

Effects of Backwash Water and Chemical Addition on Biofiltration

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The David L. Tippin Water Treatment Facility (Facility) is an advanced water treatment facility in Tampa, with a capacity up to 120 mil gal per day (mgd) consisting of coagulation, flocculation, sedimentation, ozonation, and biofiltration processes. The finished water has seasonally exhibited a very high chlorine/chloramine demand, up to 5 mg/L as chlorine, which has incurred a higher chemical cost. Previous research at this facility suggested that biofiltration is the culprit (Marda et al, 2008). The issue of high chlorine demand with ozone and biofiltration was also reported by Wilczak et al (2003) and Vokes (2007) and attributed to biofiltration not performing well.

Biofiltration prevents regrowth in the distribution system by relying on bioactivity in the filters to consume biodegradable carbon, increasing the biostability of the finished water in the distribution system (Escobar et al, 2001; Urfer et al, 1997; Wang et al, 1995; Price et al, 1993; LeChevallier et al, 1992; Rittmann et al, 1989; Bouwer and Crowe 1988). When the nutrient molar ratio of 100:10:1 (carbon:nitrogen:phosphorus) required by heterotrophic bacteria is met, assimilable organic carbon (AOC) becomes the limiting factor of biofilm formation (LeChevallier et al, 1991). LeChevallier et al (1996) found a direct correlation between AOC and regrowth potential.

As a single cause of increased chlorine/chloramine demand in biofiltration has not been identified, multiple avenues aiming at improving the postfilter chlorine/chloramine demand have been investigated. Amirtharajah (1993) examined the importance of the air scouring during the process of

filter backwash, where air and water were used simultaneously to create a phenomenon known as “collapse-pulsing.” A high-speed camera was used to confirm the theoretical basis of the method. Collapse-pulsing increases the detachment of particles during backwash, preventing mud-ball formation and increasing filter effluent quality after backwash.

Ahmad et al (1998) found that collapse-pulse backwashing, followed by traditional water backwash with at least 25 percent bed expansion, produced water with lower AOC than without air scouring. It also produced lower AOC than a nonbiological filter, and the type of filter backwash water impacts filter performance as well. Lower levels of AOC are associated with nonchlorinated backwash water (Ahmad et al, 1998). Overall, nonchlorinated water for filter backwash has provided many advantages over chlorinated water. The removal of aldehydes, AOC, and total organic carbon (TOC) is higher, while chlorine/chloramine decays more slowly (Vokes, 2007; Miltner et al, 1995; Wang et al, 1995).

Granular activated carbon (GAC) generally performs better than anthracite for biofiltration. Ahmad and Amirtharajah (1998) found that bacteria remain better attached to GAC than anthracite during backwash. Not only could GAC hold three to eight times more biomass than anthracite, it also provides better aldehyde removal at colder temperatures and establishes biofilms quicker than anthracite (Urfer et al, 1997; Wang et al, 1995). Anthracite filter performance is negatively affected by chlorinated backwash water more significantly than GAC (Urfer et al, 1997).

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In multiple studies, organic carbon has been identified as the limiting nutrient for biofilm formation and regrowth in finished water and correlated with AOC formation (Chandy and Angles, 2001; LeChevallier et al, 1992; LeChevallier et al, 1991). Biofilm formation is more prominent in waters with increased chloramine decay rates (Chandy and Angles, 2001). LeChevallier et al (1991) identified the limiting nutrient molar ratio of 100:10:1 (carbon, ammonia-nitrogen, and orthophosphate-phosphorus) for biofilm formation. Based on this ratio, where biofilm development is being prevented, Lauderdale et al (2012) investigated the addition of nutrients to biofilters, where biofilm development is a positive trait.

Carbon, nitrogen, and phosphorus were first quantified in prefiltration water. The $\text{NH}_4\text{-N}$ and $\text{PO}_4\text{-P}$ were determined to be the deficient nutrients and subsequently added to the top of the filters. The basis for this is twofold. For one, if sufficient nitrogen and phosphorus are not available, bacteria in the filters are not removing the maximum amount of biodegradable carbon. Secondly, bacteria produce more biofilm when “stressed,” meaning a nutrient in limited supply may increase the amount of biofilm material formed in the filters, leading to excessive clogging. Lauderdale et al (2012) also investigated the addition of hydrogen peroxide to provide microorganisms with increased dissolved oxygen and depolymerize the extracellular polymeric substances (EPS) and observed a 60 percent decrease in terminal headloss during the 10-day study.

The primary materials of biofilm are EPS, with polysaccharides as one of the major components (Tsuneda et al, 2003). Liu et al (2006) identified the relationship between nutrients and microbial production and secretion of

Table 1. Water Quality of the Feed Water to the Pilot Plant

	Average	Max	Min
pH	7.4	7.8	6.7
Temperature (°C)	25.8	29.3	20.2
TOC (mg/L)	3.3	4.1	1.6
Ammonia (mg/L as N)	0.27	0.35	0.18
Phosphorous (mg/L as P)	0.02	0.042	< 0.01
Carboxylic acids (µg/L as C)	86	141	34

EPS. Lauderdale et al (2012) found that nutrient addition decreased terminal head loss by approximately 15 percent, possibly attributed to less EPS. The significance and implications of soluble microbial products (SMPs) in wastewater treatment, of which EPS is a constituent, are well documented in a review published by Barker and Stuckey (1999). The SMPs are the assortment of organic products and byproducts from microbial reactions involved in biological treatment. While most SMP research is in wastewater treatment, it is likely that SMPs and EPS have effects that have not been quantified on biological filtration in drinking water treatment. Mauclair et al (2004) studied the effect of EPS on slow sand filtration, attributing at least 7 percent of clogging to EPS, a greater percentage than that of particle deposition.

The goal of this study was to examine the effects of nonchloraminated backwash water, nutrient addition, media type, and hydrogen peroxide addition on biologically activated filters to improve their operation at the Facility, which is currently backwashed by water drawn from the clearwells, with the chloramine level around 5 mg/L. This study encompasses extensive test results from a two-year period of pilot and full-scale investigations, a time frame much longer than most studies, which allowed more realistic technology transfer from pilot to full-scale. The filter performance under chloraminated and nonchloraminated backwash water was compared back-to-back and confirmed by cycling between chloraminated and nonchloraminated water, with each condition run over several months. Similarly, the chemical additions were run for an extended period of time (at least one month). Some of the findings from this study deviate from previously published literature and reflect the complexity of water treatment technology.

Materials and Methods

Experimental Design

The pilot plant filters used in this study, emulating the full-scale system at the Facility, take water directly from the full-scale plant after coagulation and ozonation and before biofiltration. As a result, the water quality of the feed water to the pilot plant does not vary as much as the raw water. Constituents relevant to this study are summarized in Table 1, covering the same time span of this study from May 2011 through December 2012.

Four factors were evaluated for their potential efficacy in improving the performance of biofiltration utilizing the six 1×1 ft sq filters at the pilot plant. The detailed experimental matrix is summarized in Table 2. The first con-

Table 2. Summary of Experiments Performed to Study the Effects of Nutrient and Hydrogen Peroxide on Filter Performance

Test conditions	Filter loading rate (gpm/ft ²)	Duration (month)	Pilot filters					
			Anthracite #1	Anthracite #2	GAC #1	GAC #2	GAC #3	GAC #4
Backwash water	1	3	Chloraminated backwash					
	1	5	Non-chloraminated backwash					
	> 1.8 (= full-scale)	2	Chloraminated backwash					
	> 1.8 (= full-scale)	4	Non-chloraminated backwash					
Nutrient addition	2	3	Control	N, P	Control	Control	N, P	N, P
H ₂ O ₂ addition	2	2.5	Control	1 mg/L	Control	Control	1 mg/L	1 mg/L
	2	1	Control	1 mg/L	Control	Control	2 mg/L	2 mg/L

dition was media material, with anthracite¹ (0.8 – 1.0 mm) placed in the first two filters labeled as anthracite #1 and #2 GAC² (0.8 – 1.0 mm) and in the remaining four filters labeled as GAC #1, #2, #3, and #4, all at a depth of 24 in. of media atop 12 in. of sand³ (0.45 – 0.55 mm). These six filters had been in operation for several years, with the GAC media over two years old and the anthracite media acclimated for three months before this study. As a result, the adsorption removal of TOC was minimal.

The second condition was the effect of chloramine present in backwash water. To test this condition, all six filters were run for three months with chloraminated backwash water, followed by five months of nonchloraminated backwash water, all at a filter loading rate of 1 gal per minute per sq ft (gpm/ft²). At that point, the backwash operation was automated, allowing higher loading rates to be tested with more frequent backwashes. To confirm the findings with a loading rate identical to a full-scale plant (typically about 2 gpm/ft²), the filters were switched back to chloraminated backwash water for two months and then nonchloraminated backwash water for four months. Filters were run for at least one month before any samples were collected to allow the bioactivity to recover whenever the backwash water was changed from chloraminated to nonchloraminated water.

Both nutrient and hydrogen peroxide addition were studied with nonchloraminated backwash water, summarized in Table 2. With the DOC removal up to 1.5 mg/L, NH₄-N (as ammonium chloride) and PO₄-P (as phosphoric acid) were added at a dose of 0.351 mg/L and 0.078 mg/L, respectively, to anthracite #2, GAC #3, and GAC #4 from the top of these filters, allowing a direct performance

comparison between GAC and anthracite. This dose will meet the C:N:P molar ratio requirement of 100:10:1 with both N and P a little bit in excess to overcome the adsorption of N or P. Following nutrient addition, hydrogen peroxide was added from the top of the same three filters: anthracite #2, GAC #3, and GAC #4. During the course of each condition, samples were collected and tested for pH, temperature, chlorine demand, TOC, AOC, and carboxylic acids. Samples were taken from before and after the pilot filters, as well as from the full-scale system, allowing a comparison of performance.

Pilot Plant

The pilot filters were operated at loading rates of 1-2.5 gpm/ft², with turbidity, headloss, and flow rate recorded to supervisory control and data acquisition (SCADA) software. Turbidity was measured by an online analyzer⁴ verified monthly and calibrated every three months; headloss and flow rate were also measured by online analyzers^{5,6} that were calibrated or inspected every six months. All other measurements were done by taking samples to the on-site water quality laboratory transported on ice in coolers. The GAC used in the pilot plant was acquired from the full-scale system after being in use for over two years and was already bioactive. Anthracite was acquired new and had not been previously used; therefore, the filters were run for three months prior to performing any tests. The three-month acclimation period was chosen based on findings reported by Velten et al (2011), which showed that bioactivity reached a plateau, based on DOC removal and adenosine triphosphate (ATP) analysis, after approximately two months.

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Backwash water was stored in a 1,000 L high-density polyethylene (HDPE) tank. When chloraminated water was to be used for backwash, finished water from the clearwell of the full-scale Facility filled the tanks. When nonchloraminated water was to be used, effluent water from the pilot filters was collected and pumped into the tank.

Nutrient addition was accomplished using a 120 L HDPE tank combined with a Cole-Parmer MasterFlex peristaltic pump, with the nutrients feeding into the top of the filters. The ammonia solution was prepared from ACS (American Chemical Society)-grade ammonium chloride (NH₄Cl)⁷. The phosphorus solution was prepared from ACS-grade 85-percent phosphoric acid⁷. Hydrogen peroxide addition was accomplished using the same system using ACS-grade 30-percent hydrogen peroxide⁸.

When the project first started, filters were manually backwashed twice a week (Tuesday and Friday), with their headloss recorded immediately prior to backwash. Starting in December 2011, or eight months into studying the effect of chloraminated backwash water, the filters were put on an automatic backwash sequence identical to the one utilized for the full-scale Facility filtration system, using run time, turbidity, and headloss as the set points. All subsequent studies, including the confirmation tests for chloraminated and nonchloraminated backwash water and the impact of nutrient and hydrogen peroxide additions, were performed with automated filter backwash. The run time set point was changed from 80 hours to 120 hours in April 2012 to accommodate increased filter run time; it was further raised to 150 hours in May 2012. The backwash procedure consisted of first draining the filter water level to 1 ft above the media, followed by 90 seconds of air scouring at 3 standard cu ft per minute per sq ft (scfm/ft²). Low-rate backwash at 7 gpm/ft² began in tandem with 45 seconds of air

scouring and continued for another 45 seconds, followed by 7 minutes of high-rate backwash at 17 gpm/ft². High rate backwash is followed by 1 minute of low-rate backwash to finish the cycle and the filter is then put back in service.

Analytical Methods

Chlorine demand, measured by how fast the monochloramine would decay, was obtained in duplicate by dosing the waters with ammonia and chlorine sequentially at a 1.05:1 molar ratio of ammonia to chlorine, and later increased to 1.2:1 to avoid the potential breakpoint chlorination issues due to the ammonia deficiency. Monochloramine was used for the chlorine demand study to better simulate full-scale conditions, as this was the type of chlorine applied to the finished water for maintaining disinfectant residual. The target chloramine dose was 8 mg/L, with an adjusted pH of 7.70. This pH was selected to better simulate full-scale conditions. Total chlorine was measured 45 minutes after dosing.

Following day one, total chlorine was measured daily at approximately the same time during the remaining four days by Standard Method 4500G-Cl Chlorine (Residual), diethyl-p-phenylenedamine (DPD) colorimetric method (*Standard Methods*, 2005). Chlorine used for dosing was prepared from a 5-6 percent hypochlorite solution⁷. Ammonia used for dosing was prepared from ACS-grade ammonium chloride⁷. Phosphate buffer solution and DPD indicator solution were purchased factory prepared⁸. Potassium iodide was prepared from ACS-grade potassium iodide⁷.

The TOC was measured according to Standard Method 5310C (*Standard Methods*, 2005)⁹. The AOC was analyzed following Standard Method 9217B (*Standard Methods*, 2005) by an outside laboratory¹⁰. Three carboxylic acids, including acetate, formate, and oxalate, were analyzed according to an ionic chromatographic method reported by Peldszus et al (1996), Kuo (1998), and Kuo et al (1996),

with minor modifications¹¹. In summary, 20 mg/L mercury chloride was used as a preservative and a sample holding time of 17 days was adopted. Postozone samples were not aerated since ozone residuals were consistently close to nondetect. The calculated method detection limits (MDLs) were 3.7, 2.5, and 2.5 µg/L for acetate, formate, and oxalate, respectively. Carboxylic acid analysis beginning in May 2012 was performed by an outside laboratory¹² using the same method and identical instrument.

The EPS was analyzed in both backwash water and filter media for all six pilot plant biofilters. The media samples were extracted following a protocol published by Lauderdale et al (2011) to allow the differentiation of free and bound EPS, and quantified using the Dubois method (1956). This method quantifies polysaccharides, which are the dominant components of EPS. For filter backwash water, the procedure was similar to the EPS measurement on the media. Since the dislodging of biofilm was already accomplished during backwash, the sonication step was not needed. The backwash water was directly centrifuged and the supernatant analyzed for free EPS and pellet after centrifugation was extracted and analyzed for bound EPS with the same procedure previously mentioned. The media samples were taken from the top layer of the filters when the filters had a headloss between 4 and 6 ft to ensure similar conditions and similar stage of EPS development between backwash cycles. Immediately after the media samples were collected, the filters were forced to backwash to enable the collection of backwash water samples under similar conditions.

Results

Effect of Nonchloraminated Backwash Water and Media Type

Carboxylic Acid Removal

At the full-scale Facility, finished water with a typical chloramine residual of around 5 mg/L is used to backwash filters, which was reported to possibly have a negative impact on biofilter performance (Miltner et al, 1995). Table 3 shows the total concentrations of the three carboxylic acids in the feed/influent and in the effluent water for both GAC and anthracite filters at the pilot plant. The carboxylic acid concentrations in the feed water varied greatly from 41 µg/L-C to 162 µg/L-C, most of which were removed by the biofilters, with the removal percentage consistently over 70 percent. For the same time period, the removal of carboxylic acids at the full-scale plant averaged

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Table 3. Total Carboxylic Acid Removal: Comparison of Chloraminated and Nonchloraminated Backwash Water

Backwash water, Filter loading rate	Test months	GAC			Anthracite		
		Influent (µg/L-C)	Effluent (µg/L-C)	Removal (%)	Influent (µg/L-C)	Effluent (µg/L-C)	Removal (%)
Non chloraminated, 1 gpm/ft ²	July, Aug, Sept 2011	93 ± 28	17 ± 12	82 ± 6	82 ± 34	21 ± 12	72 ± 7
Chloraminated, 1 gpm/ft ²	May, June, Nov 2011	91 ± 43	16 ± 12	81 ± 7	92 ± 39	26 ± 18	75 ± 7
Non-chloraminated, 2.5 gpm/ft ²	Oct 2011	111 ± 19	22 ± 1	80 ± 2	100	24	76
Chloraminated, 2 gpm/ft ²	Dec 2011	116 ± 23	17 ± 1	85 ± 2	101 ± 0	22 ± 4	79 ± 4

Figure 1. Chlorine Curves with Nonchloraminated Backwash and Filter Loading Rate of 1 gpm/ft²

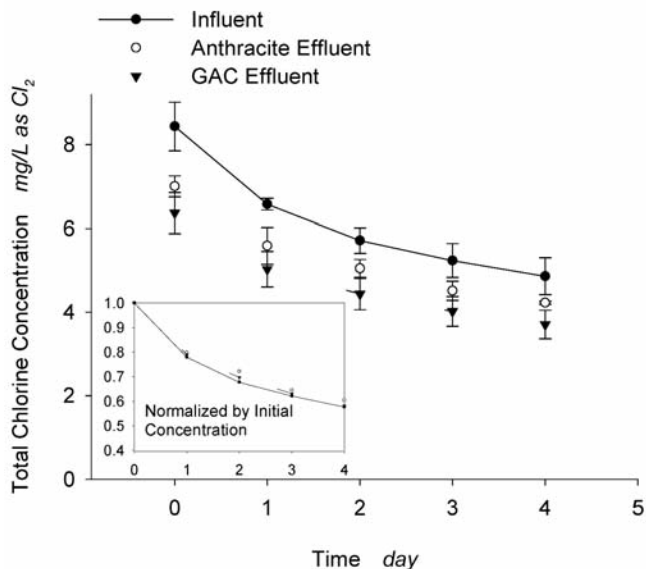
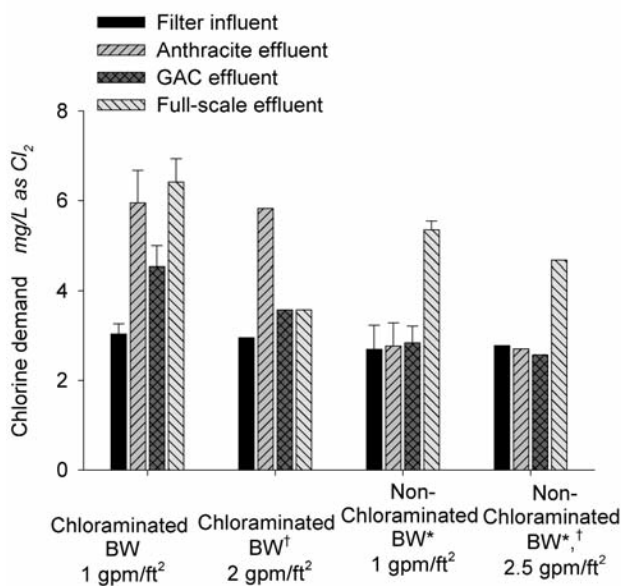


Figure 2. Comparison of Chloraminated and Nonchloraminated Backwash Water on Chlorine Demand With Different Filter Loading Rates



*Full scale filters still have chloraminated backwash

[†]Only one sampling event occurred for these loading rates

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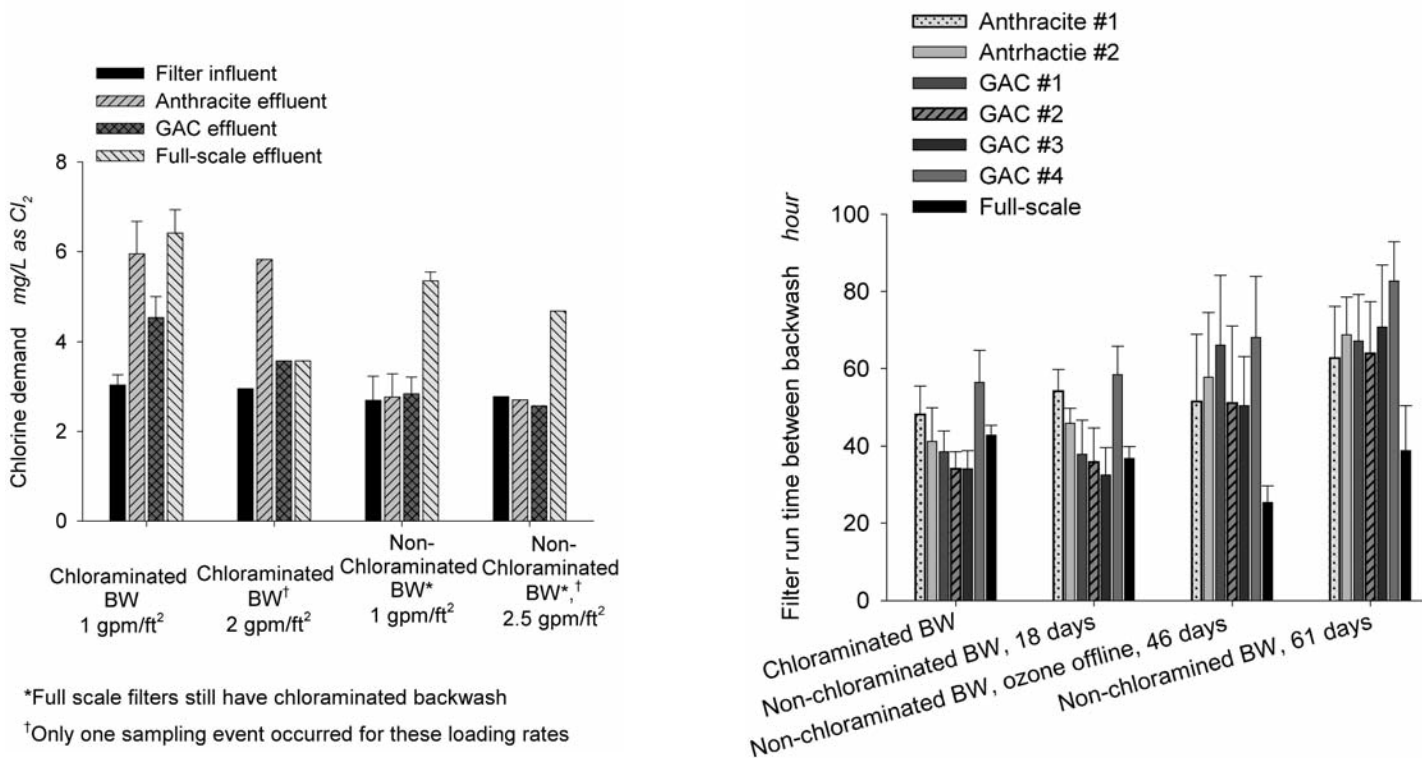
at 82 ± 6 percent. Apparently, the GAC filters at the pilot plant achieved similar removals of carboxylic acids to the full-scale GAC filters, while anthracite consistently underperforms GAC throughout all conditions in regards to the removal of carboxylic acids.

For both GAC and anthracite filters, nonchloraminated backwash water didn't improve the removal of carboxylic acids, and the filter loading rates also did not result in any difference in removal. This could be attributed to the fact that the removals are fairly high with chloraminated backwash water and there is no room left for improvement with nonchloraminated water. The TOC removal showed similar trending (results not presented), but is overall lower than the removal of carboxylic acids, typically in the range between 18 to 45 percent.

Chlorine Demand of Filter Effluent

Chlorine demand for both influent and effluent of all the filters was another metric used to evaluate the impact of nonchloraminated backwash water and filter media on filter performance. The same set of water samples from Table 3 were first dosed with chloramine at the target concentrations and chloramine residuals were measured daily. Figure 1 shows the chloramine decay kinetics over a five-day period under one of the test conditions and Figure 2 shows the summary of chlorine demand for all the samples generated in Table 3; the chlorine demand during the same time period for full-scale filters is also presented in Figure 2 as a reference point. Note that in the figure, the full-scale filters were always backwashed with chloraminated water, with the filter loading rate fluctuated around 2 gpm/ft² during the entire pilot study. The error bars in Figure 2 merely reflected water quality variation rather than the experimental error because they were averaged based on samples collected monthly over a three-month period for chloraminated backwash water

Figure 3. Impact of Chloramine in Filter Backwash Water on Filter Run Time (BW – Backwash)



and a five-month period for nonchloraminated backwash water.

Results in Figure 2 have shown a pronounced effect of chloraminated backwash water on chlorine demand. When the filters were backwashed with chloraminated water, the chlorine demand of the filter effluent at the pilot plant was similar to the full-scale plant. Pilot GAC filters at the loading rate of 1 gpm/ft² performed a little bit better than full-scale filters, which treated water at a loading rate of 2 gpm/ft². When the loading rate of pilot plant was increased to 2 gpm/ft², no difference in chlorine demand was observed between pilot GAC filters and the full-scale filters. Overall, anthracite media perform significantly worse than GAC with the difference between the two media more pronounced when the loading rate was increased from 1 to 2 gpm/ft².

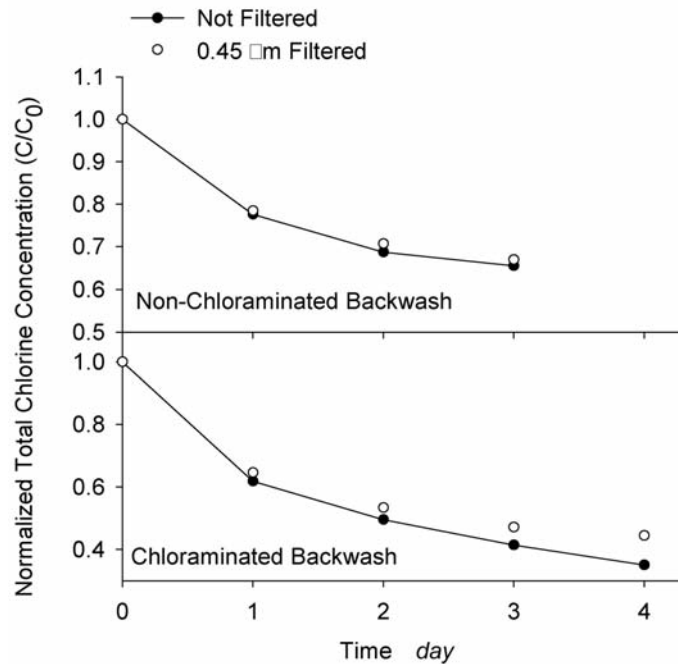
In contrast, under nonchloraminated filter backwash conditions, with a filter loading rate of 1 gpm/ft² (Figure 1), all four GAC filters, as well as the two anthracite filters, exhibit similar chloramine decay kinetics and chlorine demand despite different media and other differences observed among the six filters, such as filter run time and removal of TOC and carboxylic acids. This is also true for the 2.5 gpm/ft² filter loading rate as demonstrated in Figure 2 whenever nonchloraminated water was used for filter backwash. In both cases, the chlorine demands for pilot plants for both GAC and anthracite filter effluent were significantly lower than full-scale filter effluent, which was still backwashed with chloraminated water.

In the full-scale plant, the chlorine demand for filter effluent is higher than the influent; in other words, the biofiltration adds additional chlorine demand to the water being treated, which was undesirable and caused problems to the distribution system's water quality maintenance. Results in Figure 2 suggest that this problem could be eliminated by switching to nonchloraminated backwash water and the resulted improvement will be persistent regardless of the filter loading rate and media type.

Filter Run Time

Lower chlorine demand is one benefit with nonchloraminated water for filter backwash. Another benefit is a significant longer

Figure 4. Effect of 0.45 μ m Filter on Pilot Granular Activated Carbon Effluent Chlorine Demand



filter run time (Figure 3), which was recorded after December 2011 when the pilot plant began to be backwashed by the fully automated SCADA system. Figure 3 is presented following the temporal order and grouped by various testing conditions shown in the x-axis. In this figure, the pilot and full-scale plants were operated with the same filter loading rate, the same backwash procedures, and same source water; however, the backwash water for full-scale always contained chloramine with residual up to 5 mg/L, depending on the level in the clearwell where the backwash water was drawn. The pilot plant was initially backwashed with the same type of chloraminated water, as shown in Figure 3, and switched to nonchloraminated water to study the impacts. The improvement in filter run time for both anthracite and GAC filters from nonchloraminated backwash water is significant.

Near the end of the test, anthracite and GAC showed 70 percent and 84 percent improvement, respectively, over full-scale filters, on average. These results also suggest that it takes time for biological activity to reach its full potential. On day 18, after nonchloraminated backwash, longer filter run time was already observed and continued to increase over the course of the entire testing period for nonchloraminated backwash water. The simultaneous improvement in filter effluent chlorine demand was noticed, as well as after

the switch of backwash water, as discussed previously. Another lesson learned was the ability to recognize the differences among the filters of identical conditions. Filters GAC #3 and GAC #4 can be best used to demonstrate this point and despite the same conditions, GAC #4 consistently had much longer filter run time under all test conditions. In summary, all four GAC and both anthracite filters exhibited differences in filter run time to various extents. As a result, it is strongly recommended that biofiltration be studied, at least in duplicate.

Mechanism of Filter Performance Improvement

To elucidate the underlying mechanism for improved filter performance, the effluent from one GAC filter was treated by 0.45 micrometre (μ m) filter and the difference in chlorine demand before and after filtration was studied under chloraminated and nonchloraminated filter backwash conditions.

The results are shown in Figure 4, normalized by initial concentration.

When nonchloraminated backwash water was used, no discernible difference was noted after the sample was treated by the 0.45 μ m filter. With chloraminated backwash water, the 0.45 μ m filtration decreased chlorine demand significantly. On day 3, a 15 percent improvement was observed, in contrast to the miniscule difference when nonchloraminated water was used for filter backwash. These results have suggested that particles small enough to avoid being retained by the GAC but large enough to be stopped by a 0.45 μ m filter is the explanation for the improved chloramine decay. Marda et al (2008) observed the similar phenomenon with chloraminated backwash water, but provided no solution to resolve this issue. The results presented in Figure 4 clearly demonstrated that the nonchloraminated filter backwash water could help filters better retain particles larger than 0.45 μ m and cut down chlorine demand.

Effect of Nutrient and Hydrogen Peroxide Addition

The purpose of nutrient and hydrogen peroxide addition is to better manage bioactivity on the filter media and control the secretion of EPS. To evaluate the benefits to the Facility, both were studied at its pilot plant, but

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with different study criteria; more specifically, the removals of TOC and carboxylic acids, chlorine demand, and filter run time. Also studied were turbidity, head loss, and filter loading rate, which were continuously recorded by the online analyzers.

Starting in May 2012, filters anthracite #2, GAC #3, and GAC #4 had ammonia chloride and phosphoric acid added to the top of the filters to test the effect of nutrient addition on biofilter performance. The dosed concentrations were based on DOC using the 100:10:1 C:N:P molar ratio identified by LeChevallier et al (1991) as the limiting ratios for biofilm formation in drinking water. Ammonia concentrations in the effluent of the six pilot filters were all below 0.1 mg/L, with the actual levels varying among the six filters, and the levels for ammonia added to the filters were not statistically higher than those without ammonia addition.

Phosphorous concentrations in the effluent showed a different trending. They were all below 0.01 mg/L for the six pilot filters one month after three of the six filters were dosed with the nutrient. However, monitoring conducted two months later showed the phosphorous levels for nutrient treated filters averaged 0.016 mg/L versus less than 0.010 mg/L for filters without nutrient addition, apparently attributing to nutrient breakthrough. These results suggested that enough nutrients were dosed and any benefit from nutrient ad-

dition should show if such benefit does exist.

Figure 5 shows the removal for TOC and carboxylic acids and the associated chlorine demand as a result of nutrient addition. For both GAC and anthracite filters, nutrient addition clearly had no effect on the removal of TOC and carboxylic acids, or chlorine demand. There may be a slight negative effect of nutrient addition on the removal of TOC and carboxylic acids for GAC media, but it is within statistical error. Additionally, no difference was observed in regards to filter head loss and filter run time. The results presented here failed to confirm the benefits reported by Lauderdale et al (2012). This is likely due to the complexity of the water treatment process, the different source water, and other unknown factors.

Following the nutrient addition, hydrogen peroxide dosed at 1 mg/L and 2 mg/L was tested. Hydrogen peroxide of 1 mg/L was added for 70 days to filters anthracite #2, GAC #3, and GAC #4, while the rest of the filters had no addition and served as controls. The effects of hydrogen peroxide addition can then be evaluated by comparing the performance of anthracite #2 versus anthracite control, and GAC #3 and GAC #4 versus GAC controls. Afterward, hydrogen peroxide dose was increased to 2 mg/L and applied to the same three filters continuously for the following 34 days. No significant differences in TOC removal, carboxylic acid removal, or chlorine

demand were observed for either anthracite or GAC media with either 1 or 2 mg/L hydrogen peroxide added.

Filter run time is summarized in Figure 6. Because the tests were run over six months, source water was expected to change over the time period. As a result, controls were used to take into account changes in source water. For anthracite media, nutrient and hydrogen peroxide addition appears to have a positive effect on filter run time based on relative difference between the test and control filters; however, GAC does not exhibit the same results.

The GAC #4 seems to be positively affected by either nutrient or hydrogen peroxide addition, but GAC #3 showed the opposite effect. The absolute filter run time of GAC #3 had increased when 1 mg/L hydrogen peroxide was added to the filter. However, when the relative ratio between GAC #3 and the GAC control (GAC #1 or 2) was compared, its performance stayed flat with nutrient and 1 mg/L hydrogen peroxide addition and became worse when hydrogen peroxide was fed at 2 mg/L. This illustrated again the importance of evaluating biofilters at least in duplicate to account for variations between filters. Overall, the improvement in filter run time from either nutrient or hydrogen addition is inconclusive for GAC media and a slight advantage is observed for anthracite media. This could be due to the better biological activity and retention exhibited by GAC filters

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Figure 5. Effect of Nutrient Addition on Total Organic Carbon Removal, Carboxylic Acid Removal, and Chlorine Demand

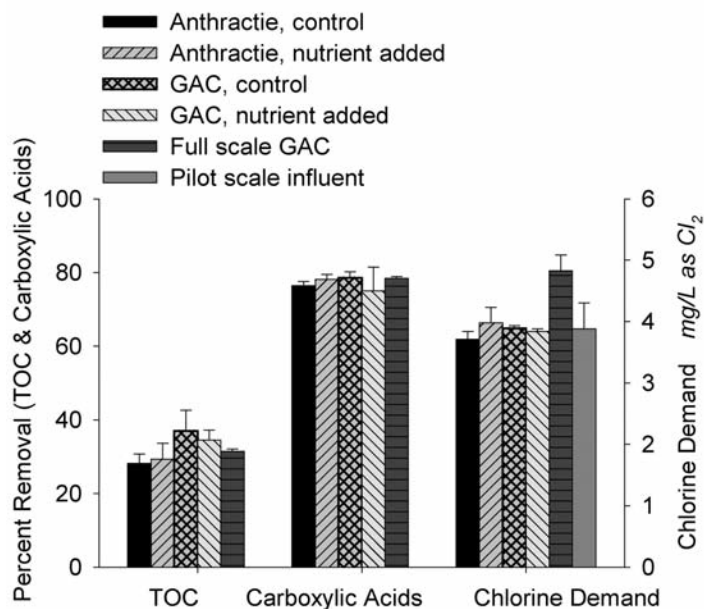
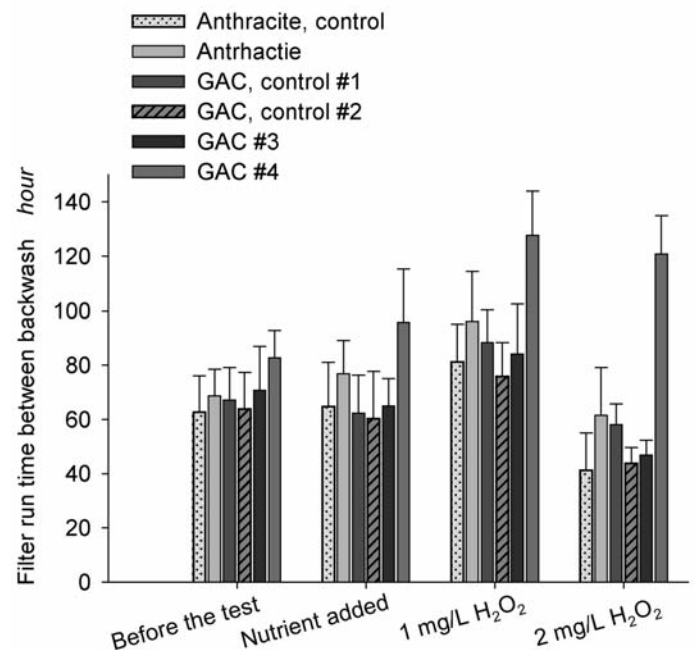


Figure 6. Impact of Nutrient and Hydrogen Peroxide Addition on Filter Run Time



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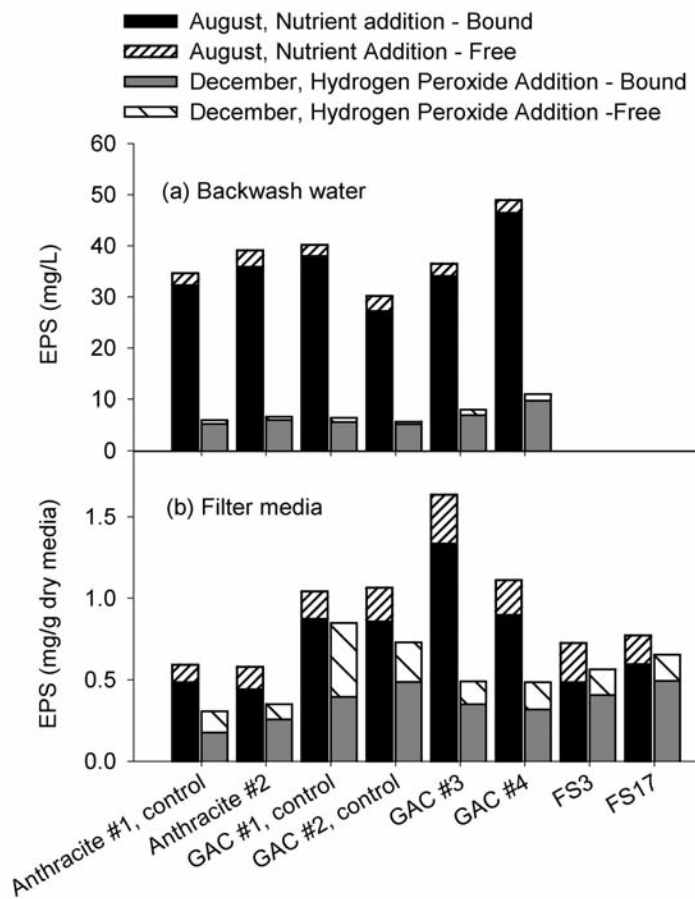
(Ahmad et al, 1998), and as a result, there is not much room left for improvement.

To help better understand the results and elucidate the reasons for the observed difference from Lauderdale et al (2012), EPS was monitored in filter backwash water and on the media. The results are summarized in Figure 7. In filter backwash water, less than 15 percent of EPS was present as unbound; on the media, EPS was still mostly bound, but the unbound EPS concentration became more significant. These data have shown EPS levels are greatly affected by seasonal temperature changes. The relatively warmer month of August directly resulted in higher EPS, both in filter backwash water and on the media, regardless of the media type. The seasonal difference was more pronounced in the pilot plant than the full-scale plant, likely due to the fact that unlike the full-scale plant, the pilot plant used nonchloraminated water for filter backwash and had more bioactivity.

In filter backwash water, nutrient and hydrogen peroxide addition did not cause any difference to EPS concentrations. Despite the difference observed among the six filters, the EPS levels for the controls of both GAC and anthracite fell well within the same range as the testing filters. The GAC #4 did exhibit relatively higher EPS concentration in the backwash water, which seems to be consistent with this filter's exceptionally longer filter run time. For some reason, which could be better perforation in the supporting plate in the underdrain system, this filter's backwash apparently is more efficient and removes more EPS. Overall, regardless of chemical additions, the level of EPS in backwash water seems to correlate with filter run time and can be used as a rough indicator of the potential filter run time.

On the media, as expected, higher levels of EPS were observed on GAC when compared to anthracite. The levels of EPS on both media are slightly higher than EPS on sand (Mauclair et al, 2004), but still within the same order of magnitude. No direct comparison could be made with data reported by Lauderdale et al (2012), where EPS on the media was reported

Figure 7. Effect of Nutrient and Hydrogen Peroxide Addition on Extracellular Polymeric Substances Concentrations in (a) Backwash Water and (b) Filter Media



All samples were run in quadruplicate with errors less than 20 percent

in the unit of mg/L. In this study, nutrient addition did not decrease EPS for GAC or anthracite media when compared to the control groups, which explained the lack of improvement in filter performance from the nutrient addition. Hydrogen peroxide addition, however, did decrease EPS for GAC filters with GAC #3 and #4 showing less EPS compared to their corresponding control filters.

Despite the improvement in EPS levels, the filters with hydrogen peroxide addition did not show longer filter run time (Figure 6) or less chlorine demand (Figure 5), nor did they show better removal of TOC and carboxylic acids (Figure 5). Based on these results and the significant differences from previously published literatures (Lauderdale et al, 2012), further studies on nutrient and hydrogen peroxide addition are strongly recommended to include a more diversified coverage of geological locations and source waters.

Implications to Full-Scale Plant and Future Studies

This study has revealed the high variability of biofilter performance, in spite of identical configurations and operational procedures. It is recommended that future studies be conducted with duplicate or even triplicate filter columns, which is challenging considering the scale and demanding nature of pilot testing. Yet, capturing and being able to foresee variability of biofilters is an important and often neglected issue. Each filter's run time in this study not only differs by up to 50 percent compared to each other, it also varies by 20 to 30 percent between backwashes. It should be noted that despite the significantly different run time among the different filters, the chlorine demand and removal percentages of TOC and carboxylic acids were very close under identical conditions. The data suggest that as run time increases, variance increases. Filter run time is very sensitive to variations in source water quality, with extreme peaks and drops within short time spans compared to other metrics of filter performance.

Based on pilot plant study results, the recommended resolution for the high chlorine demand problem in finished water is to use nonchloraminated water for filter backwash. The estimated savings for chlorine and ammonia is about 20 to 30 percent of their current cost, depending on time of the year and water demand. Approximately one third of the savings is from ammonia and two thirds from chlorine, depending on market prices. Additional savings should come from the lower volume of backwash water required due to longer filter run times. Collectively, these add up to a total savings of around \$270,000, assuming the cost to produce water remains around \$500 per mil gal (MG). More importantly, the biofilters will be optimized and pose less operational challenges, especially when dealing with the control of nitrification problems at the furthest end of the distribution system.

Conclusion

The performance of biofiltration was studied using a multitude of factors, aiming at solving the high chlorine demand problem in finished water via filter optimization. Based on

this study, increased bioactivity should be desired, as it can improve filter performance. The chloramine in the backwash water had a strong negative effect on the filter performance with respect to both chlorine demand and filter run time. A switch to nonchloraminated backwash water exhibited the most significant improvement on the biofiltration system out of all the factors studied, and subsequently led to the largest cost savings. Using nonchloraminated backwash water, the chlorine demand in filter effluent remained the same as the influent, representing a 50 percent improvement for anthracite and a 30 percent improvement for GAC when compared with chloraminated backwash water. The filter run time was increased by approximately 40 percent as a result of using nonchloraminated backwash water, which directly translated into a 40 percent decrease in backwash water usage.

Altogether, switching to nonchloraminated water for filter backwash will result in an estimated annual cost saving of \$270,000 once implemented at the full-scale Facility. Nonchloraminated backwash water did not show any significant effects on the removal of TOC or carboxylic acids. Generally, GAC media perform better than anthracite media, but anthracite still performs sufficiently well for many utilities to consider due to the significant cost difference between GAC and anthracite.

This study showed no major effect from the addition of nutrient and hydrogen peroxide. Their potential benefit judged by the removal of TOC and carboxylic acids, chlorine demand of the effluent, and filter run time was very minor. Nutrient addition did not cause significant impact on EPS concentrations on the media. Hydrogen peroxide addition decreased EPS levels, but without any associated benefits. Higher levels of EPS were observed on GAC when compared to anthracite and in the relatively warmer summer month of August when compared to December. EPS in filter backwash water appeared to be a rough indicator of the effectiveness of backwash and subsequently affected filter run time.

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Footnotes

- ¹ Anthracfilter Inc., Niagara Falls, N.Y.
- ² ActiCarb, Dunnellon, Fla.
- ³ Standard Sand & Silica Company, Davenport, Fla.
- ⁴ HACH, model SC100 controller with a 1720E sensor, Loveland, Colo.
- ⁵ Endress+Houser, model PMD70, Greenwood, Ind.
- ⁶ Endress+Houser, magmeter Promag 10, Greenwood, Ind.
- ⁷ Fisher Scientific, Fair Lawn, N.J.
- ⁸ Sigma Aldrich, St. Louis, Mo.
- ⁹ Teledyne Tekmar TOC Fusion, Thousand Oaks, Calif.
- ¹⁰ MWH Laboratories, Monrovia, Calif.
- ¹¹ Dionex ICS 3000, Sunnyvale, Calif.
- ¹² Underwriters Laboratory, South Bend, Ind.

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