Biofiltration for Meeting Today’s Water Quality Challenges: Design and Operational Considerations

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Agenda

• Background – drivers and basics
• Experiences with biofiltration
• Design and operational considerations
• Conclusions and recommendations
Background
Drivers for biofiltration

- Degrading water supplies
- Climate change and extreme weather events
  - Increased levels of natural organic matter
  - Higher levels of DBP precursors
  - More algal growth – toxic algal byproducts and tastes and odors
- More stringent future regulations
- Increased consumer sensitivity

Based on *Confronting Climate Change in the U.S. Northeast*
Biofiltration is Filtration (with a twist)

Conventional Treatment Process

Aerobic Biological Treatment

Hozalski and Bouwer, Water Research, Vol 35, Jan 2001
Benefits of Biofiltration

- DBP control
- Taste and odor control
- Trace organic contaminant removal
- Distribution system water quality control
  - Stability/regrowth control – BDOC/AOC removal
  - *Legionella*
Biofiltration is still filtration.....

Must also consider

- Turbidity/particle removal
- Iron/manganese
- Filter operations - headloss, filter run length
Biofiltration can be a Delicate Balance of Priorities

Particle Removal

- AOC/BDOC
- Optimized Coagulation
- Filter Runtime / Hydraulics
- GAC
- Contaminant Removal

Contaminant Removal

- Ozone
- Nutrient Enhancement
- Uniformity Coefficient
- Taste and Odor
- Hydraulic Loading Rate
- Free Chlorine / Chlorammines

Distribution System Ops.

- Anthracite
- Distribution System Ops.
- L/D
- Backwash
- Manganese

DBPs

- H₂O₂
- Media Size
A Holistic View of Biofiltration considers:

• The goals of biofiltration must consider the whole system
  • Raw water quality
  • Pretreatment
  • Post-treatment and distribution

• Benefits of biofiltration must be weighed against potential drawbacks
Holistic Biofiltration Example: Stability

- Stability in distribution is a function of biodegradable (BDOC/AOC)

Raw Water → Rapid Mix → Coagulant, PAC, KMnO₄, Cl₂ → Floc / Sedimentation → Ozone → Filtration / Biofiltration → Chlorine Contact → Distribution

- NBDOC = 90%
- TOC = 3.6 mg/L
- AOC = 10%

- Conventional Filt.: TOC = 2 mg/L
  - AOC = 400 ug/L

- Biofiltration (75% AOC Removal):
  - TOC = 1.7 mg/L
  - AOC = 100 ug/L

- Settled TOC = 2 mg/L
- Post-Ozone TOC = 2 mg/L

- NBDOC = 90%
- AOC = 10%
- Cl₂

- NBDOC = 80%
- AOC = 20%
- NH₃?
Experiences with Biofiltration
BAF Challenges

- **Biological Regrowth**
  - Colored water complaints, taste and odor, corrosion

- **Headloss Concerns**
  - Issue: Headloss on biological filters reducing plant capacity

- **Manganese**
  - Question: Can manganese be controlled adequately without pre-filter chlorine?

- **Limited removal of DBP precursors (NOM)**

- **Particle passage**
Approaches for optimizing biofiltration

• Nutrient Enhancement – “Engineered Biofiltration”
  • Goal: DBP control (better TOC removal)
  • Goal: Control EPS and improve biology through nutrient balancing

• Operations
  • Pay attention to proper filter operations
  • Conduct filter media inspections regularly - annually
  • Media – fines at the top with GAC (tarping effect)
  • Oxidant addition before filters

• Filter Design
  • In many cases the filter media designs for biofiltration are same as those for conventional filtration
BAF Filter Nutrient Enhancement

- BAF showed limited microbial response to nutrient enhancement over the course of the studies
- No increase in TOC removal across test filters compared to controls

Cape Fear Public Utility Authority

Gwinnet County, GA (Amburgy, 2014)
Biofiltration Headloss Concerns

- The Issue: Significant Headloss Through Biofilters
The results of these experiments suggest that water treatment facilities treating source waters with moderate organic matter concentrations and/or employing biologically active filtration have a greater potential for oocyst breakthrough and proper coagulation is critical for effective removal of oocysts in the filters.

- 28% reduction in bed porosity
Biofiltration and headloss

- EPS makes up vast majority of filtration media biofilm
- EPS can reduce effective porosity of filter bed

Take this into account when designing media
Nature of the Biofilm is important

• EPS – Extracellular Polymeric Substance
  • Organisms “excrete” EPS for adhesion, protection, energy storage
  • Polymer type material, capable of binding and clogging

• EPS has been linked to head loss buildup and clogging of filters

• Organisms are more likely to excrete EPS when “stressed”
  • Food or nutrient limited
  • “In hospitable” growth environment

• EPS makes up vast majority of filtration media biofilm

Theory: Control EPS and Control Filter Headloss Issues
Nutrient Enhancement Findings.....

• Results of Testing
  • No improvement with chlorinated backwash
  • Limited success with nutrient balancing and/or peroxide addition

• Still an issue last summer

• Need to take this into account when designing filters
Holistic Approach to Optimizing Biofiltration

Design and Operations

Contaminant Removal

Turbidity Removal

Chemistry

Physics

Biology

Hydraulic Performance

Biological Growth
Nutrients Ratios, AOC, EPS, ATP

Role of Pretreatment
Coagulation, Oxidation

Collector Efficiency,
Backwash, Pretreatment
Pre-filter oxidant addition
WSSC Patuxent Full-scale Plant Schematic

**Filters:**
- 20 inches anthracite
  - 1.1 mm ES
  - < 1.8 UC
- 9 inches sand
  - 0.47 mm ES
  - < 1.7 UC
- 2 inches illminite
  - 0.23 mm ES
  - < 1.8 UC

**Chemical Addition**
- Flocculation
- Clarification - tube settlers
- 2 inches illminite

**Corrosion Fluoride**
- Clearwell

**To System**
## Raw Water Quality

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbidity</td>
<td>3 - 5 ntu</td>
</tr>
<tr>
<td>Particle counts</td>
<td>10,000 - 15,000/mL</td>
</tr>
<tr>
<td>TOC</td>
<td>3 mg/L</td>
</tr>
<tr>
<td>pH</td>
<td>7 - 7.6</td>
</tr>
<tr>
<td>Alkalinity</td>
<td>17 - 25 mg/L (CaCO3)</td>
</tr>
</tbody>
</table>
Effect of Intermediate Chlorination on Filtered Water Turbidity

Source: WaterRF 2725
Effect of Intermediate Chlorination on Filtered Water Particle Counts

Patuxent Plant
Filter 7

Source: WaterRF 2725
WSSC Patuxent Pilot Plant

Raw Water → Static mixer → Flocculation/Clarification
-- Superpulsator

alum polymer

 Filters: 60 inches GAC (1.3 mm ES, < 1.4 UC)
12 inches sand (0.48 mm ES, < 1.5 UC)

Deep bed GAC/sand filters

$O_3$

Effluent
Effect of Intermediate Ozonation on Filtered Water Turbidity

Raw Water:
- Particle counts ~ 12,000/mL
- Turbidity: ~ 2.8 ntu

Filtration Rate: (6 gpm/sf)

Deep bed GAC/sand filters

Ozone train: 1 – 1.5 mg/L O₃
Effect of Intermediate Ozonation on Filtered Water Particle Counts

Raw Water:
Particle counts ~ 12,000/mL
Turbidity: ~ 2.8 ntu

Filtration Rate: (6 gpm/sf)
Deep bed GAC/sand filters

Ozone train: 1 – 1.5 mg/L \( \text{O}_3 \)

Source: WaterRF 2725
Effect of Ozone on Particle Removal

![Graph showing the effect of ozone on particle removal over time.

- Ozone air feed turned off.
- Ozone air feed turned back on.
- Ozone generator turned off.
- Ozone generator turned back on.

Elapsed Time (hr): 12 14 16 18 20 22 24
Total Particle Counts (#/mL): 0 100 200 300 400 500 600

Filtration Rate: 4 gpm/ft²
Deep bed GAC/sand filters

Source: WaterRF 2725}
Schematic Picture of a NOM Adsorbed Layer and the Electric Double Layer

Solid Particle Surface

Natural Organic Macromolecule

$$\Psi_0$$

$$\Psi_d$$

$$\Psi$$

stern layer

diffuse layer

bulk solution
Filter media design
Filtration Model

Dr. Jin Shin
Dissertation – Johns Hopkins University

PACKED BED FILTRATION IN POTABLE WATER TREATMENT:
PRETREATMENT CHEMISTRY FOR THE REMOVAL OF
PARTICLES AND NATURAL ORGANIC MATTER

October 2004
Filtration Equations
Transport Mechanisms

\[ \eta_T = \eta_D + \eta_I + \eta_G \]

Diffusion:
\[ \eta_D = 0.9 \left[ \frac{kT}{\mu d_p d_m U} \right]^{2/3} \]

Interception:
\[ \eta_I = \frac{3}{2} \left[ \frac{d_p}{d_m} \right]^2 \]

Sedimentation:
\[ \eta_G = \frac{[\rho_p - \rho]gd_p^2}{18 \mu U} \]

Yao, Habibian, and O’Melia (1971)
\[ \frac{C_e}{C_o} = e^{-\frac{3}{2} \left[ 1 - \varepsilon \right] \alpha \eta_T \left[ \frac{L}{d_m} \right]} \]

Yao, Habibian, and O’Melia (1971)
Filtration model w/ripening

\[
\ln \frac{C_i}{C_0} = -\frac{3}{2} (1 - f) \left( \frac{L}{d_c} \right) \eta_c \alpha \left[ 1 + \eta_p \alpha_p \beta U \frac{\pi}{4} d_p^2 \sum C_o \Delta t \exp \left[ -\frac{3}{2} (1 - f) \eta_{r,i-1} \left( \frac{L}{d_c} \right) \right] \right]
\]

Where:
- \( C_i \): Effluent water quality
- \( C_0 \): Influent water quality
- \( f \): Porosity
- \( L \): Length of media
- \( d_c \): Diameter of the collector
- \( d_p \): Diameter of the particle
- \( \Delta t \): Time
- \( U \): Surface loading rate
- \( \eta_c \): Single collector efficiency of media
- \( \eta_p \): Single collector efficiency of particle
- \( \alpha \): Collector efficiency
- \( \beta \): Retained particles that act as additional collectors
Model Inputs

**Operational Parameters:**
- Surface loading rate
- Run time

**Influent Characteristics:**
- Particle concentration
- Particle size
- Particle density
- Water temperature

**Filter Characteristics:**
- Collector efficiency
- Collection efficiency of retained particles
- Contribution of retained particles to headloss

**Media Properties:**
- Depth
- Effective size
- Uniformity coefficient
- Porosity
- Media density
Headloss Equation

\[
\frac{h_f}{L} = \frac{36k \mu U}{d_c^2 \rho g f^3} (1 - f)^2 \left(1 + \beta' \frac{N_p}{N_c} \left(\frac{d_p}{d_c}\right)^2 \right)^2
\]

Where;
- \(h_f\): Headloss
- \(k\): Kozeny constant
- \(f\): Porosity
- \(L\): Length of media
- \(d_c\): Diameter of the collector
- \(d_p\): Diameter of the particle
- \(U\): Surface loading rate
- \(\rho\): Density of water
- \(\mu\): Viscosity of water
- \(g\): Gravitational acceleration
- \(N_c\): Collector grains
- \(N_p\): Retained particles
- \(\beta'\): Retained particles that contribute to headloss
Model Outputs

• Filtrate Quality (Anthracite)
• Filtrate Quality (Anthracite + Sand)
• Headloss (Anthracite)
• Headloss (Anthracite + Sand)
• Anthracite:
  • Depth = 18 inches
  • L/d = 1118
  • ES = 0.9 mm
  • Conventional mode (porosity 0.45)

particle size = 0.5 µm
4 gpm/ft²
• Anthracite:
  • Depth = 18 inches
  • L/d = 1118
  • ES = 0.9 mm
  • Conventional mode (porosity 0.45)
  • Particle size = 0.5 µm
  • 4 gpm/ft²
**Anthracite:**
- Depth = 18 inches
- \( L/d = 1118 \)
- \( ES = 0.9 \) mm
- Biological mode (porosity 0.40)

Particle size = 0.5 µm

Flow rate = 4 gpm/ft²
• Anthracite:
  • Depth = 18 inches
  • L/d = 1118
  • ES = 0.9 mm
  • Biological mode (porosity 0.32)

particle size = 0.5 µm
4 gpm/ft²
- Anthracite:
  - Depth = 24 inches
  - L/d = 1164
  - ES = 1.1 mm
  - Biological mode (porosity 0.32)

particle size = 0.5 µm
4 gpm/ft$^2$
• Anthracite:
  • Depth = 24 inches
  • L/d = 1079
  • ES = 1.3 mm
  • Biological mode (porosity 0.32)

particle size = 0.5 \( \mu \text{m} \)
4 gpm/ft\(^2\)
• Anthracite:
  • Depth = 60 inches
  • L/d = 1626
  • ES = 1.5 mm
  • Biological mode (porosity 0.32)

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particle size = 0.5 µm
4 gpm/ft²
Conclusions and Recommendations
Biologically Active Filters - Conclusions

• Biofiltration is a viable process that can improve distribution system water quality and meet regulations
  • Taste and odors
  • Dirty water
  • Biologically stable water
  • DBP control

• Converting to biofiltration can result in filtration issues including:
  • Higher filtered water particle counts if preoxidant is not used
  • Excessive head loss development and short filter runs
  • Poor AOC/BDOC removal
  • Poor manganese removal
Biologically Active Filters - Recommendations

• Use pre-filter oxidant
  • Ozone or chlorine dioxide

• Design filter media to account for biofilm
  • Larger effective size media
  • Deeper beds
  • Uniformity coefficient – as low as possible!!!
  • Keep the layer of sand
  • Validate with pilot testing

• Test and maintain filters
  • Imperative to conduct filter surveillance monitoring:
    • Core samples, sieve analysis, solids retention analysis, spent filter backwash turbidity profile

• Perform monitoring of process and trend analysis
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THANK YOU!!!

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