                               |
| Ozone Residual                                     | Indigo Method, HACH Method 8311         | Settled Water, Ozone Effluent                                                                           | 5 x/week                                               |
| pH                                                 | EPA Method 10257                        | AWT Feed, Settled Water, Ozone Effluent, BAC 1 Effluent, BAC 2 Effluent, GAC 1 Effluent, GAC 2 Effluent | 5 x/week                                               |
| Iron, Total                                        | HACH Method 10306                       | AWT Feed, Settled Water, GAC 2 Effluent                                                                 | 1 x/week                                               |
| Iron, Dissolved                                    | HACH Method 10306                       | AWT Feed, Settled Water, GAC 2 Effluent                                                                 | 1 x/week                                               |
| Total Alkalinity                                   | Colorimetric Method, HACH 10239         | AWT Feed, Settled Water, Ozone Effluent, BAC 1 Effluent, BAC 2 Effluent, GAC 1 Effluent, GAC 2 Effluent | 3 x/week                                               |
| Nitrate                                            | Dimethylphenol Method, HACH 10206       | AWT Feed, Ozone Effluent, BAC 1 Effluent, BAC 2 Effluent, GAC 1 Effluent, GAC 2 Effluent                | 3 x/week                                               |
| Nitrite                                            | Diazotization Method, HACH 10237        | AWT Feed, Ozone Effluent, BAC 1 Effluent, BAC 2 Effluent, GAC 1 Effluent, GAC 2 Effluent                | 3 x/week                                               |
| Ammonia                                            | Salicylate Method, HACH 10205           | AWT Feed, Settled Water, Ozone Effluent, BAC 1 Effluent, BAC 2 Effluent, GAC 1 Effluent, GAC 2 Effluent | 3 x/week                                               |
| Total Phosphorus                                   | Ascorbic Acid Method, HACH 10209/10210  | AWT Feed, Ozone Effluent, BAC 1 Effluent, BAC 2 Effluent, GAC 1 Effluent, GAC 2 Effluent                | 3 x/week                                               |
| Soluble Reactive Total Phosphorus (Orthophosphate) | Ascorbic Acid Method, HACH 10209/10210  | AWT Feed, Ozone Effluent, BAC 1 Effluent, BAC 2 Effluent, GAC 1 Effluent, GAC 2 Effluent                | 3 x/week                                               |
| Total Chemical Oxygen Demand                       | EPA Reactor digestion Method, HACH 8000 | AWT Feed, Settled Water, Ozone Effluent, BAC 2 Effluent, GAC 2 Effluent                                 | 3 x/week                                               |
| Solids, Total Dissolved                            | Standard Method 2540C-20                | AWT Feed, Settled Water, GAC 2 Effluent                                                                 | 1 x/week<br>Pilot Study 1<br>3 x/week<br>Pilot Study 2 |
| Solids, Total Suspended                            | Standard Method 2540D-20                | AWT Feed, Settled Water, GAC 2 Effluent                                                                 | 1 x/week<br>Pilot Study 1<br>3 x/week<br>Pilot Study 2 |
| Carbonaceous Biochemical Oxygen Demand             | Standard Method 5210B-16                | AWT Feed, Settled Water, GAC 2 Effluent                                                                 | 1 x/week<br>Pilot Study 1<br>3 x/week<br>Pilot Study 2 |
| Total Kjeldahl Nitrogen                            | EPA Method 351.2 Rev. 2.0               | AWT Feed, Settled Water, Ozone Effluent, BAC 2 Effluent, GAC 2 Effluent                                 | 1 x/week                                               |
| Dissolved Organic Carbon                           | Standard Method 5310B-00,14             | AWT Feed, Settled Water, Ozone Effluent, BAC 1 Effluent, BAC 2 Effluent, GAC 1 Effluent, GAC 2 Effluent | 2 x/week                                               |
| Total Organic Carbon                               | Standard Method 5310B-00,14             | AWT Feed, Settled Water, Ozone Effluent, BAC 1 Effluent, BAC 2 Effluent, GAC 1 Effluent, GAC 2 Effluent | 3 x/week                                               |

**Table A2.** Larger suite of water quality parameters tested with less frequency at each pilot location.  
Note: PFAS were only tested in Pilot Study 1.

| Parameter                    | Locations Tested                                                                                        | Frequency                         |
|------------------------------|---------------------------------------------------------------------------------------------------------|-----------------------------------|
| Odor                         | AWT Feed, GAC 2 Effluent                                                                                | Minimum 3 x/duration of pilot     |
| Color                        | AWT Feed, GAC 2 Effluent                                                                                | Minimum 3 x/duration of pilot     |
| Foaming Agents               | AWT Feed, GAC 2 Effluent                                                                                | Minimum 3 x/duration of pilot     |
| Bromate                      | AWT Feed, Settled Water, Ozone Effluent, GAC 2 Effluent                                                 | 1 x/week during challenge testing |
| Corrosivity                  | AWT Feed, Settled Water, Ozone Effluent, GAC 2 Effluent                                                 | 1 x/week during challenge testing |
| Sulfate                      | AWT Feed, Settled Water, Ozone Effluent, GAC 2 Effluent                                                 | 1 x/week during challenge testing |
| Bromide                      | AWT Feed, Settled Water, Ozone Effluent, GAC 2 Effluent                                                 | 1 x/week during challenge testing |
| Chlorite                     | AWT Feed, Settled Water, Ozone Effluent, GAC 2 Effluent                                                 | 1 x/week during challenge testing |
| MBAS                         | AWT Feed, Settled Water, Ozone Effluent, GAC 2 Effluent                                                 | 1 x/week during challenge testing |
| Sulfamethoxazole             | AWT Feed, Settled Water, Ozone Effluent, GAC 2 Effluent                                                 | 1 x/week during challenge testing |
| Formaldehyde                 | AWT Feed, Settled Water, Ozone Effluent, BAC 1 Effluent, BAC 2 Effluent, GAC 2 Effluent                 | 1 x/week during challenge testing |
| Acetone                      | AWT Feed, Settled Water, Ozone Effluent, BAC 1 Effluent, BAC 2 Effluent, GAC 2 Effluent                 | 1 x/week during challenge testing |
| Carbamazepine                | AWT Feed, Settled Water, Ozone Effluent, GAC 2 Effluent                                                 | 1 x/week during challenge testing |
| Assimilable Organic Carbon   | AWT Feed, Settled Water, Ozone Effluent, BAC 1 Effluent, BAC 2 Effluent, GAC 1 Effluent, GAC 2 Effluent | 1 x/week during challenge testing |
| 1–4 Dioxane                  | AWT Feed, Settled Water, Ozone Effluent, BAC 1 Effluent, BAC 2 Effluent, GAC 1 Effluent, GAC 2 Effluent | 1 x/week during challenge testing |
| Nitrosamines                 | AWT Feed, Settled Water, Ozone Effluent, BAC 1 Effluent, BAC 2 Effluent, GAC 1 Effluent, GAC 2 Effluent | 1 x/week during challenge testing |
| Haloacetic Acids (HAA5)      | AWT Feed, BAC 2 Effluent, GAC 2 Effluent                                                                | Minimum 3 x/duration of pilot     |
| Total Trihalomethanes (TTHM) | AWT Feed, GAC 2 Effluent                                                                                | Minimum 3 x/duration of pilot     |
| Gross Alpha                  | AWT Feed, GAC 2 Effluent                                                                                | Minimum 3 x/duration of pilot     |
| Gross Beta                   | AWT Feed, GAC 2 Effluent                                                                                | Minimum 3 x/duration of pilot     |
| Radium 226                   | AWT Feed, GAC 2 Effluent                                                                                | Minimum 3 x/duration of pilot     |
| Radium 228                   | AWT Feed, GAC 2 Effluent                                                                                | Minimum 3 x/duration of pilot     |
| Uranium                      | AWT Feed, GAC 2 Effluent                                                                                | Minimum 3 x/duration of pilot     |
| Silicon                      | AWT Feed, GAC 2 Effluent                                                                                | Minimum 3 x/duration of pilot     |
| Sulfide, Total               | AWT Feed, GAC 2 Effluent                                                                                | Minimum 3 x/duration of pilot     |
| Sodium, Total                | AWT Feed, GAC 2 Effluent                                                                                | Minimum 3 x/duration of pilot     |
| Sodium, Dissolved            | AWT Feed, GAC 2 Effluent                                                                                | Minimum 3 x/duration of pilot     |
| Manganese, Dissolved         | AWT Feed, GAC 2 Effluent                                                                                | Minimum 3 x/duration of pilot     |
| Manganese, Total             | AWT Feed, GAC 2 Effluent                                                                                | Minimum 3 x/duration of pilot     |
| Silver, Dissolved            | AWT Feed, GAC 2 Effluent                                                                                | Minimum 3 x/duration of pilot     |
| Silver, Total                | AWT Feed, GAC 2 Effluent                                                                                | Minimum 3 x/duration of pilot     |
| Zinc, Dissolved              | AWT Feed, GAC 2 Effluent                                                                                | Minimum 3 x/duration of pilot     |
| Zinc, Total                  | AWT Feed, GAC 2 Effluent                                                                                | Minimum 3 x/duration of pilot     |

Table A2. Cont.

| Parameter                                        | Locations Tested         | Frequency                     |
|--------------------------------------------------|--------------------------|-------------------------------|
| 1,2-Dibromo-3-Chloropropane (DBCP)               | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| DEET                                             | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Dicamba                                          | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| 2(2,4,5-Trichlorophenoxy)propionic acid (Silvex) | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| 2,3,7,8-Tetrachlorodibenzodioxin (TCDD, Dioxin)  | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| 2,4-Dichlorophenoxyacetic acid (2,4-D)           | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| 3-Hydroxycarbofuran                              | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Alachlor                                         | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Aldicarb                                         | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Aldicarb sulfoxide                               | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Aldicarb sulfone                                 | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Atrazine                                         | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Benzo[a]pyrene                                   | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Butachlor                                        | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Carbaryl                                         | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Carbofuran                                       | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Chlordane                                        | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Dalapon                                          | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Di(2-ethylhexyl)adipate                          | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Di(2-ethylhexyl)phthalate                        | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Dinoseb                                          | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Diquat                                           | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Endothall                                        | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Endrin                                           | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Ethylene Dibromide (EDB)                         | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Glyphosate (Round-Up)                            | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Heptachlor                                       | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Heptachlor epoxide                               | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Hexachlorobenzene                                | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Hexachlorobutadiene                              | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Hexachlorocyclopentadiene                        | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Lindane                                          | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Methiocarb                                       | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Methomyl                                         | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Methoxychlor                                     | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Metolachlor                                      | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Metribuzin                                       | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Oxamyl (Vydate)                                  | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Pentachlorophenol                                | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Picloram                                         | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Polychlorinated Biphenyls (Arochlor 1016–1260)   | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Simazine                                         | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Toxaphene                                        | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| 1,1,1,2-Tetrachloroethane                        | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| 1,1,1-Trichloroethane                            | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |

Table A2. Cont.

| Parameter                         | Locations Tested         | Frequency                     |
|-----------------------------------|--------------------------|-------------------------------|
| 1,1,2,2-Tetrachloroethane         | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| 1,1,2-Trichloroethane             | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| 1,1-Dichloroethane                | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| 1,1-Dichloroethylene              | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| 1,1,-Dichloropropene              | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| 1,2,4-Trichlorobenzene            | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| 1,2,3-Trichloropropane            | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| 1,2,4-Trichlorobenzene            | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| 1,2,4-Trimethylbenzene            | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| 1,2-Dichlorobenzene               | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| 1,2-Dichloroethane                | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| 1,2-Dichloropropane               | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| 1,3,5-Trimethylbenzene            | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| 1,3-Dichlorobenzene               | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| 1,3-Dichloropropane               | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| 1,4-Dichlorobenzene               | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| 2,2-Dichloropropane               | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| 2-Chlorotoluene                   | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| 4-Chlorotoluene                   | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Benzene                           | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Carbon Tetrachloride              | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| cis-1,2-Dichloroethylene          | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| cis-1,2-Dichloroethene            | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| cis-1,3-Dichloropropene           | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Dichloromethane                   | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Ethylbenzene                      | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Monochlorobenzene                 | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Styrene                           | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Tetrachloroethylene               | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Toluene                           | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| trans-1,2-Dichloroethylene        | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| trans-1,2-Dichloroethene          | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| trans-1,3-Dichloropropene         | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| tert-Butylbenzene                 | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Trichloroethylene                 | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Trichlorofluoromethane            | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Vinyl Chloride                    | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Xylenes, Total                    | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Chromium,<br>Dissolved Hexavalent | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Calcium, Dissolved                | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Calcium, Total                    | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Aluminum, Dissolved               | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Aluminum, Total                   | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Antimony, Dissolved               | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Antimony, Total                   | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Arsenic, Total                    | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |

Table A2. Cont.

| Parameter                           | Locations Tested         | Frequency                     |
|-------------------------------------|--------------------------|-------------------------------|
| Asbestos, Total                     | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Barium, Dissolved                   | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Barium, Total                       | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Beryllium, Dissolved                | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Beryllium, Total                    | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Boron, Total                        | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Cadmium, Dissolved                  | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Cadmium, Total                      | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Chloride                            | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Chromium, Dissolved                 | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Chromium, Hexavalent                | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Chromium, Total                     | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Cobalt, Dissolved                   | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Cobalt, Total                       | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Copper, Dissolved                   | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Copper, Total                       | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Cyanide                             | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Cyanide, Free                       | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Lead, Dissolved                     | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Lead, Total                         | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Magnesium, Dissolved                | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Magnesium, Total                    | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Molybdenum, Total                   | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Fluoride, Total                     | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Mercury, Total                      | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Nickel, Dissolved                   | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Nickel, Total                       | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Potassium, Dissolved                | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Potassium, Total                    | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Selenium, Dissolved                 | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Selenium, Total                     | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Strontium, Total                    | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Thallium, Dissolved                 | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Thallium, Total                     | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Tin, Total                          | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Titanium, Total                     | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Vanadium, Dissolved                 | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Vanadium, Total                     | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Coliform, Total                     | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| <i>E. coli</i>                      | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Whole Effluent Toxicity             | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Microcystins                        | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Perfluorobutanoic acid (PFBA)       | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Perfluorobutanesulfonic acid (PFBS) | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Perfluorodecanoic acid (PFDA)       | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Perfluoro-3,6-dioxahexanoic acid    | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Perfluorododecanoic acid (PFDoA)    | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |

Table A2. Cont.

| Parameter                                                | Locations Tested         | Frequency                     |
|----------------------------------------------------------|--------------------------|-------------------------------|
| Perfluoro (2-ethoxyethane) sulfonic acid (PFEEESA)       | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Perfluoroheptanoic acid (PFHpA)                          | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Perfluoroheptanesulfonic acid (PFHpS)                    | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Perfluorohexanoic acid (PFHxA)                           | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Perfluorohexanesulfonic acid (PFHxS)                     | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Perfluoro(4-methoxybutanoic acid)                        | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Perfluoro-3-methoxypropanoic acid (PFMPA)                | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Perfluorononanoic acid (PFNA)                            | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Perfluorooctanoic acid (PFOA)                            | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Perfluorooctanesulfonic acid (PFOS)                      | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Perfluoropentanoic acid (PFPeA)                          | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Perfluoropentanesulfonic acid (PFPeS)                    | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Perfluorotetradecanoic acid (PFTeDA)                     | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Perfluorotridecanoic acid (PFTrDA)                       | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Perfluoroundecanoic acid (PFUnA)                         | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| 11-Chloroeicosafluoro-3-oxaundecane-1-sulfonic acid      | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| 1H,1H,2H,2H-Perfluorohexane sulfonic acid (4:2 FTS)      | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| 1H,1H,2H,2H-Perfluorooctane sulfonic acid (6:2 FTS)      | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| 1H,1H,2H,2H-Perfluorodecane sulfonic acid (8:2 FTS)      | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| 9-Chlorohexadecafluoro-3-oxanonane-1-sulfonic acid       | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| 4,8-Dioxo-3H-perfluorononanoic acid (ADONA)              | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Hexafluoropropylene Oxide Dimer Acid (HFPO-DA)           | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| N-ethylperfluorooctanesulfonamidoacetic acid (NEtFOSAA)  | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| N-methylperfluorooctanesulfonamidoacetic acid (NMeFOSAA) | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| 11-Chloroeicosafluoro-3-oxaundecane-1-sulfonic acid      | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| 1H,1H,2H,2H-Perfluorohexane sulfonic acid (4:2 FTS)      | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| 1H,1H,2H,2H-Perfluorooctane sulfonic acid (6:2 FTS)      | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| 1H,1H,2H,2H-Perfluorodecane sulfonic acid (8:2 FTS)      | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| 9-Chlorohexadecafluoro-3-oxanonane-1-sulfonic acid       | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| 4,8-Dioxo-3H-perfluorononanoic acid (ADONA)              | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Hexafluoropropylene Oxide Dimer Acid (HFPO-DA)           | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| N-ethylperfluorooctanesulfonamidoacetic acid (NEtFOSAA)  | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| N-methylperfluorooctanesulfonamidoacetic acid (NMeFOSAA) | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Acetaminophen                                            | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Amoxicillin                                              | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Androstenedione                                          | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Atenolol                                                 | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Azithromycin                                             | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Caffeine                                                 | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Carbadox                                                 | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Carbamazepine                                            | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Cimetidine                                               | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Codeine                                                  | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Cotinine                                                 | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |

Table A2. Cont.

| Parameter                           | Locations Tested         | Frequency                     |
|-------------------------------------|--------------------------|-------------------------------|
| Dexamethasone                       | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Diazepam                            | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Diltiazem                           | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Diphenhydramine                     | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Epitestosterone                     | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Erythromycin                        | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Fluoxetine                          | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Lincomycin                          | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Meprobamate                         | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Metformin                           | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Monensin                            | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Narasin                             | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Nicotine                            | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Oleandomycin                        | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| 1,7-Dimethylxanthine (Paraxanthine) | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Phenazone                           | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Primidone                           | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Progesterone                        | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Roxithromycin                       | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Salinomycin                         | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Sulfamethoxazole                    | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Sulfadiazine                        | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Sulfadimethoxine                    | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Sulfamerazine                       | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Sulfamethazine                      | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Sulfamethizole                      | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Sulfasalazine                       | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Sulfathiazole                       | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Testosterone                        | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Theobromine                         | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Trimethoprim                        | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Tylosin                             | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Virginiamycin M1                    | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Actinolite (MFL)                    | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Amosite (MFL)                       | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Anthophyllite (MFL)                 | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Chrysotile (MFL)                    | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Crocidolite (MFL)                   | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Naphthalene                         | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Quinoline                           | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| TCEP                                | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| TCPP                                | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| TDCPP                               | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Tremolite (MFL)                     | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Bromochloromethane                  | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Benzene                             | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Bromobenzene                        | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |

Table A2. Cont.

| Parameter                      | Locations Tested         | Frequency                     |
|--------------------------------|--------------------------|-------------------------------|
| Bromomethane                   | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Chlorobenzene                  | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Chloroethane                   | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Chloromethane                  | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Dibromomethane                 | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Dichlorodifluoromethane        | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Isopropylbenzene               | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| m,p-Xylene                     | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Methylene Chloride             | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| Methyl-tert-butyl-ether (MTBE) | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| n-Butylbenzene                 | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| n-Propylbenzene                | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| o-Xylene                       | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| p-Isopropyltoluene             | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |
| sec-Butylbenzene               | AWT Feed, GAC 2 Effluent | Minimum 3 x/duration of pilot |

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