Webcast
Guidance Manual for Monitoring Biological Filtration of Drinking Water

April 11, 2019
Focus Area Objectives

Provide guidance

<table>
<thead>
<tr>
<th>Implementation</th>
<th>Enhancement</th>
<th>Monitoring</th>
<th>Optimization</th>
</tr>
</thead>
</table>

Develop communications

| Biofiltration attributes | Effects on overall treatment effectiveness |
Focus Area Projects

Development of a Biofiltration Knowledge Base

Total WRF Funding - $1,525,000
Total Value - $4,625,000

- Simultaneous Removal of Multiple Chemical Contaminants Using Biofiltration
- Optimizing Biofiltration for Various Source Water Quality
Guidance Manual for Monitoring Biological Filtration of Drinking Water

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Biological Filtration

biological treatment within a filter at a drinking water treatment facility, with the operational practice of managing, maintaining, and promoting biological activity on granular media in the filter to enhance the removal of organic and inorganic constituents before treated water is introduced into the distribution system.

Biofilm = bacteria + extracellular polymeric substances (EPS)
How do we monitor biofilters?

• A Monitoring and Control Toolbox for Biological Filtration (WRF 4231)
  – Screening of 40 monitoring and control tools

• Bioprocess Monitoring Tools for Biological Filtration (WRF 4620)
  – What to monitor for
  – How samples should be collected
  – What values are acceptable
  – What action items are needed

• Biofiltration Guidance Manual for Rapid Rate Filtration Facilities (WRF 4719)
Pilot and Full Scale Testing

- **Method Refinement Sampling**
  - One-time sampling
  - 5 facilities
  - Reproducibility and interlaboratory testing

- **Tool Validation Testing**
  - 9-month study
  - 15 facilities
  - Pilot testing
    - Substrate loading
    - Chlorine spike testing
  - Reproducibility and interlaboratory testing
## Utility Overview

<table>
<thead>
<tr>
<th>Utility</th>
<th>Facility</th>
<th>Pilot or Full Scale?</th>
<th>Source Water</th>
<th>Flow (MGD)</th>
<th>Media Type</th>
<th>Pre-Oxidant</th>
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<tbody>
<tr>
<td>American Water</td>
<td>Delaware River</td>
<td>F</td>
<td>River</td>
<td>40</td>
<td>GAC</td>
<td>O₃</td>
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<tr>
<td></td>
<td>Swimming River</td>
<td>F</td>
<td>Reservoir</td>
<td>36</td>
<td>GAC</td>
<td>O₃/KMnO₄/Cl</td>
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<td>Aurora Water</td>
<td>Binney</td>
<td>F</td>
<td>Reservoir</td>
<td>53</td>
<td>GAC</td>
<td>UV/H₂O₂</td>
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<tr>
<td>CFPUA</td>
<td>Sweeney</td>
<td>F</td>
<td>River</td>
<td>35</td>
<td>GAC</td>
<td>O₃</td>
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<td>CUWCD</td>
<td>Duchesne Valley</td>
<td>F</td>
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<td>100</td>
<td>Anthracite</td>
<td>O₃</td>
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<td>Columbus Water</td>
<td>Hap Cremean</td>
<td>F</td>
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<td>90</td>
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<td>O₃</td>
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<tr>
<td></td>
<td>Dublin Road</td>
<td>F</td>
<td>Reservoir</td>
<td>80</td>
<td>GAC</td>
<td>O₃</td>
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<td>Denver Water</td>
<td>Recycling Plant</td>
<td>F</td>
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<td>30</td>
<td>Anthracite</td>
<td>Cl₂</td>
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<td>Fairfax</td>
<td>Griffith</td>
<td>F</td>
<td>Reservoir</td>
<td>120</td>
<td>GAC</td>
<td>O₃</td>
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<tr>
<td>GCWW</td>
<td>Richard Miller</td>
<td>F</td>
<td>River</td>
<td>240</td>
<td>Sand</td>
<td>none</td>
</tr>
<tr>
<td>Gwinnett County</td>
<td>Shoal Creek Filter Plant</td>
<td>P</td>
<td>Lake</td>
<td>6 gpm</td>
<td>Anthracite</td>
<td>O₃</td>
</tr>
<tr>
<td>Halifax</td>
<td>JD Kline</td>
<td>P</td>
<td>Lake</td>
<td>4 gpm</td>
<td>Anthracite</td>
<td>KMnO₄</td>
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<tr>
<td>Tampa Bay</td>
<td>Tampa Bay Surface WTP</td>
<td>F</td>
<td>River</td>
<td>120</td>
<td>GAC</td>
<td>O₃</td>
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<tr>
<td>West Palm Beach</td>
<td>West Palm Beach</td>
<td>F</td>
<td>Lake</td>
<td>47</td>
<td>GAC</td>
<td>none</td>
</tr>
</tbody>
</table>
# Biofiltration Monitoring Tools

## Biological
- Biofilm formation rate
- DO consumption
- Adenosine triphosphate (ATP)
- Adenosine monophosphate (AMP)
- Extracellular polymeric substances (EPS)
- Microbial community analysis

## Natural Organic Matter (NOM)
- TOC
- DOC
- UV254
- SUVA254
- DBPFP
- peCOD
- Carboxylic acids
- Fluorescence EEM

## Water Quality
- pH
- Temperature
- Turbidity
- Nutrients

## Filter Hydraulics and Operational
- Headloss
- Headloss accumulation rate or filtration rate
- EBCT
- UFRV
- Backwash pump pressure
- Oxidant residual
Biofilm Formation Rate

• Pipe loops with sacrificial coupons
• Measure ATP from biofilm formed on the coupon surface
• Filter influent is a surrogate (estimate) of the rate of bacterial growth
• Filter effluent measures biostability

Flow control orifice
Sight Tube
Coupon holders
Flow in
Flow out

Flow = 0.5 gpm (0.37 ft/s)

Biofilm Formation Rate Coupons
Bacteria
Biofilm
Two Weeks
Water Flow

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Procedure
1. Install polycarbonate coupons
2. Incubate for two weeks
3. Harvest coupon and place in LuminUltra UltraLyse 7 extraction tube
4. Measure ATP using LuminUltra DSA kit

5. Calculate Biofilm Formation Rate:

\[
\text{Biofilm Formation Rate} \left( \frac{pg\ ATP}{mm^2\ d} \right) = \frac{ATP (pg)}{\text{Coupon Surface Area (mm}^2\) \times \text{Incubation Time (d)}}
\]
Biofilm Formation Rate

Two week incubation period is sufficient

Incubation Time (days)

Biofilm Formation (pg ATP/mm²)

- Delaware River Influent
- Delaware River Effluent
- Halifax Influent
- Halifax Effluent
- Swimming River Influent
- Swimming River Effluent
- Dublin Road Influent
- Hap Cremeann Influent
- Central Utah Influent
- GCWW Influen
- Tampa Bay Influent
Biofilm Formation Rate

Influent | Effluent

- Delaware River
- Swimming River
- Dublin Road
- Hap Cremean
- Central Utah
- GCWW
- Halifax
- Tampa Bay

0.6 mg/L Cl Residual

Biofilm Formation Rate (pg ATP/mm²/d)
Previous Biofilm Formation Rate Testing

• WRF 4321 used coupons to evaluate biostability of finished water and distribution systems
• Biofilm formation rates covered several orders of magnitude
• Concentrations higher in this study, but similar to monitoring in distribution systems

*LeChevallier et al 2015, WRF 4321 – An Operational Definition of Biostability*
Biofilm Formation Rate

Biofilters increased biostability

<table>
<thead>
<tr>
<th>Location</th>
<th>Biofilm Formation Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delaware River</td>
<td>100%</td>
</tr>
<tr>
<td>Dublin Road</td>
<td>100%</td>
</tr>
<tr>
<td>Hap Cremean</td>
<td>100%</td>
</tr>
<tr>
<td>Central Utah</td>
<td>60%</td>
</tr>
<tr>
<td>GCWW</td>
<td>100%</td>
</tr>
<tr>
<td>Halifax</td>
<td>20%</td>
</tr>
<tr>
<td>Tampa Bay</td>
<td>100%</td>
</tr>
</tbody>
</table>
Temperatures >15 deg C had a higher biofilm formation rate
Biofilm Formation Rate and DOC Removal

\[ y = 0.11 \ln(x) + 0.10 \]
\[ R^2 = 0.60 \]

Influent Biofilm Formation Rate (pg ATP/mm²/d)

DOC Removal (mg/L)

- Delaware River
- Haifax
- Dublin Road
- Hap Cremeon
- Central Utah
- GCWW
- Tampa Bay

\[ y = 0.0004x + 0.13 \]
\[ R^2 = 0.33 \]

Temperature > 15 °C

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Dissolved Oxygen (DO) Consumption

- Online Luminescent DO Probes
- Used to quantify biological activity

\[
\text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2 \rightarrow 6\text{CO}_2 + 6\text{H}_2\text{O}
\]
DO Consumption

- Probe installation in a flow through cell, pole-mounted or in a stilling well
- Limit of detection is 0.1 mg/L and upper limit is 43 mg/L
- Calculated as the change from the filter influent to effluent

\[
DO\ \text{Consumption}\left(\frac{mg}{L}\right) = \text{Influent DO} \left(\frac{mg}{L}\right) - \text{Effluent DO} \left(\frac{mg}{L}\right)
\]

[Graph depicting weekly average DO consumption with marked limit of detection]
Accuracy Under Supersaturated Conditions

<table>
<thead>
<tr>
<th>Water Type</th>
<th>Measured DO (mg/L)</th>
<th>Expected DO (mg/L)</th>
<th>RPD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air saturated Water</td>
<td>8.48±0.34</td>
<td>8.71</td>
<td>2.7%</td>
</tr>
<tr>
<td>99% Oxygen saturated Water</td>
<td>43.3±0.68</td>
<td>42.9</td>
<td>0.9%</td>
</tr>
</tbody>
</table>
Filter influent DO was supersaturated at ozone plants.
DO consumption was in excess of predicted values based on DOC removal.
Theoretical Oxygen Demand \( \left( \frac{mg O_2}{L} \right) \) = DOC removal \( \left( \frac{mg}{L} \right) \) \( \times \) \( \left( \frac{1 \text{ mmole C}}{12 mg C} \right) \) \( \times \) \( \left( \frac{1 \text{ mmole O}_2}{1 \text{ mmole C}} \right) \) \( \times \) \( \left( \frac{32 \text{ mg O}_2}{1 \text{ mmole O}_2} \right) \)

At non-ozone plants, DO consumption was in-line with predicted values based on DOC removal.
Volumetric DO Consumption and Biofilm Formation Rate

Volumetric DO Consumption \( \left( \frac{mg}{L \cdot d} \right) = \frac{\text{Filter Influent DO} \ (\frac{mg}{L}) - \text{Filter Effluent DO} \ (\frac{mg}{L})}{EBCT \ (min)} \times 1440 \ (\frac{min}{d}) \)

\[ y = 1.57x - 86.9 \]
\[ R^2 = 0.69 \]
DO Consumption – Substrate Pulse

Halifax Water Pilot

- Before Spike
- 2 mg-C/L Ethanol Spike
- After Spike

DOC (mg/L)

DO (mg/L)

- Raw Water
- Biofilter Influent
- Biofilter Effluent
- Filter Influent DO
- Filter Effluent DO

2 mg-C/L ethanol pulse

7/10 7/15 7/20 7/25 7/30 8/4 8/9
DO Consumption – Chlorine Spike

Halifax Water Pilot

- **Biofilter Influent**
- **Biofilter Effluent**
- **Influent Chlorine Residual**

**DOC (mg/L)**

- Before
- 0.5 mg/L Chlorine Pulse
- 5 mg/L Chlorine Pulse

**DO Consumption (mg/L)**

- 8/26
- 8/28
- 8/30
- 9/1

**Filter Influent Chlorine Residual (mg/L)**

- 0.5 mg/L chlorine
- 5 mg/L chlorine
Adenosine Triphosphate (ATP)

- Bioenergy molecule present in all living organisms
- Indicator of biomass
- Measured using LuminUltra’s Deposit Surface Analysis (DSA) test kit

**ATP Filter Media Sample Analysis**

1 g Filter Media → 5 Minute Incubation → 1 mL UltraLyse 7 → Invert 3X to Mix → 100 µL of Each Swirl to Mix → ATP on Filter Media

- Scale
- ATP UltraLyse 7 Tube
- ATP UltraLyse 7 Tube
- ATP UltraLyse 7 Tube
- ATP UltraLute Tube
- ATP UltraLute Tube
- ATP UltraLute Tube
- ATP Analysis Vial
- ATP Analysis Vial
- Luminometer
- Luminometer
ATP Sample Collection

ATP (pg/g dry wt)

0 days 1 day 2 days 1 week

On Site CDM Smith
Delaware River Swimming River Denver Water GCWW

On Site CDM Smith
Gwinnett County
ATP on Filter Media

\[ y = 0.10 \ln(x) - 0.93 \]

\[ R^2 = 0.26 \]

**Average Temperature (°C)**

- Delaware River
- Dublin Road
- Hap Cremeon
- Central Utah
- Halifax
- GCWW
- Gwinnett
- Tampa Bay

**Average ATP (pg ATP/g dry wt.)**

- Delaware River
- Dublin Road
- Hap Cremeon
- Central Utah
- GCWW
- HALIFAX
- Gwinnett
- Tampa Bay

**Average DOC Net Removal (mg/L)**
ATP on Filter Media

Gwinnett County Pilot

Substrate loading test had no impact on ATP

Chlorine spike testing showed sensitivity to inhibitory conditions
Adenosine Monophosphate (AMP)

- LuminUltra developed test kits for the oil and gas industry
- Ratio of AMP/ATP as indicator of biological activity of biomass
- AMP/ATP Index – for oil & gas
  - > 10 is high stress
  - 1 to 10 is little to no stress
  - < 1 is “healthy” biomass

**AMP Filter Media Sample Analysis**

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100 µL of Each Swirl to Mix</td>
</tr>
<tr>
<td>2</td>
<td>5 Minute Incubation</td>
</tr>
<tr>
<td>3</td>
<td>ATP + AMP on Filter Media</td>
</tr>
<tr>
<td>4</td>
<td>AMP = (AMP + ATP) – ATP</td>
</tr>
</tbody>
</table>

charged battery

H₂O

energy

H₂O

dead battery

energy

charged battery

H₂O

energy

AMP

Pi

AMP

Pi

ATP

AMP

Pi

ATP

Pi

AMP

Pi

ATP

AMP

Pi

ATP

AMP

Pi

ATP

AMP

Pi

ATP

AMP

Pi

ATP

AMP

Pi

ATP

AMP

Pi

ATP

AMP

Pi

ATP

AMP

Pi

ATP

AMP

Pi

ATP
Adenosine Monophosphate (AMP)

Halifax Water Pilot

Potential tool but requires additional validation
Extracellular Polymeric Substances (EPS)

Quantify amount of excess biofilm present that can impact filter hydraulic performance
Extracellular Polymeric Substances (EPS)

- **Composition:**
  - Proteins ~ 90%
  - Carbohydrates <10%
  - Humics <1%
  - Nucleic acids <1%
- **Proteins:** modified Lowery Assay using the Pierce bicinchoninic acid (BCA) protein kit and bovine serum albumin (BSA) standard
- **Carbohydrates:** Dubois phenol/sulfuric acid assay
EPS Composition

EPS is primarily composed of proteins; thus only proteins were characterized in this study.

![Graph showing the relationship between proteins and carbohydrates in EPS.]
EPS Quantification

Protein analysis was carried out through the modified Lowery Assay with the Pierce bicinchoninic acid (BCA) protein kit and bovine serum albumin (BSA) standard.
EPS Sample Collection and Analysis

Analyze within 24 hours

Collect samples at the end of a filter run

EPS Proteins (mg BSA/g TS)

Collect samples at the end of a filter run

<table>
<thead>
<tr>
<th>Location</th>
<th>1 day</th>
<th>2 days</th>
<th>7 days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delaware River</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Swimming River</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Denver Water</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Greater Cincinnati</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gwinnett County</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Before Filter Run  
After Filter Run

- Delaware River
- Swimming River
- Denver Water
- Greater Cincinnati
- Gwinnett County

- Denver Water - 3/6
- Denver Water - 4/11
- GCWW - 3/1
- GCWW - 4/19
- GCWW - 6/14
EPS and Filter Hydraulics

No statistically significant relationship

Increasing UFRV associated with lower EPS
EPS and Filter Hydraulics

Volume of EPS per gram \( \left( \frac{mL}{g} \right) \) = Mass of EPS \( \left( \frac{mg \text{ BSA}}{g \text{ TS}} \right) \) ÷ EPS Density \( \left( 130 \frac{mg}{mL} \right) \)

% Pore Space as EPS = Volume of EPS per gram \( \left( \frac{mL}{g} \right) \) ÷ Pore Space Volume \( \left( \frac{mL}{g} \right) \) × 100%

<table>
<thead>
<tr>
<th>Utility</th>
<th>Facility</th>
<th>Media Type</th>
<th>Density (g/mL)</th>
<th>Porosity</th>
<th>Volume of Solids (mL in 1 g solids)</th>
<th>Pore Space (mL in 1 g of solids)</th>
<th>% Pore Space as EPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>American Water</td>
<td>Delaware River</td>
<td>GAC</td>
<td>0.56</td>
<td>0.5</td>
<td>1.79</td>
<td>1.79</td>
<td>0.96%</td>
</tr>
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<td>Aurora Water</td>
<td>Binney</td>
<td>GAC</td>
<td>0.51</td>
<td>0.5</td>
<td>1.96</td>
<td>1.96</td>
<td>0.10%</td>
</tr>
<tr>
<td>Denver Water</td>
<td>Recycling Plant</td>
<td>Anthracite</td>
<td>1.6</td>
<td>0.45</td>
<td>0.63</td>
<td>0.51</td>
<td>0.20%</td>
</tr>
<tr>
<td>GCWW</td>
<td>Richard Miller</td>
<td>Sand</td>
<td>2.675</td>
<td>0.21</td>
<td>0.37</td>
<td>0.10</td>
<td>7.15%</td>
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<tr>
<td>Gwinnett</td>
<td>Shoal Creek</td>
<td>Anthracite</td>
<td>1.6</td>
<td>0.45</td>
<td>0.63</td>
<td>0.51</td>
<td>0.30%</td>
</tr>
</tbody>
</table>
Microbial Community Analysis

Determine what microbial community is present and how they relate to seasonal/operational changes

- 16S rRNA region, Illumina Next Generation Sequencing
- Phylum and Genus level information
- Taxonomic Ranking
  - Phylum – Proteobacteria
    - Genus – *Pseudomonas*
      - Species – *aeruginosa*
Diversity and Community Dominance – Genus Level Results

Stacked bar charts are helpful for understanding diversity and abundance for phyla and genera.
Analysis Reproducibility - Field Duplicates

Stacked bar charts are helpful for understanding diversity and abundance for phyla and genera.

Percent Abundance (%)
Sample replicates between labs very divergent and had few similarities.
Future Research Needs

- Cheaper, faster microbial community characterization
- Replication (stick with one lab)
- Easy access to labs who can analyze samples and data
- Simple bioinformatics software and input format
  - PAST software
- Microbiome characterization?
- Consensus on pathogen tracking
- Other bioassays – enzymes, proteins etc.
Biofiltration Monitoring Guidance
## Biological Monitoring

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sampling Location</th>
<th>Frequency</th>
<th>Typical Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biofilm Formation Rate</td>
<td>Filter Influent and Effluent</td>
<td>Every two weeks</td>
<td>1 log removal across biofilters; POE to distribution system &lt;0.09 pg ATP/mm²/d</td>
</tr>
<tr>
<td>DO Consumption</td>
<td>Filter Influent and Effluent</td>
<td>Continuous</td>
<td>0.3 to 5 mg/L typical; 2.6 mg/L of DO consumed per 1 mg/L DOC removed</td>
</tr>
<tr>
<td>ATP</td>
<td>Filter Media</td>
<td>Monthly for start-up, optimization or research studies</td>
<td>Acclimation may take weeks to several months</td>
</tr>
<tr>
<td>EPS Proteins</td>
<td>Filter Media</td>
<td>Weekly for troubleshooting</td>
<td>If EPS occupies 7% of the pore space or greater, explore methods to lower EPS</td>
</tr>
<tr>
<td>AMP/ATP Ratio</td>
<td>Filter Media</td>
<td>Optimization/research studies</td>
<td>More research is needed, AMP/ATP &lt;1 is active biomass</td>
</tr>
<tr>
<td>Microbial Community Analysis</td>
<td>Filter Media</td>
<td>Limited during optimization/research studies,</td>
<td>Collect replicates! 10 to 30% variability is common between replicates</td>
</tr>
</tbody>
</table>
## NOM and Water Quality

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sampling Location</th>
<th>Frequency</th>
<th>Typical Range</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DOC</strong>*</td>
<td>Filter Influent and Effluent</td>
<td>At least every 2 weeks</td>
<td>Removal between 10 – 50%</td>
</tr>
<tr>
<td>pH</td>
<td>Filter Influent</td>
<td>Continuous</td>
<td>6.0 to 9.0 SU</td>
</tr>
<tr>
<td>Temperature</td>
<td>Filter Influent</td>
<td>Continuous</td>
<td>5 °C to 30 °C; higher bioactivity above 15 °C</td>
</tr>
<tr>
<td>Turbidity</td>
<td>Filter Effluent</td>
<td>Continuous</td>
<td>Meet regulatory requirements &lt;0.3 NTU in 95% samples for SWTR</td>
</tr>
<tr>
<td>Nutrients: orthophosphate, ammonia, nitrate, nitrite</td>
<td>Filter Influent</td>
<td>Monthly for troubleshooting, start-up, optimization, or research studies</td>
<td>For each mg/L of DOC removed, need approx. 0.0117 mg-N/L and 0.026 mg-P/L</td>
</tr>
</tbody>
</table>

*TOC may be used in lieu of DOC if a correlation between TOC and DOC at the filter influent and effluent exists from prior data*
## Filter Hydraulics and Operational Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sampling Location</th>
<th>Frequency</th>
<th>Typical Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Headloss, HLAR, or Surface Loading Rate</td>
<td>Filter Influent and Effluent</td>
<td>Continuous</td>
<td>Varies with filter design</td>
</tr>
<tr>
<td>Empty Bed Contact Time (EBCT)</td>
<td>Filter Effluent</td>
<td>Continuous, calculated from filter flow rate</td>
<td>5 to 15 minutes</td>
</tr>
<tr>
<td>Oxidant Residual</td>
<td>Filter Influent</td>
<td>Weekly if pre-oxidant is used upstream</td>
<td>&lt; 0.1 mg/L</td>
</tr>
<tr>
<td>Differential Pressure Profiling</td>
<td>Filter Influent, Mid-depth, Filter Effluent</td>
<td>Continuous for troubleshooting, start-up, optimization, or research studies</td>
<td>Varies with filter design</td>
</tr>
<tr>
<td>UFRV (gal)</td>
<td>Filter Effluent</td>
<td>Continuous for troubleshooting, start-up, optimization, or research studies</td>
<td>8,000 to 16,000 gpm/sf</td>
</tr>
<tr>
<td>Backwash Pump Pressure (psi)</td>
<td>Backwash Line</td>
<td>During Backwash</td>
<td>Varies with filter design</td>
</tr>
<tr>
<td>Filter Run Time (hr)</td>
<td>NA</td>
<td>Continuous</td>
<td>24 to 96 hr</td>
</tr>
</tbody>
</table>

Filter Influent and Effluent

Filter flow rate

Continuous, calculated from filter flow rate

Weekly if pre-oxidant is used upstream

Continuous for troubleshooting, start-up, optimization, or research studies

Continuous for troubleshooting, start-up, optimization, or research studies

Continuous for troubleshooting, start-up, optimization, or research studies

Continuous

Continuous

Continuous

Continuous
Top Recommended Tools

• **Biofilm formation rate** as an indicator of bioactivity and biostability

• **DO consumption** as an indicator of bioactivity for non-ozone plants only

• **DOC removal** as an indicator of bioactivity and biodegradation

• **pH, temperature, oxidant residual, and EBCT** impact bioactivity

• **Headloss accumulation rate** (constant rate filters) or **surface loading rate** (constant head filters) are important for monitoring hydraulic impacts

[http://www.waterrf.org/Pages/Projects.aspx?PID=4620](http://www.waterrf.org/Pages/Projects.aspx?PID=4620)
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Questions?
Thank You

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