Reducing Disinfection By-Products in Small Drinking Water Systems

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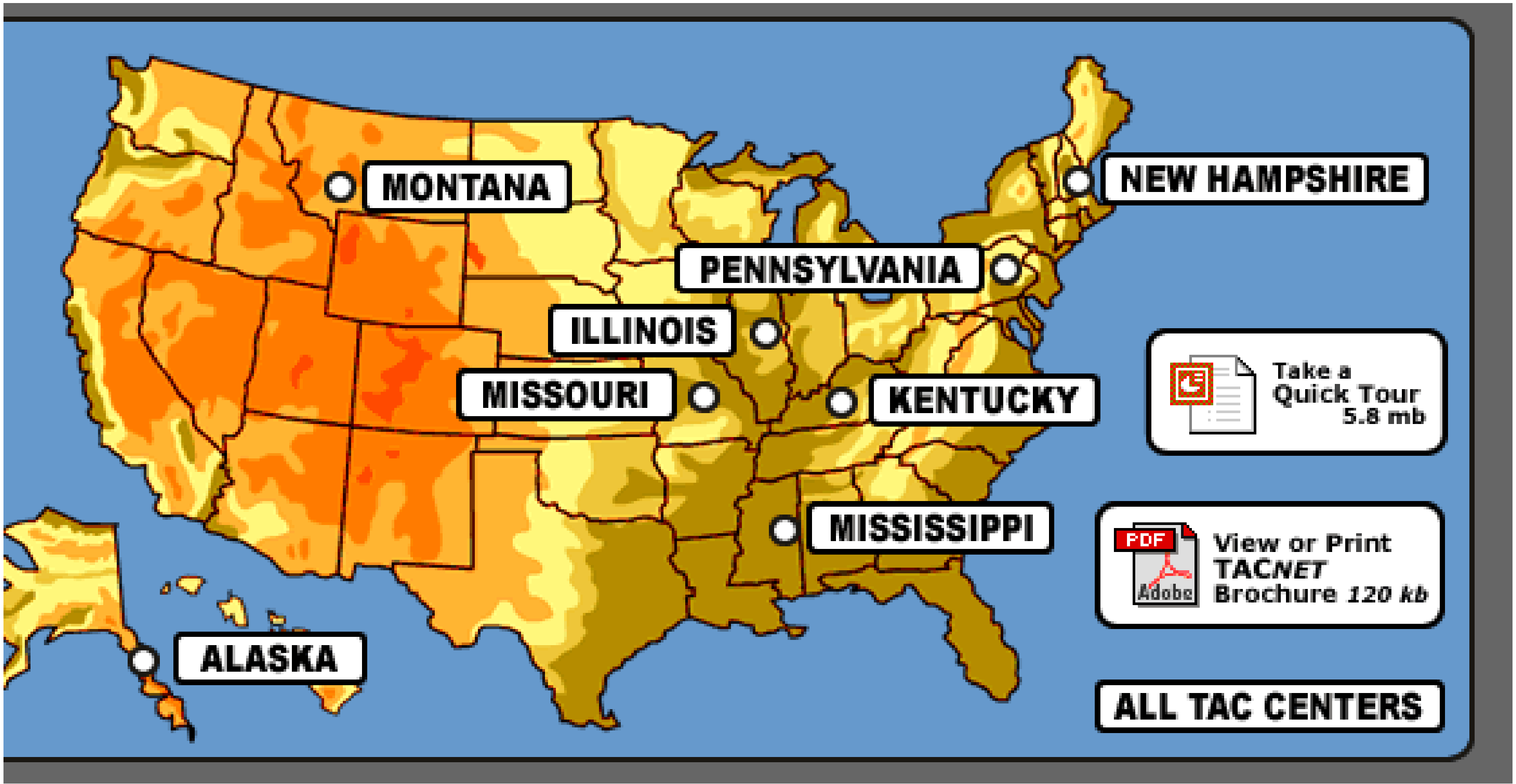
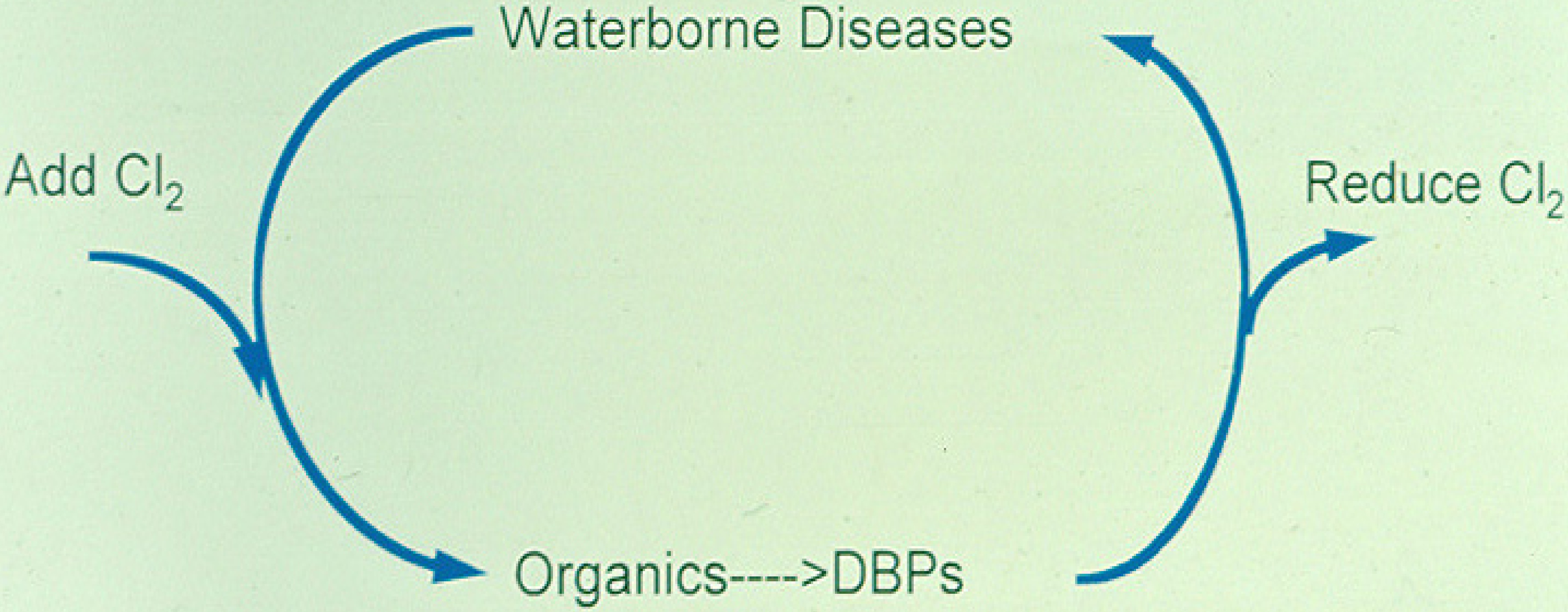
EPA TECHNICAL ASSISTANCE CENTER NETWORK (TACnet)

Assisting Small Public Water Systems…Protecting Public Health



Catch - 22



Waterborne Diseases

Add Cl_2

Reduce Cl_2

Organics---->DBPs

Disinfection Byproducts Formation

NOM + Disinfectant = DBPs

- **NOM=Natural Organic Matter=Organic Precursor**
- **Disinfectants=Chlorine, Chloramination, UV, Ozone, Chlorine Dioxide**
- **DBPs=Disinfection By-Products**
  Trihalomethanes (THMs), 80 ug/L
  Haloacetic Acids (HAAs), 60 ug/L

DBP Control

NOM + Disinfectant = DBPs

- NOM Removal/Reduction
- Alternative Disinfectants
- DBP Removal

Viable Water Treatment Options for Small Systems

- Packaged Coagulation Treatment Systems
- Pressure Filtration Systems
  - Granular Media
    - Ceramic Media
    - Diatomaceous Earth/Precoat
  - Membranes
- Biological Filtration Systems
  - Riverbank Filtration
  - Slow Sand Filtration

MAJOR COMPONENTS OF A DRINKING WATER TREATMENT SYSTEM

Source Water Collection/ Protection

Pretreatment

Filtration Treatment

Disinfection

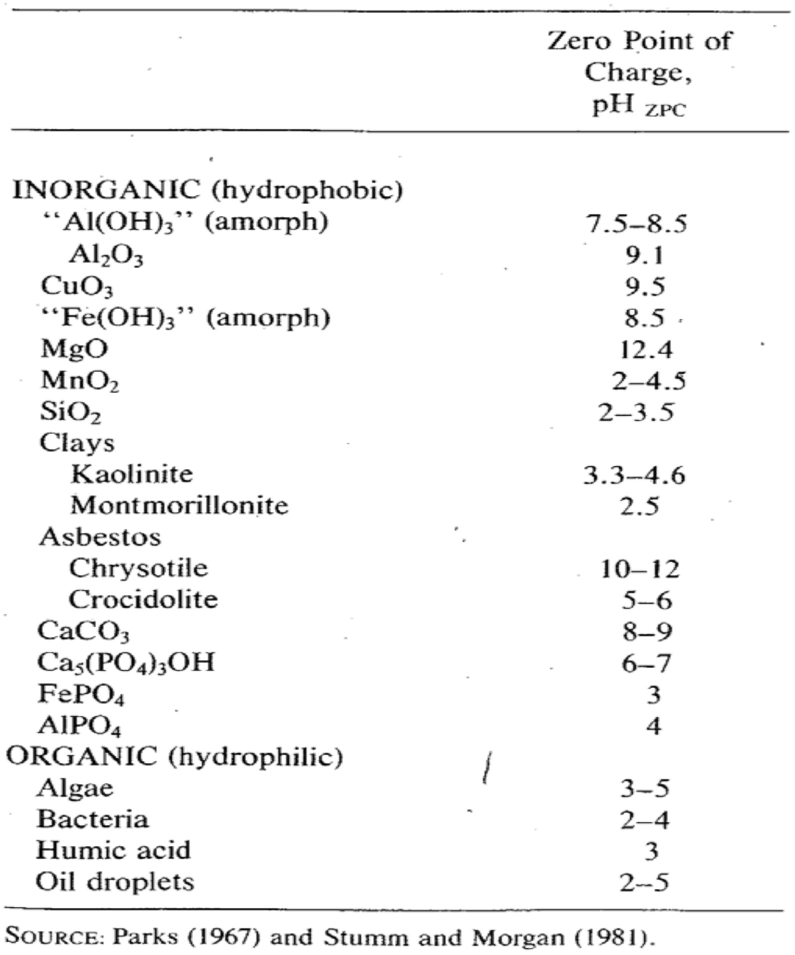
Distribution/ Storage

NOM Precursor Reduction Techniques

- Enhanced Coagulation/Clarification
- Activated Carbon/Media Adsorption
- Anionic Exchange Resins
- Biodegradation w/o & w/ Enhanced Biofiltration or Biological Activated Carbon (BAC)
- Membrane Filtration

Enhanced Coagulation

Surface Characteristics of Selected Particulates



	Zero Point of Charge, pH_{ZPC}
INORGANIC (hydrophobic)	
“$Al(OH)_3$” (amorph)	7.5–8.5
Al_2O_3	9.1
CuO_3	9.5
“$Fe(OH)_3$” (amorph)	8.5
MgO	12.4
MnO_2	2–4.5
SiO_2	2–3.5
Clays	
Kaolinite	3.3–4.6
Montmorillonite	2.5
Asbestos	
Chrysotile	10–12
Crocidolite	5–6
$CaCO_3$	8–9
$Ca_5(PO_4)_3OH$	6–7
$FePO_4$	3
$AlPO_4$	4
ORGANIC (hydrophilic)	
Algae	3–5
Bacteria	2–4
Humic acid	3
Oil droplets	2–5

SOURCE: Parks (1967) and Stumm and Morgan (1981).

What controls the coagulant dose?

- Particles versus Natural Organic Matter (NOM)?

- Characterize NOM/Aquatic Humic Substances using **Specific UV Absorbance (SUVA)**
- **SUVA = UV Absorbance @ 254 nm / mg/L of DOC** (typically expressed L/mg•m)

- Prof James Edzwald, UMass-Amherst

Guidelines: Coagulation Control

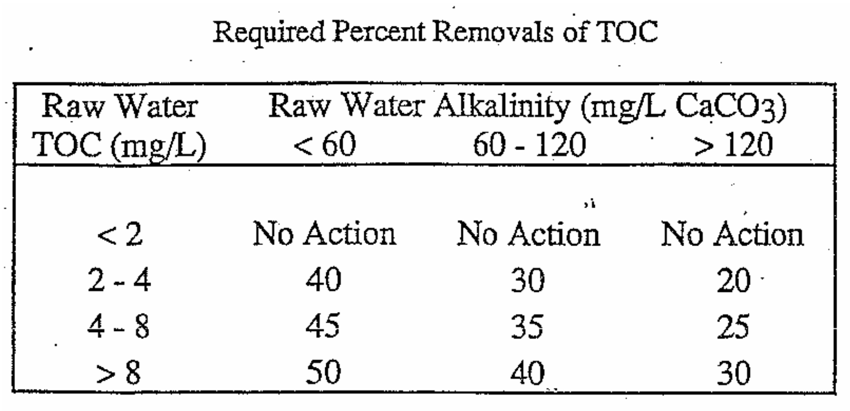
- SUVA < 2: NOM is non-humic; does nor control coagulation

- SUVA 2-4: NOM is a mixture of non-humics and humics; influences coagulation

- SUVA > 4: NOM is high in aquatics humics; controls coagulation

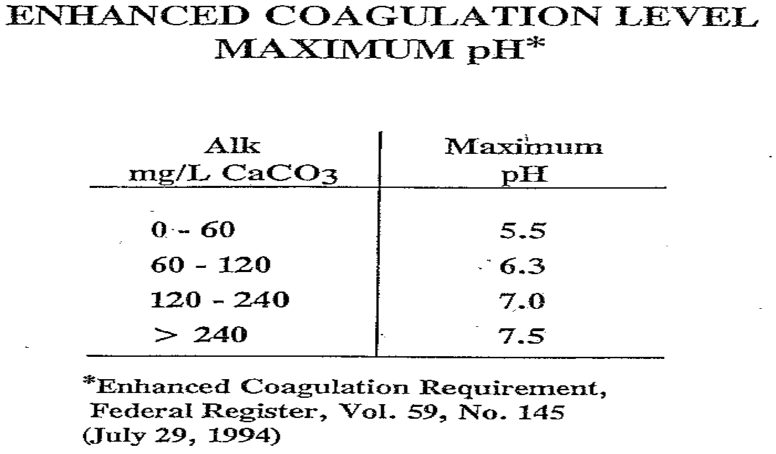
Enhanced Coagulation

- 1st Option: TOC Removal Based on Raw Water TOC & Alkalinity



Required Percent Removals of TOC

Raw Water TOC (mg/L)	Raw Water Alkalinity (mg/L $CaCO_3$) < 60	60 - 120	> 120
< 2	No Action	No Action	No Action
2 - 4	40	30	20
4 - 8	45	35	25
> 8	50	40	30



ENHANCED COAGULATION LEVEL MAXIMUM pH*

Alk mg/L $CaCO_3$	Maximum pH
0 - 60	5.5
60 - 120	6.3
120 - 240	7.0
> 240	7.5

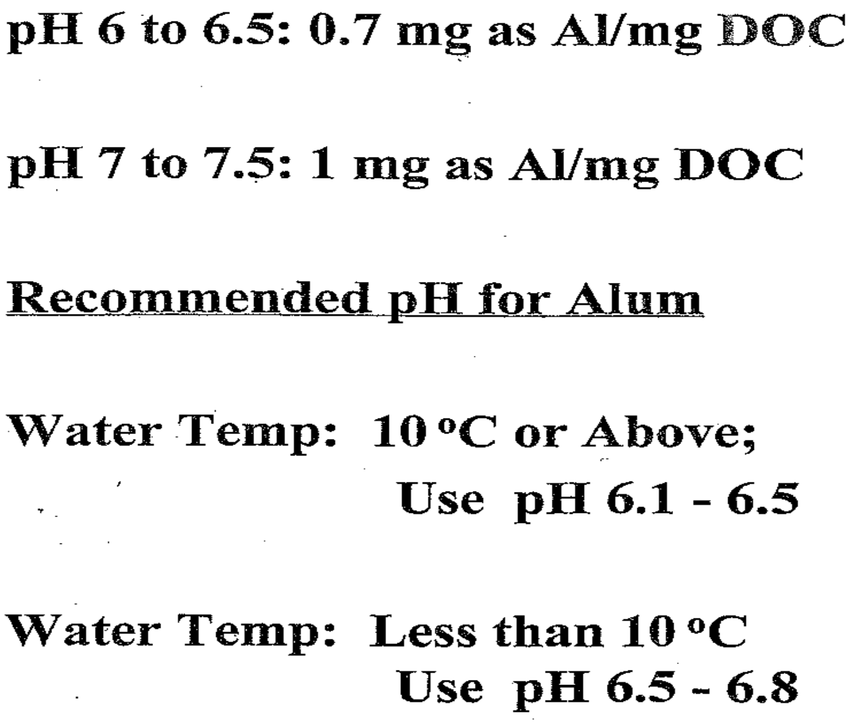
*Enhanced Coagulation Requirement, Federal Register, Vol. 59, No. 145 (July 29, 1994)

Enhanced Coagulation

- 2^{nd} Step: Bench or Pilot Testing Required
  - Addition of alum in 10 mg/L increments or equivalent amounts for ferric salts.
  - Desired dose based on point when an additional 10 mg/L alum does not decrease the residual TOC by 0.3 mg/L.

Guidelines: Coagulant dosages for water supplies where NOM controls

- Aluminum Coagulants



pH 6 to 6.5: 0.7 mg as Al/mg DOC

pH 7 to 7.5: 1 mg as Al/mg DOC

Recommended pH for Alum

Water Temp: 10 °C or Above;
Use pH 6.1 - 6.5

Water Temp: Less than 10 °C
Use pH 6.5 - 6.8

- Ferric Coagulants
  - **pH 5.5: 2 mg as Fe per mg DOC**
  - **pH 7-7.5: 4 mg as Fe per mg DOC**

- Organic Cationic Polymers
  - **0.65 – 1 mg active polymer per mg DOC**

Thusly, DOC Removals

- Depends on:
    - Nature of the NOM
    - Concentration of DOC
    - Coagulant Type and Dose
    - pH

Guidelines: Estimates of DOC Removal

- **SUVA <2**
  - **Aluminum & Ferric Coagulants ~ 20%**
  - **Organic Cationic Polymers ~ 10%**

- **SUVA 2-3**
  - **Aluminum & Ferric Coagulants ~ 20 to 50%**
  - **Organic Cationic Polymers ~ 10 to 30%**

- **SUVA 3-4 and Higher**
  - **Aluminum & Ferric Coagulants ~ 50 to 70%**
  - **Organic Cationic Polymers ~ 30 to 40%**

Empirical Model for Estimating DOC Removal **(Edwards 1997)**

- **DOC remaining after coagulation (mg/L) = non-adsorbable DOC fraction + adsorbable DOC fraction remaining after coagulation**

$$\mathbf{DOC_{non\text{-}adsorb} = (K_1 \bullet SUVA_{Raw} + K_2)x\ DOC_{initial}}$$

$$\mathbf{DOC_{adsorb\ remain} = \frac{-\ (MB + 1 - Ab) + ((MB + 1 - Ab)^2 + 4bA)^{1/2}}{2b}}$$

where $\mathbf{A = (1 - SUVA_{Raw} \bullet K_1 - K_2)\ DOC_{initial}}$

$\mathbf{B = (x_3pH^3 + x_2pH^2 + x_1pH)b}$

Table 9-9

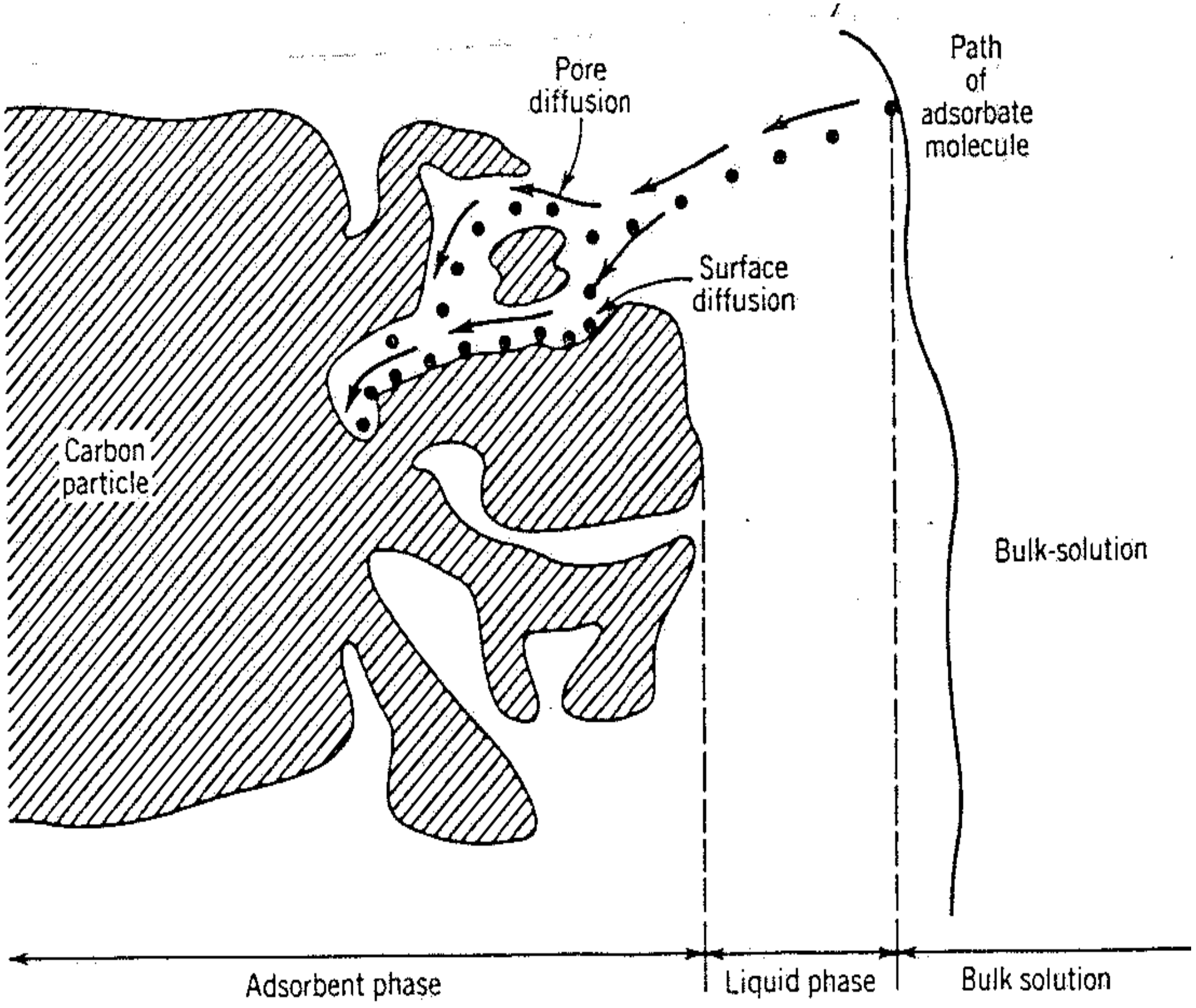
Summary of best-fit model coefficients for DOC removal with iron and aluminum

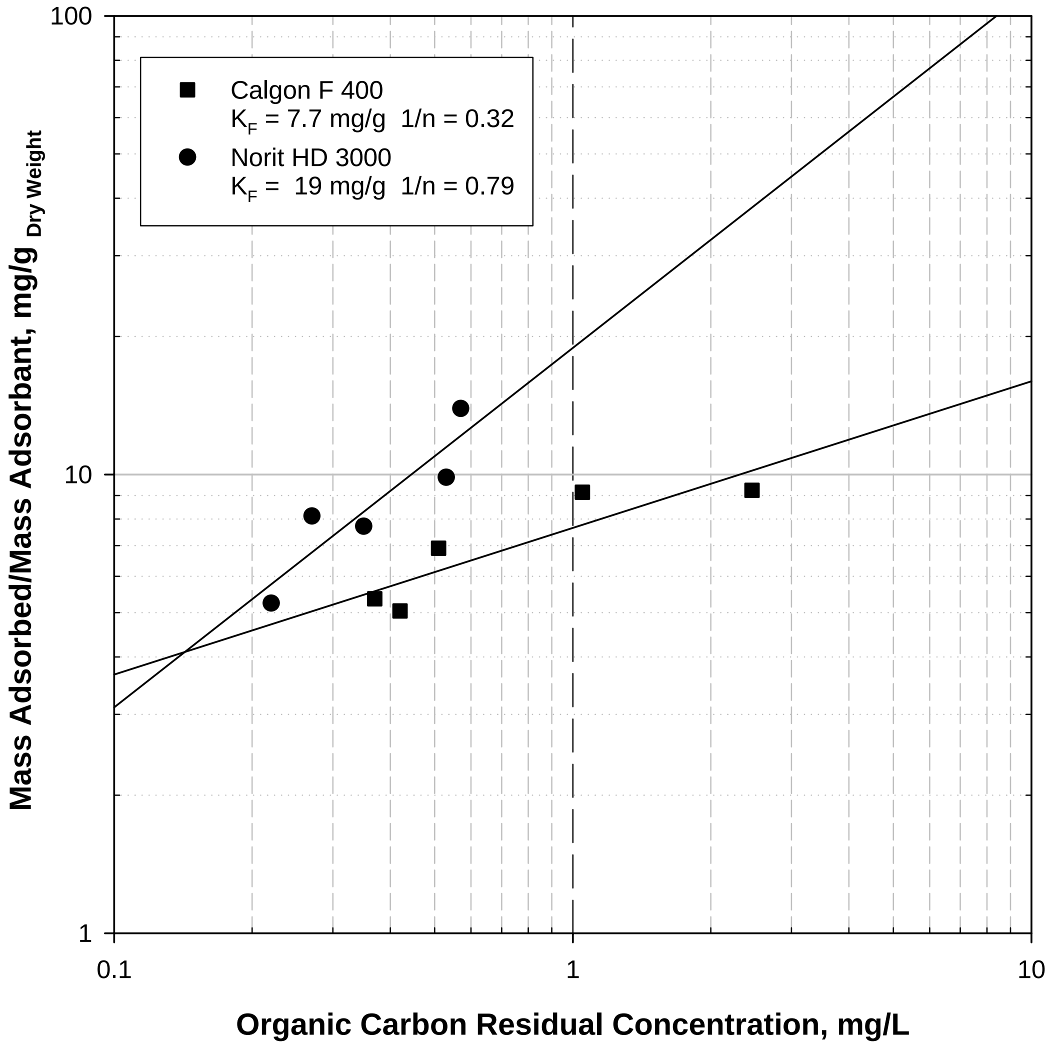
Parameter	DOC Model Coefficients	
	Iron	Aluminum
Standard error, mg/L	0.47	0.4
Standard error, %	9.3	9.5
90% confidence, %	±21	±21
x_3	4.96	4.91
x_2	–73.9	–74.2
x_1	280	284
K_1	–0.028	–0.075
K_2	0.23	0.56
b	0.068	0.147

Source: Adapted from Edwards (1997).

Activated Carbon/Media Adsorption

- Activated Carbon
  - 1 gm = 1000m2 surface area
  - Adsorption – surface phenomenon
  - Removal of organics by surface adsorption

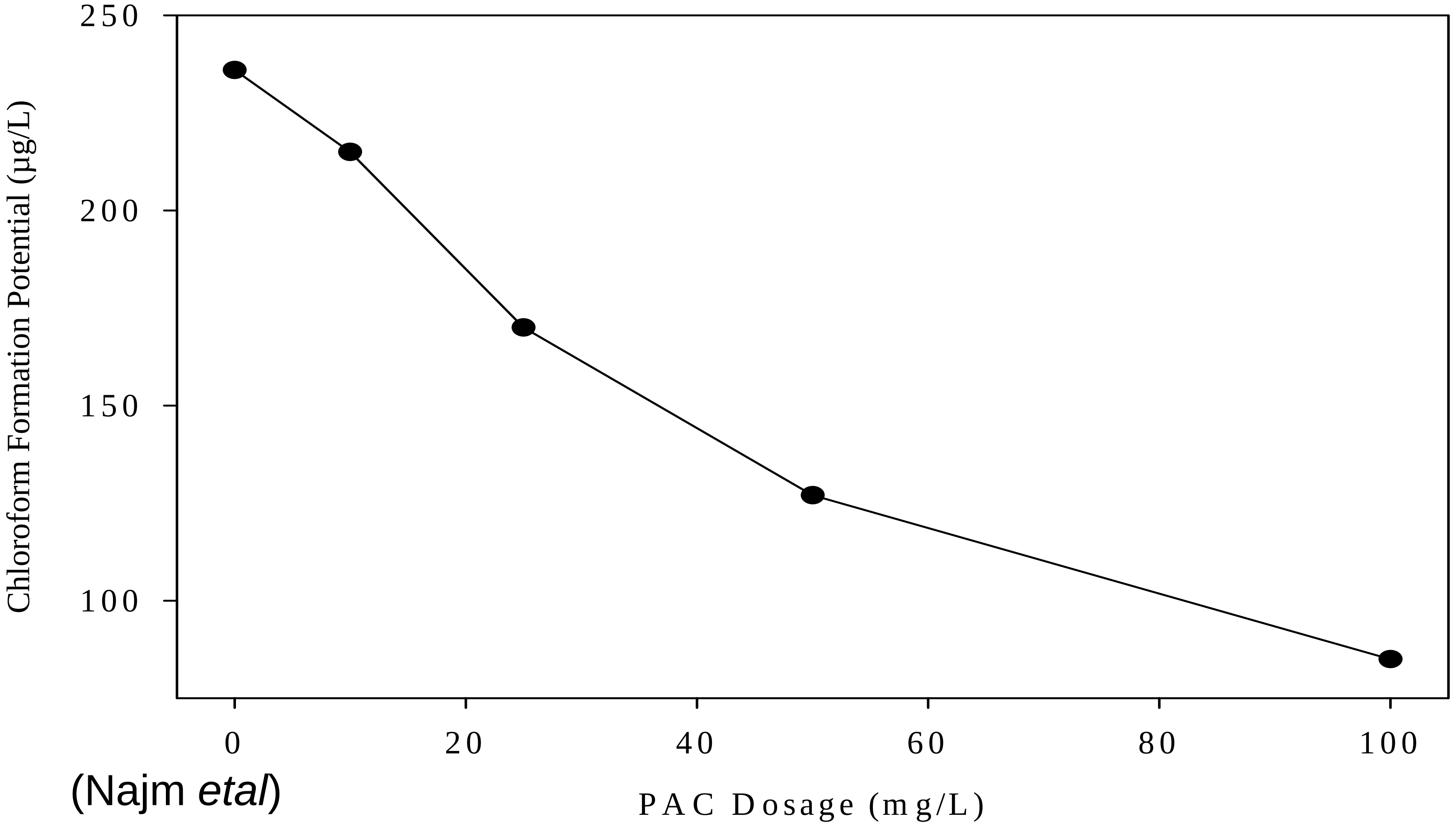




Isotherm Challenge Conditions
Initial Organic Carbon Concentration: 4.62 mg/L
pH Range: 7.00 to 7.69
Temperature: 20°C
Shaker Table: 1500 rpm
Time: 2 Hours

Figure 6. Activated Carbon Isotherm Comparisons - Winthrop, Me

PAC on DBP formation

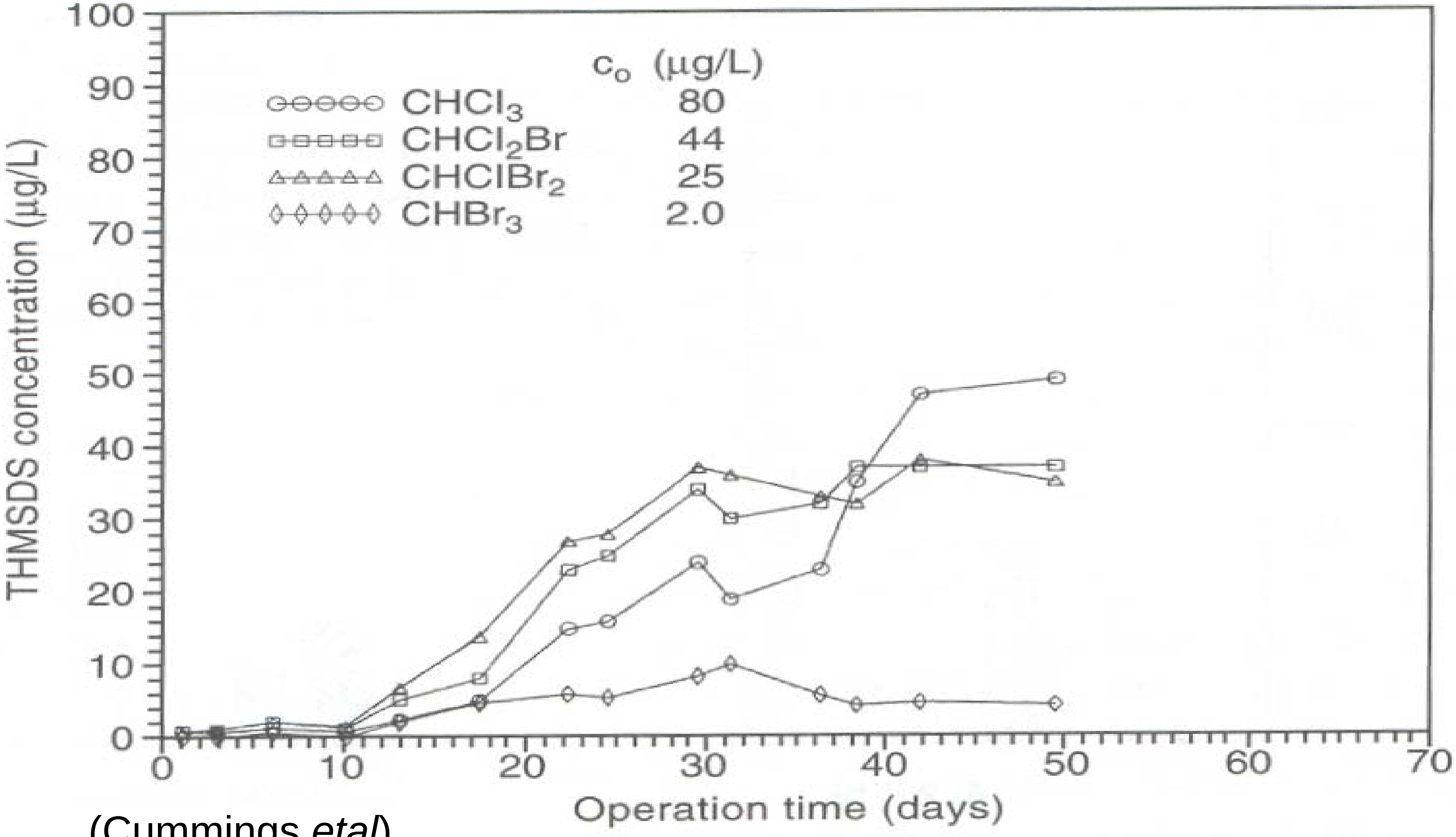


(Najm *etal*)

PAC

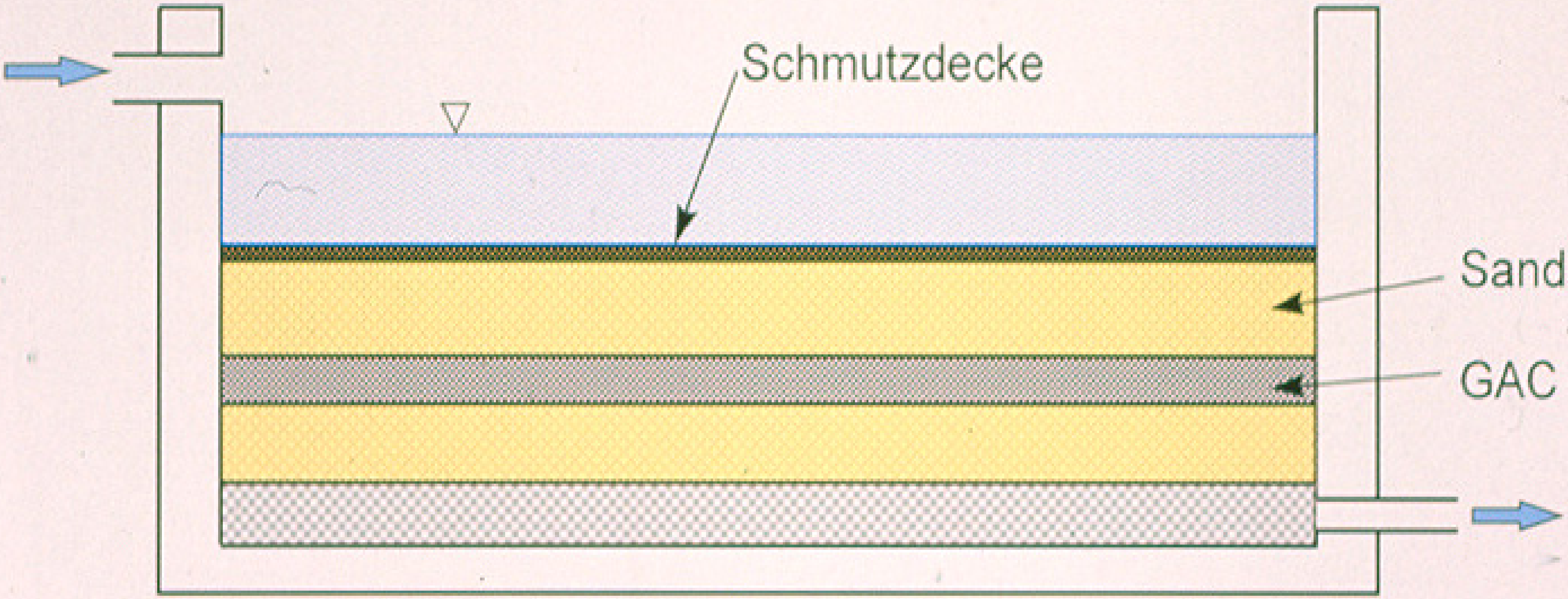
- NOM type
- Carbon type
- PAC dosage
- Contact time
- Taste, odor and color removal

GAC for DBP precursor removal

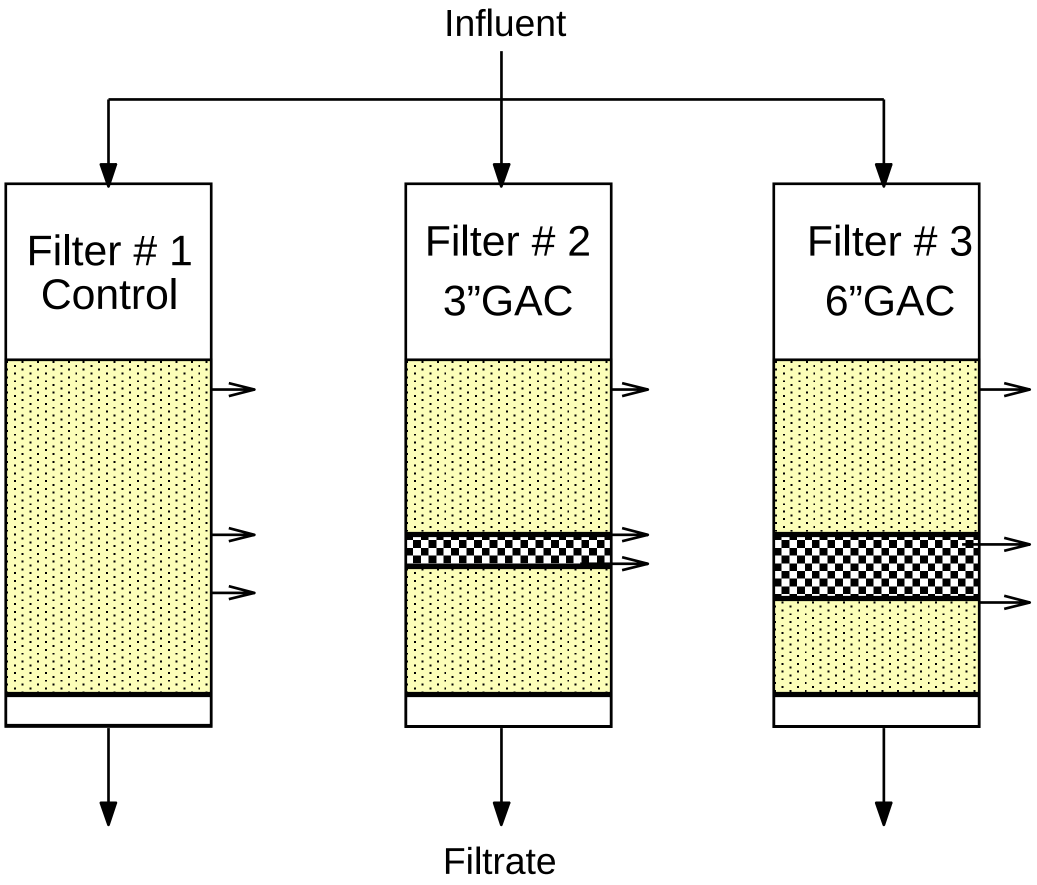


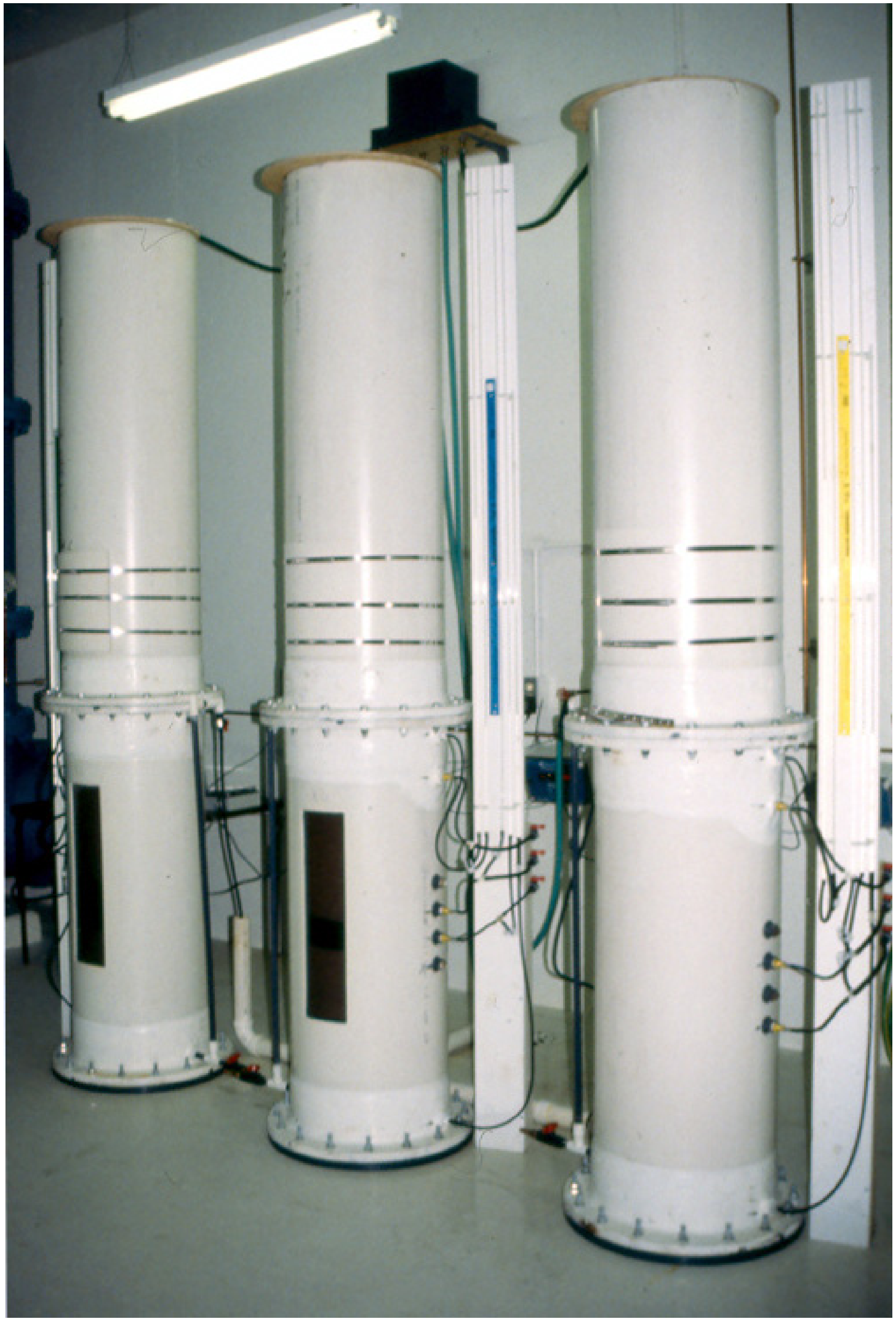
(Cummings *etal*)

Slow Sand Filter / GAC Sandwich



Experimental Design



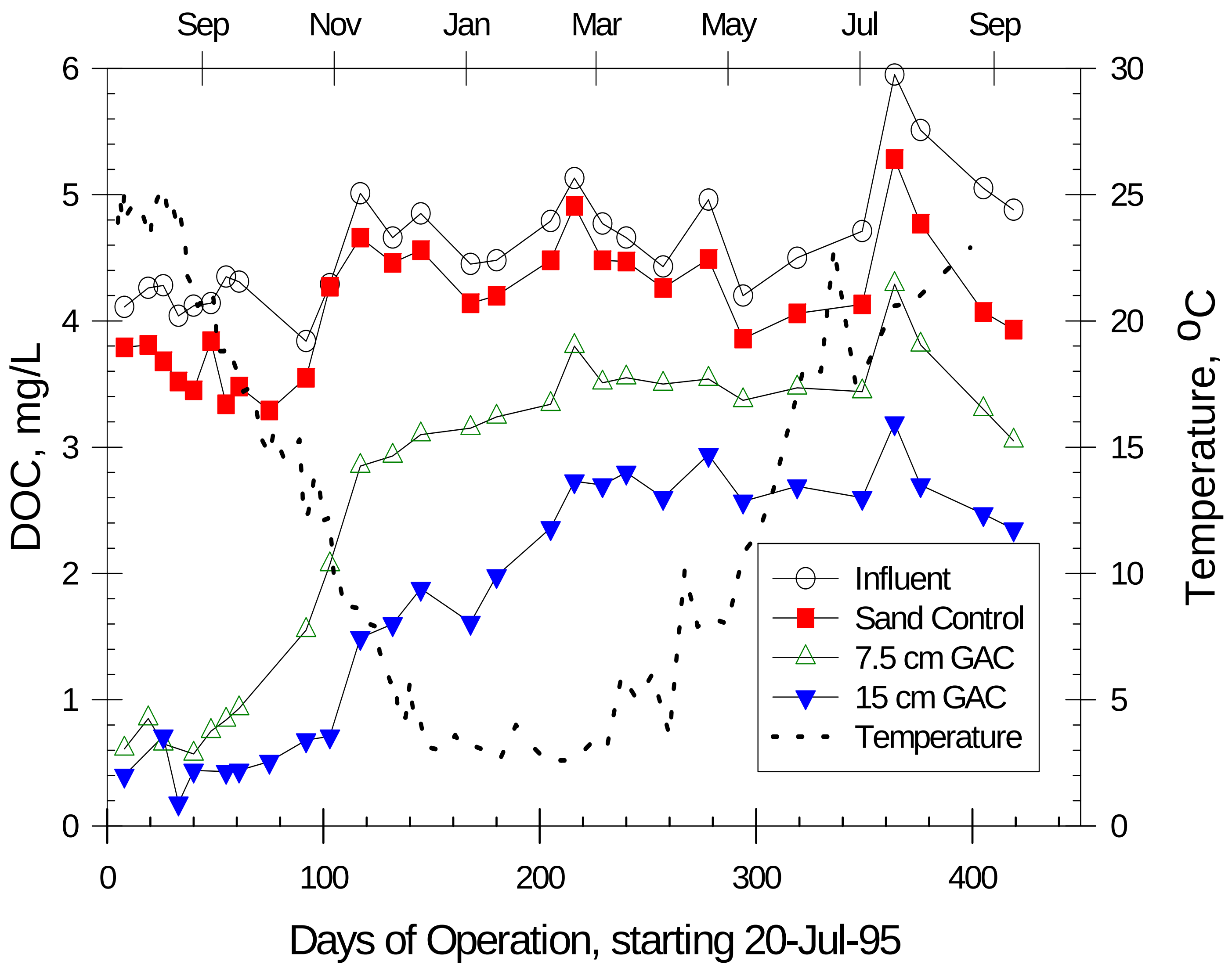


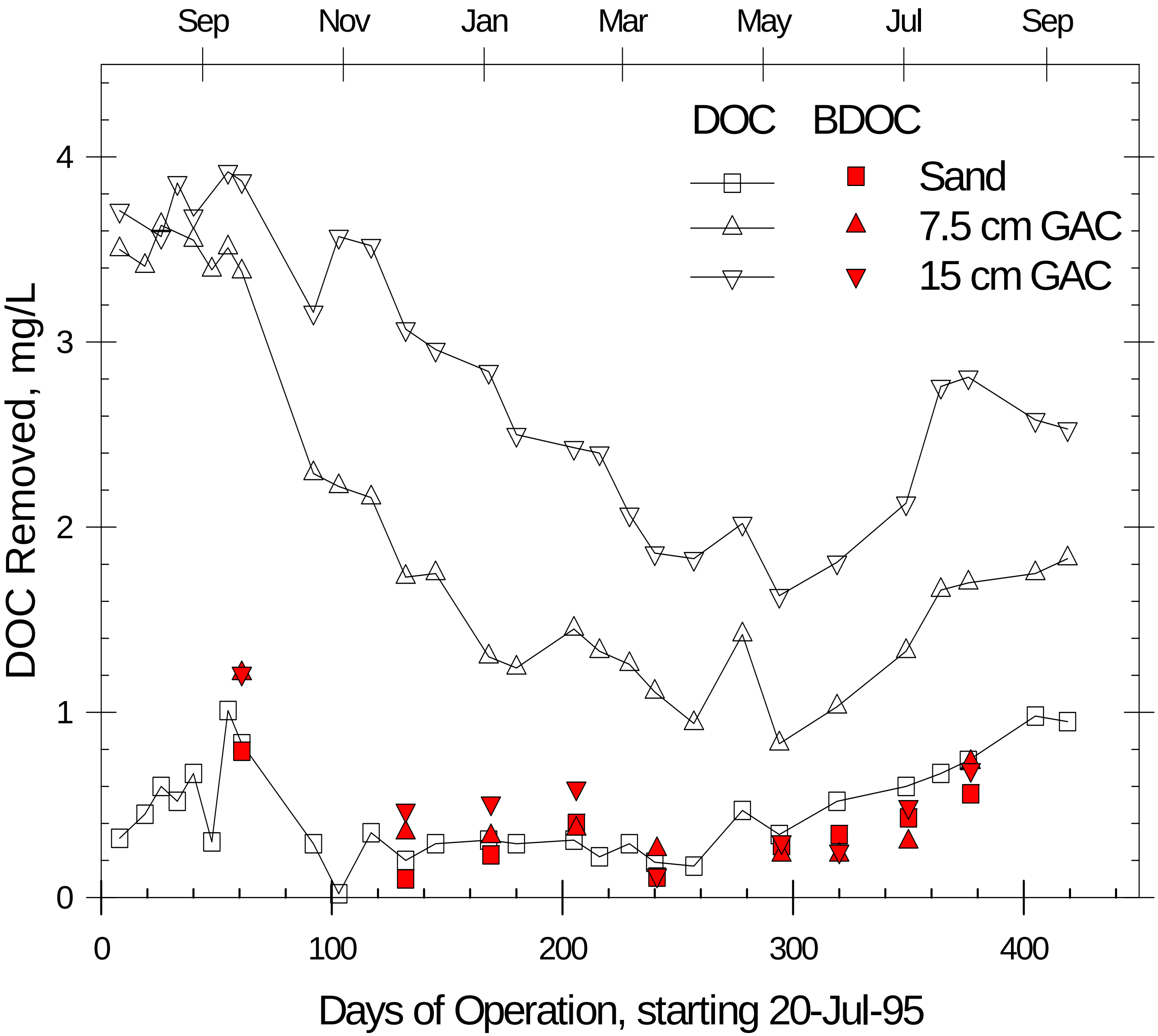
Milo Raw Water Quality

(Jul 95 - Sep 96)

Parameter	Average	Range
Turbidity, NTU	0.43	0.25 - 1.49
Color, units PtCo	24	11 - 40
DOC, mg/L	4.6	3.8 - 6.0
BDOC, mg/L	0.6	0.4 - 1.2
UV Absorbance, cm^{-1}	0.153	0.098 - 0.229
THMFP, ug/L	430	331 - 570

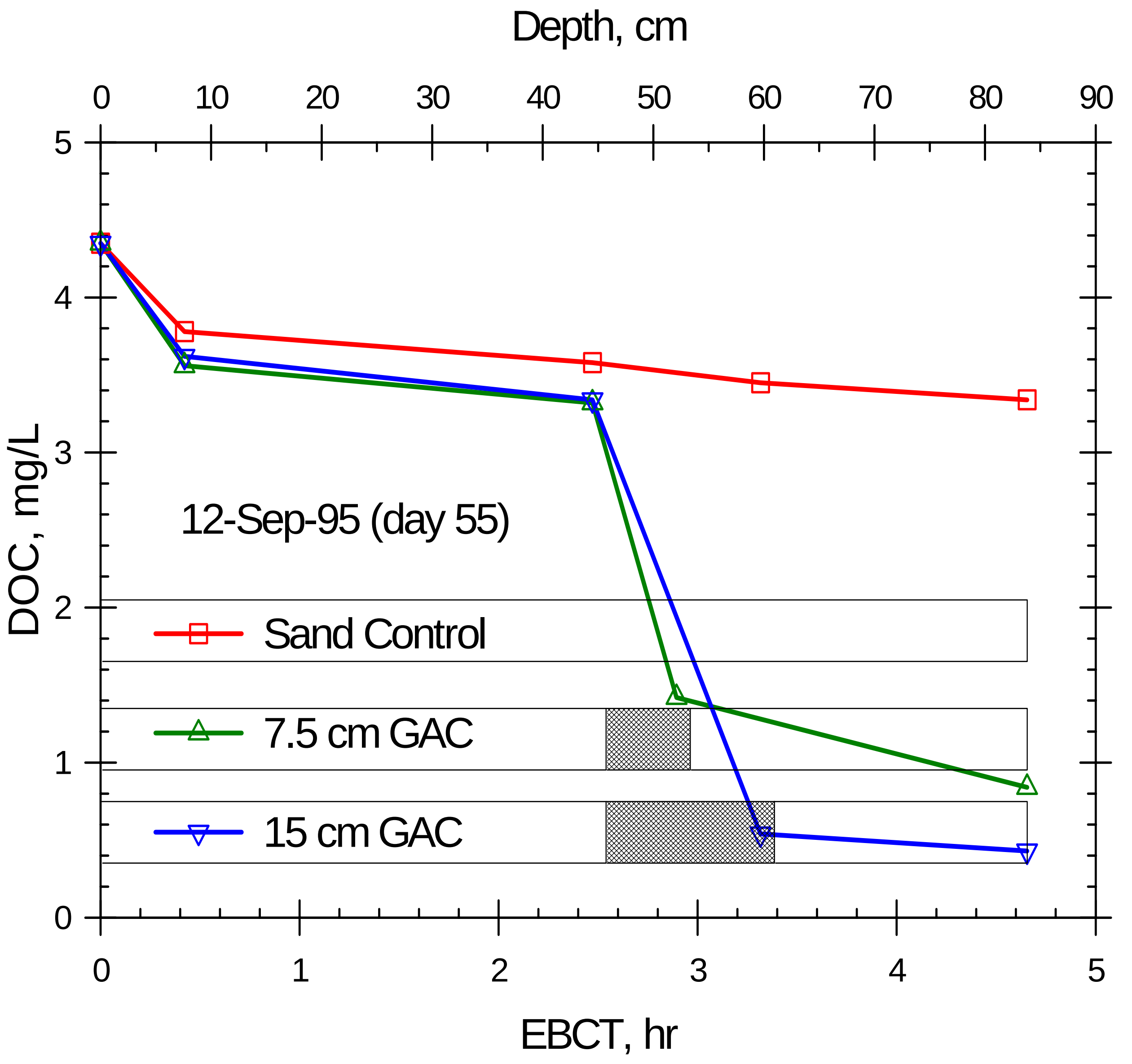
DOC Removal for Milo Pilot Filters





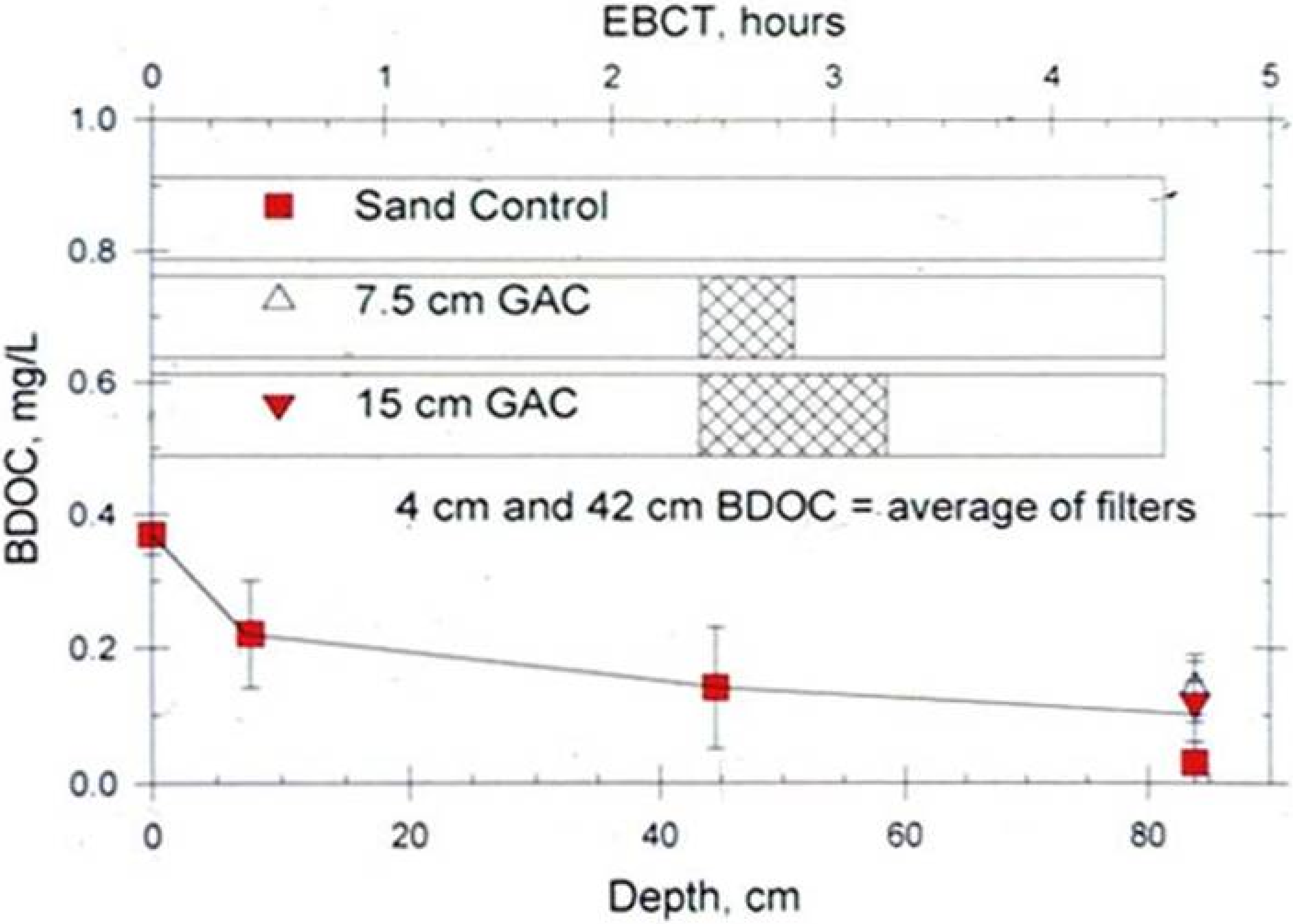
DOC and BDOC Removal for Milo Pilot Filters

DOC Removal with Depth, Milo Pilot Filters, 12-Sept-95

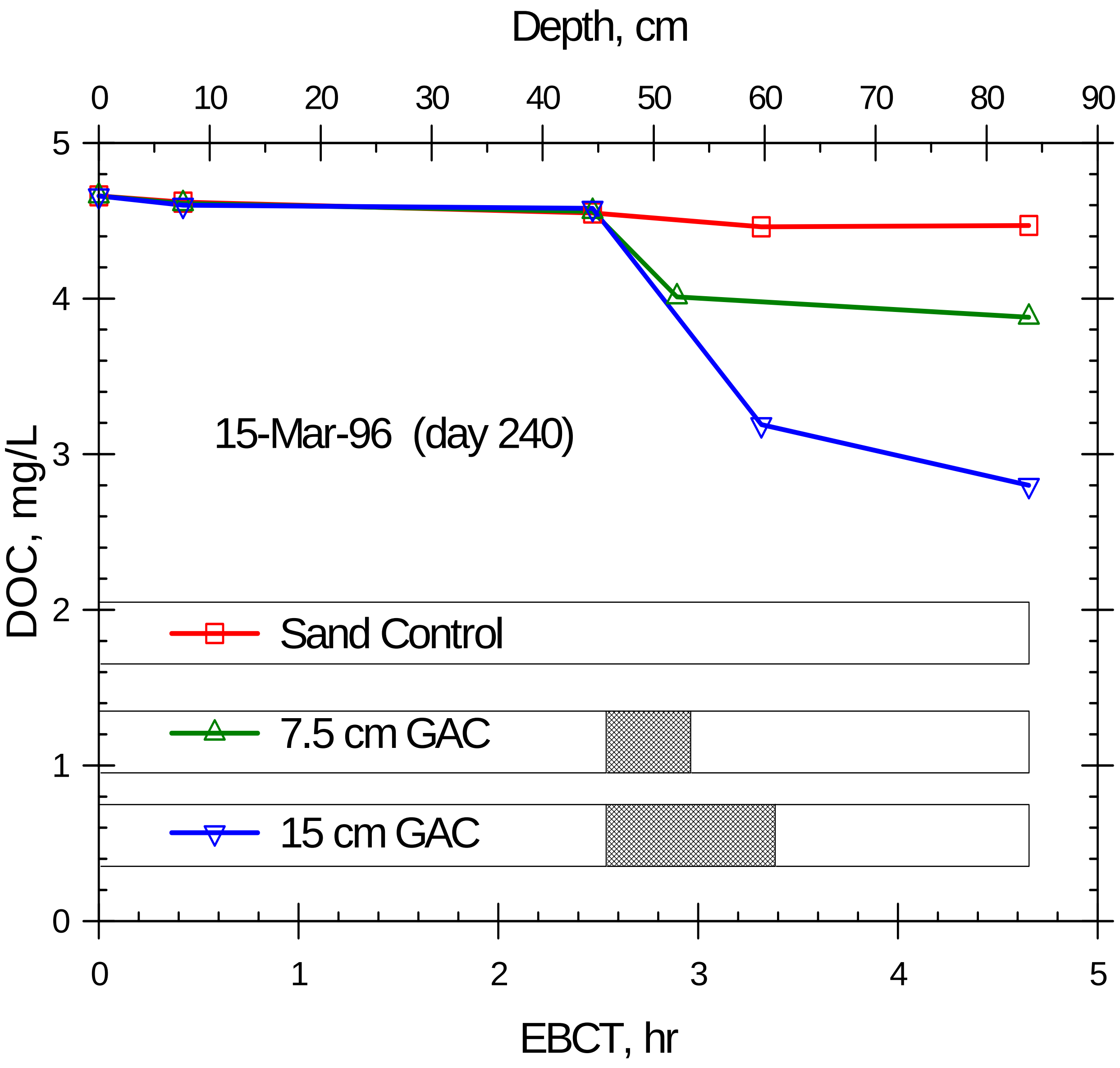


BDOC Removal with Depth

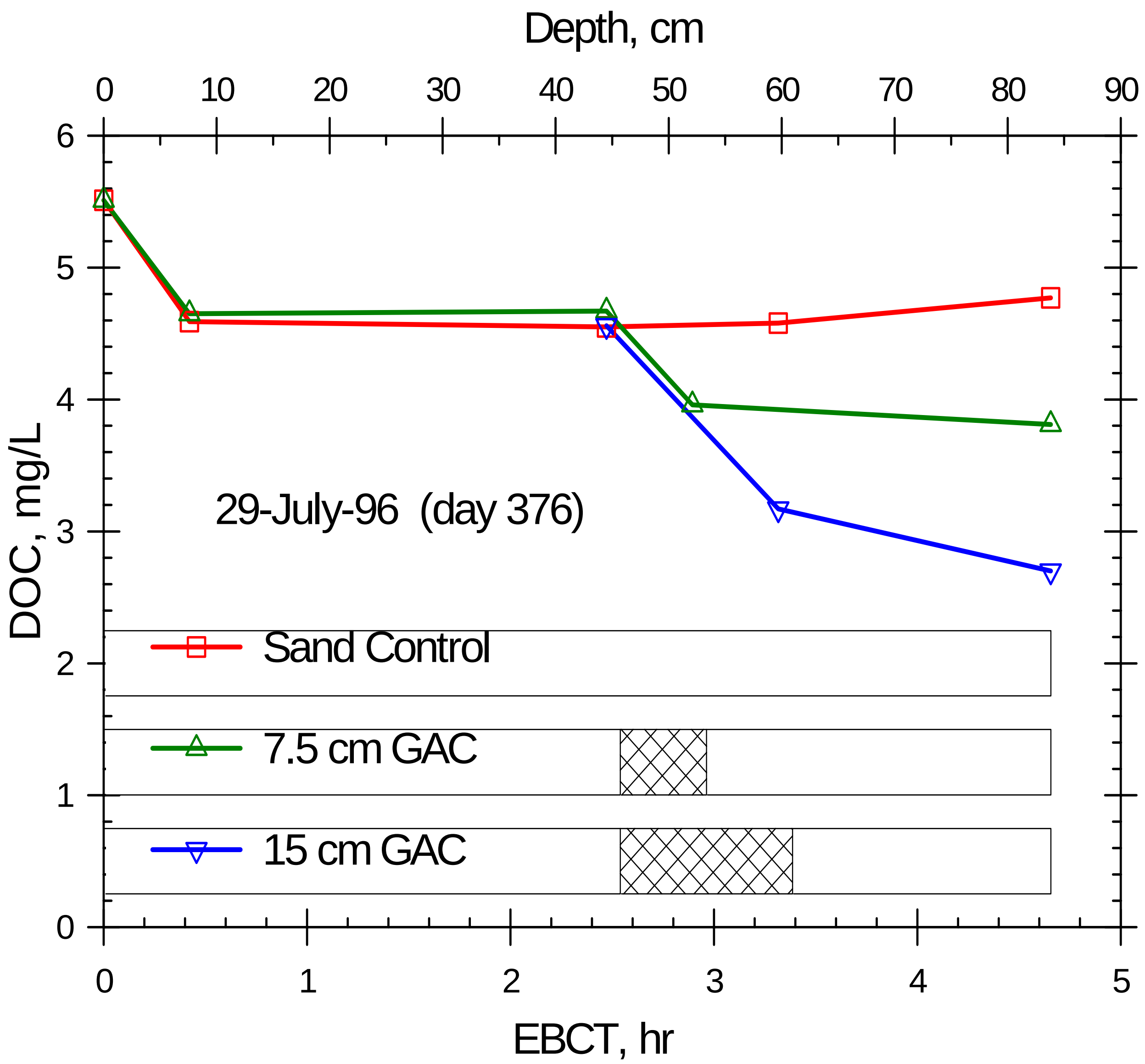
(SSF Pilot Tests at Milo, NH USA)



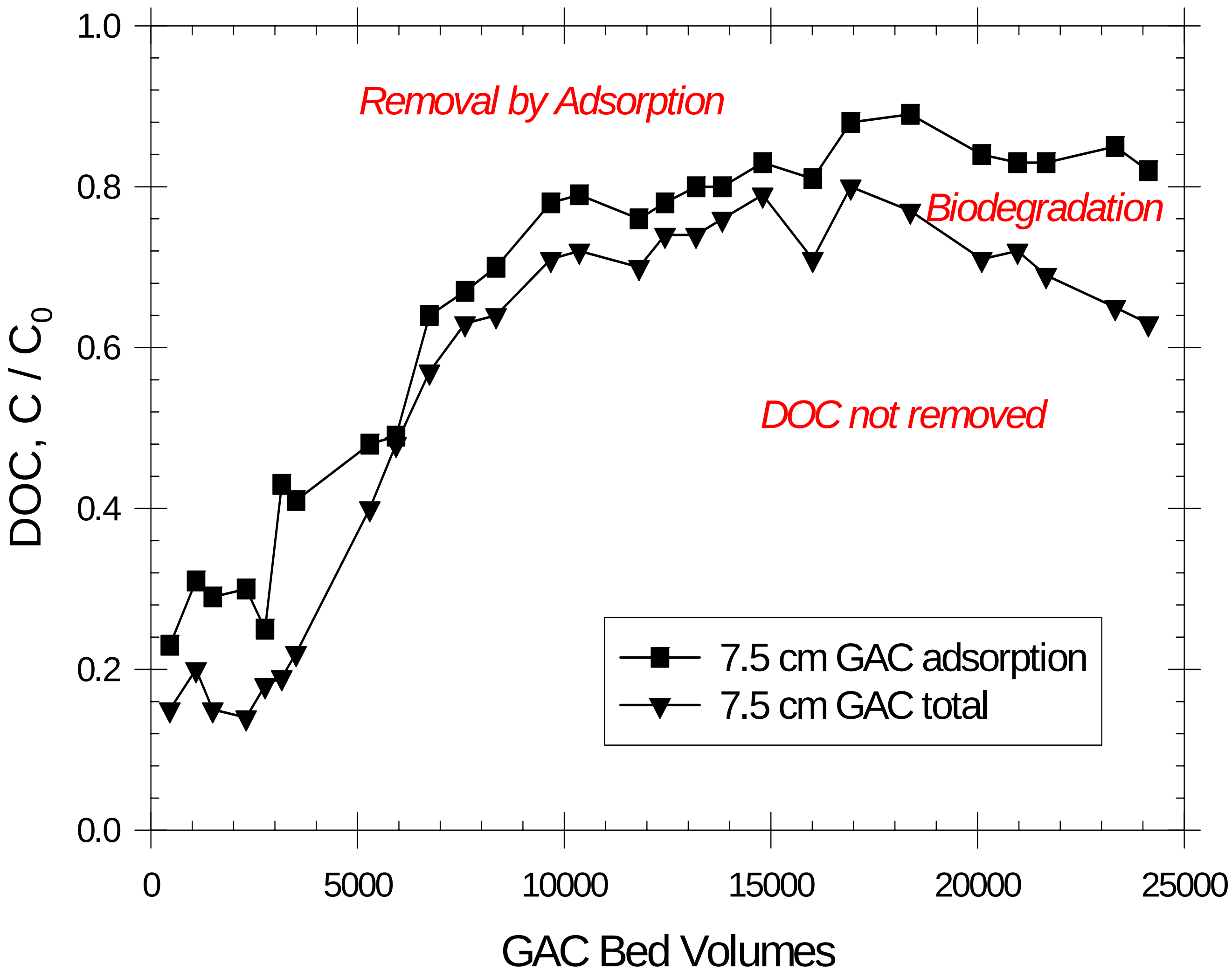
DOC Removal with Depth, Milo Pilot Filters, 15-Mar-96



DOC Removal with Depth, Milo Pilot Filters, 29-Jul-96



DOC Removal by Adsorption and Biodegradation



GAC Sandwich Summary

- Adsorption dominated first 7000 - 14000 GAC BVs.
- Removals reached pseudo steady-state after 200 - 300 days:

	Sand	7.5 cm GAC	15 cm GAC
Total	12%	28%	46%
Adsorption		16%	34%

Evidence against Enhanced Biodegradation:

- Biomass levels and BDOC removals were similar in sand and GAC sublayers.

Evidence for Slow Adsorption or Bioregeneration:

- Adsorption continued at a constant rate, even after 400+ days (11500 - 23000 GAC BVs).

Table 3. Summary of Average Total Organic Carbon and UV$_{254}$ Absorbance and % Removals for Winthrop Slow Sand Pilot Studies

1ST PILOT STUDY PHASE (3/28/03 – 11/10/03)

Filter	TOC			UV$_{254}$		
	n	mg/L	% Removal	n	cm $^{-1}$	% Removal
Raw	26	**4.66** ± *0.46*	**--**	26	**0.113** ± *0.009*	**--**
Plant 3	23	**3.16** ± *0.36*	**32** ± *11*	23	**0.080** ± *0.011*	**29** ± *6*
Pilot 1 (Old GAC)	26	**3.01** ± *0.40*	**35** ± *11*	26	**0.061** ± *0.010*	**47** ± *8*
Pilot 2 (Sand)	24	**4.10** ± *0.36*	**13** ± *10*	24	**0.101** ± *0.011*	**11** ± *5*
Pilot 3 (New GAC)	24	**2.10** ± *0.47*	**54** ± *12*	24	**0.042** ± *0.011*	**63** ± *10*

BAC STUDY

Background

FOUR SEPARATE TREATMENT TRAINS:

Train 1/DF Train = Ozone-Coag-BAC Direct Filtration

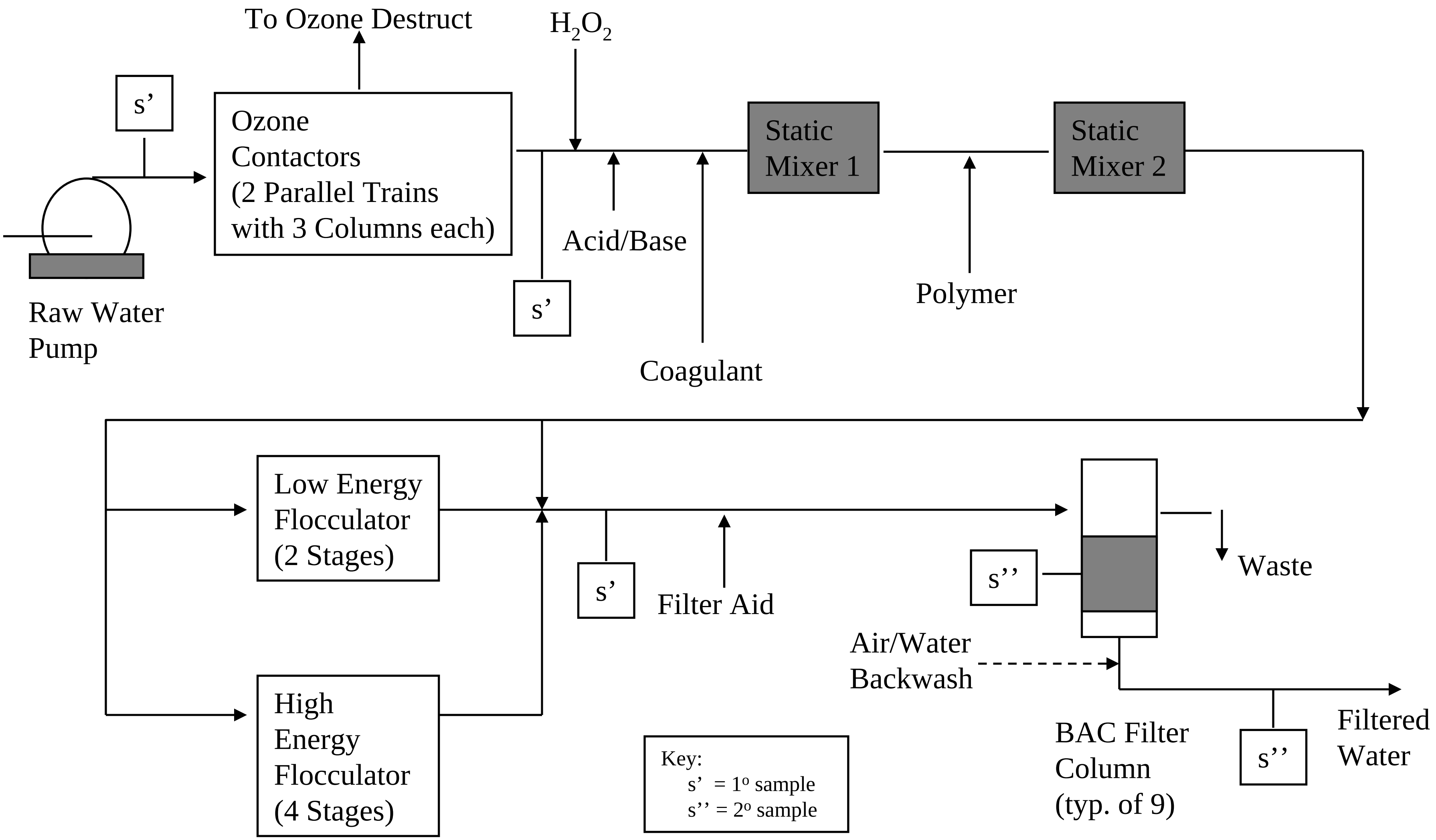
Train 2/DAF Train = Coag-DAF-Ozone-BAC Filtration

Train 3/DE Train = Ozone-BAC-DE Filtration

Train 4/MF Train = Membrane Filtration

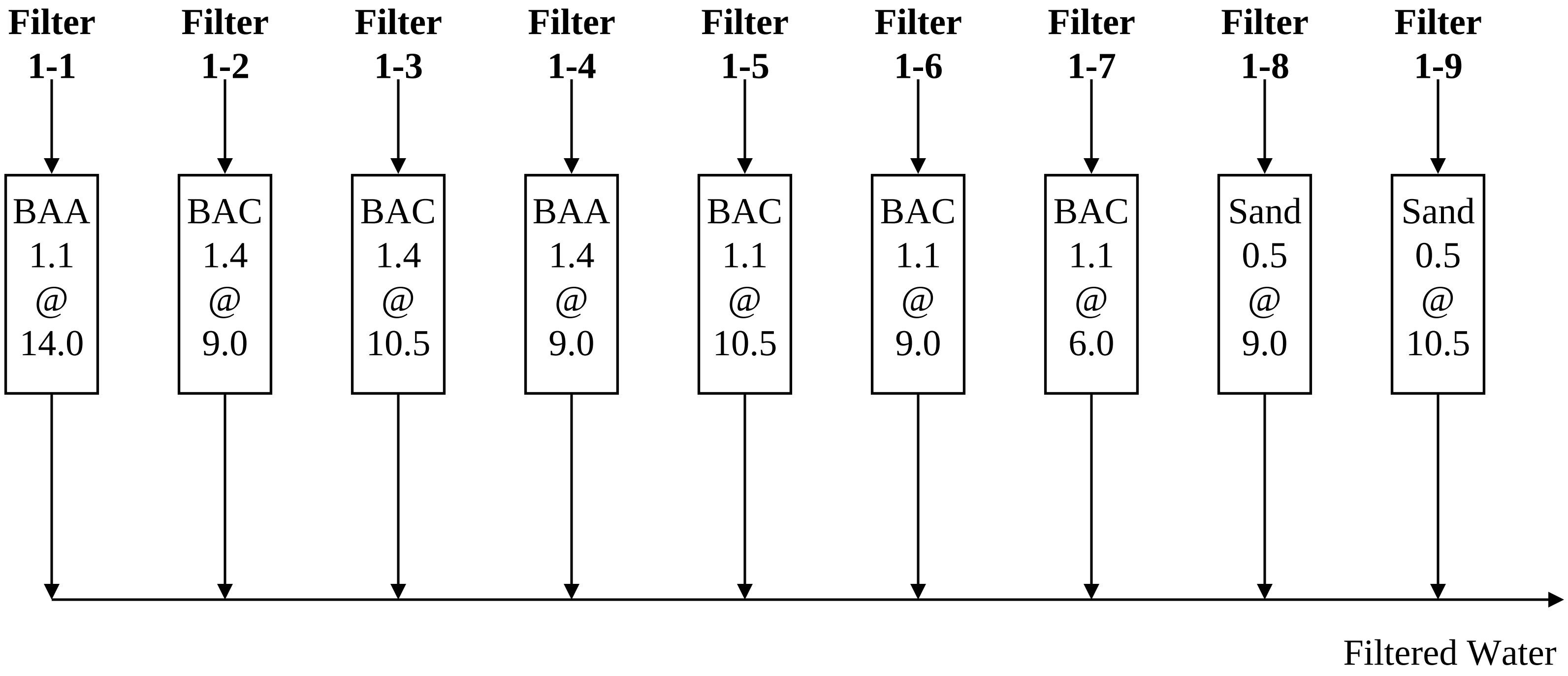
Treatment Train No.1

Ozone-BAC Direct Filtration



Treatment Train No.1

DF Biological Filters



Filter 1-1
BAA
1.1
@
14.0

Filter 1-2
BAC
1.4
@
9.0

Filter 1-3
BAC
1.4
@
10.5

Filter 1-4
BAA
1.4
@
9.0

Filter 1-5
BAC
1.1
@
10.5

Filter 1-6
BAC
1.1
@
9.0

Filter 1-7
BAC
1.1
@
6.0

Filter 1-8
Sand
0.5
@
9.0

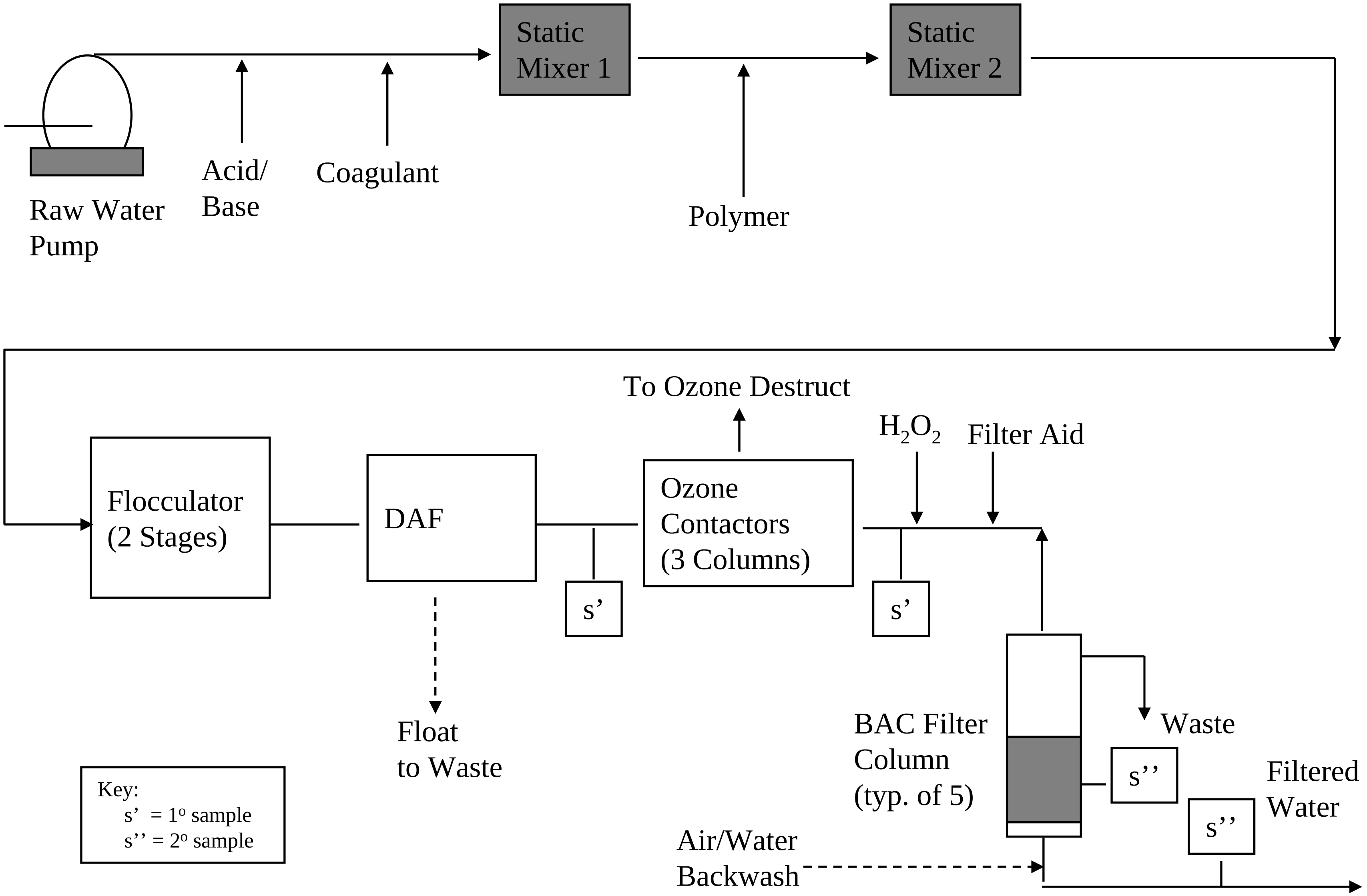
Filter 1-9
Sand
0.5
@
10.5

Filtered Water

Key:
grainsize (mm) @ loading rate (gpmsf)

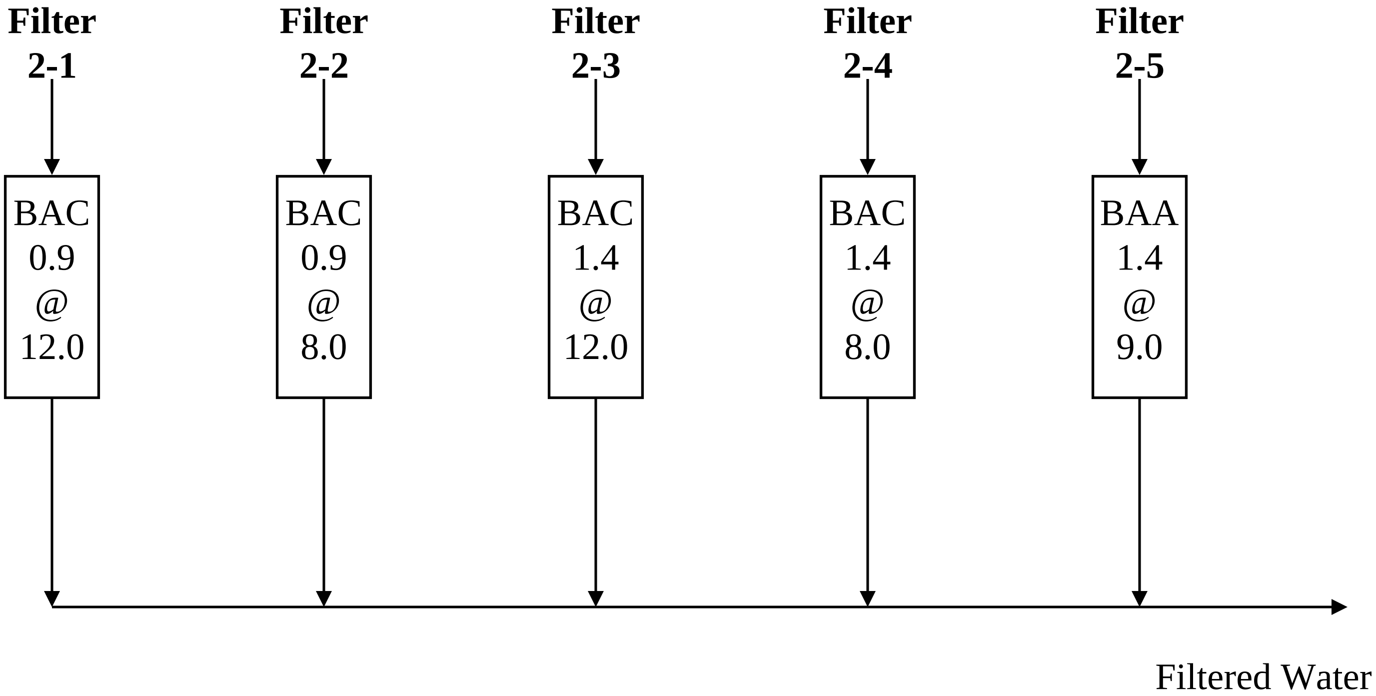
Treatment Train No.2

DAF-Ozone-BAC Filtration



Treatment Train No.2

DAF Biological Filters



Filter 2-1
BAC
0.9
@
12.0

Filter 2-2
BAC
0.9
@
8.0

Filter 2-3
BAC
1.4
@
12.0

Filter 2-4
BAC
1.4
@
8.0

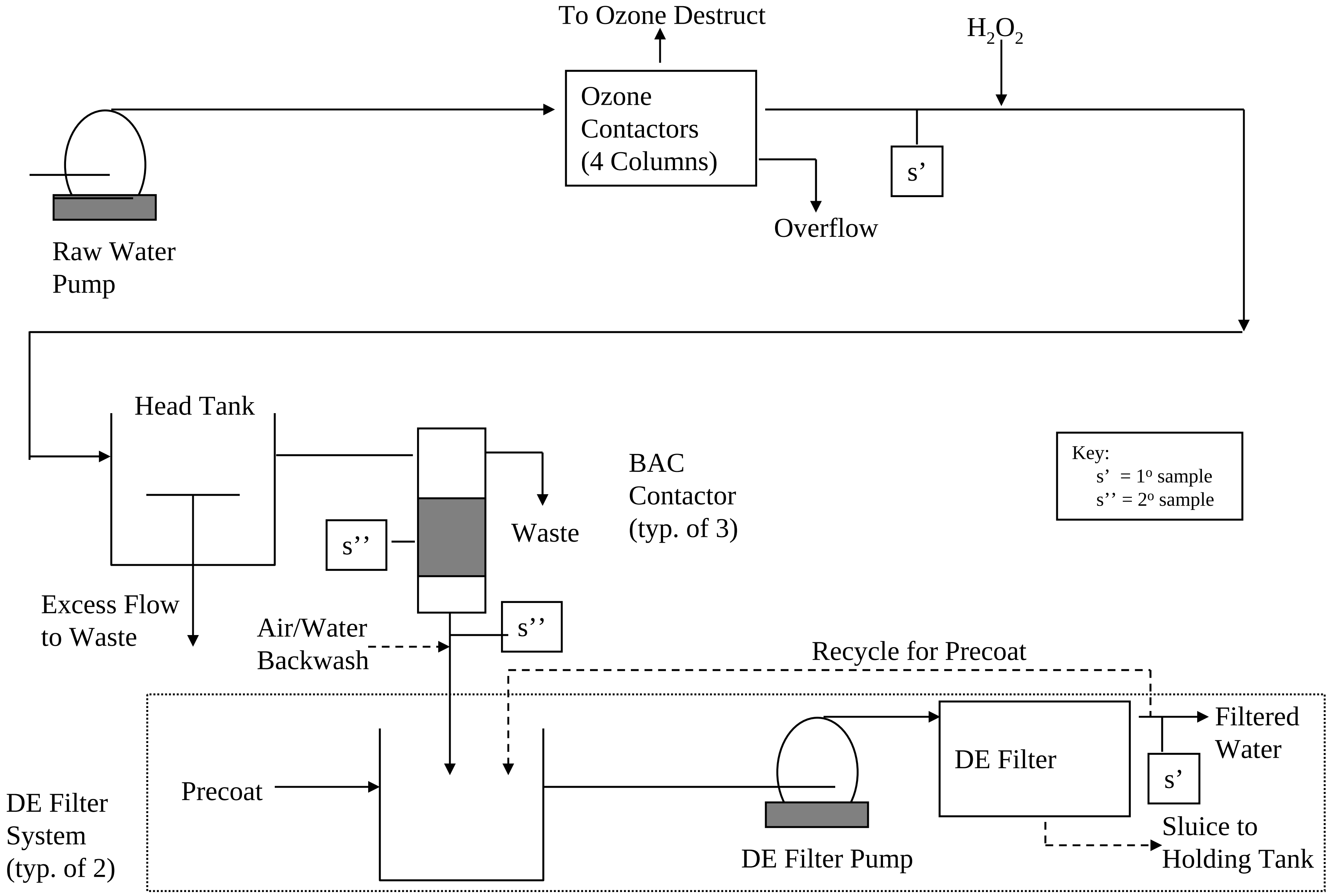
Filter 2-5
BAA
1.4
@
9.0

Filtered Water

Key:
grainsize (mm) @ loading rate (gpmsf)

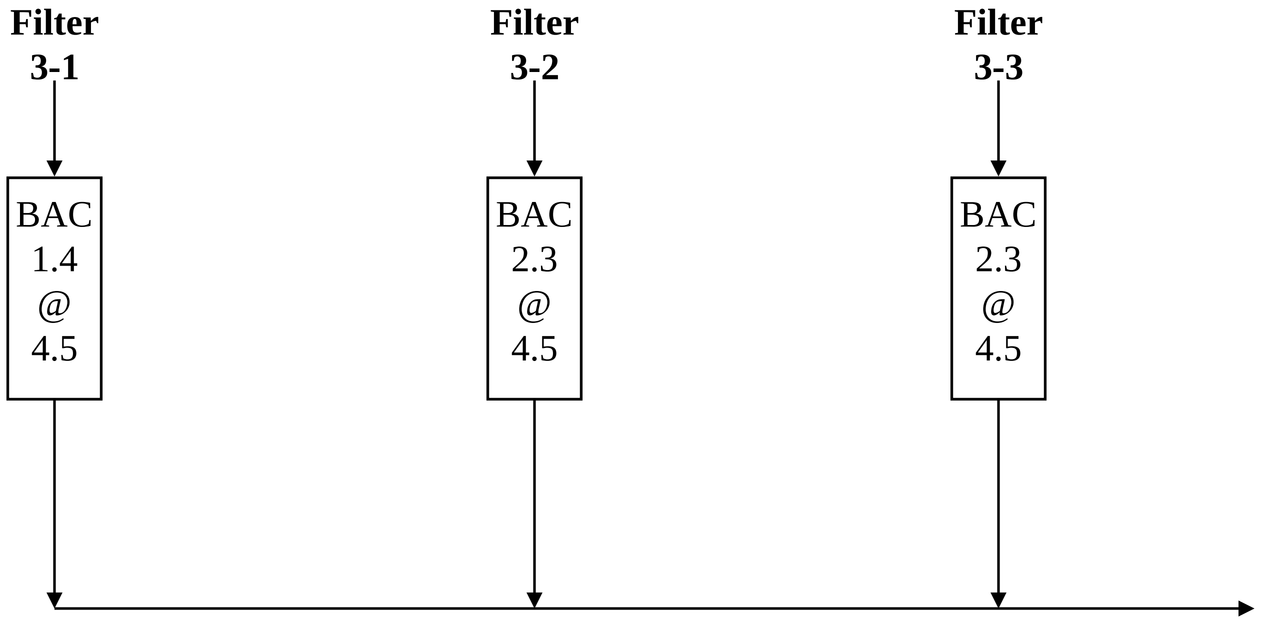
Treatment Train No.3

Ozone-BAC-DE Filtration



Treatment Train No.3

Biological Contactors



Filter 3-1

BAC
1.4
@
4.5

Filter 3-2

BAC
2.3
@
4.5

Filter 3-3

BAC
2.3
@
4.5

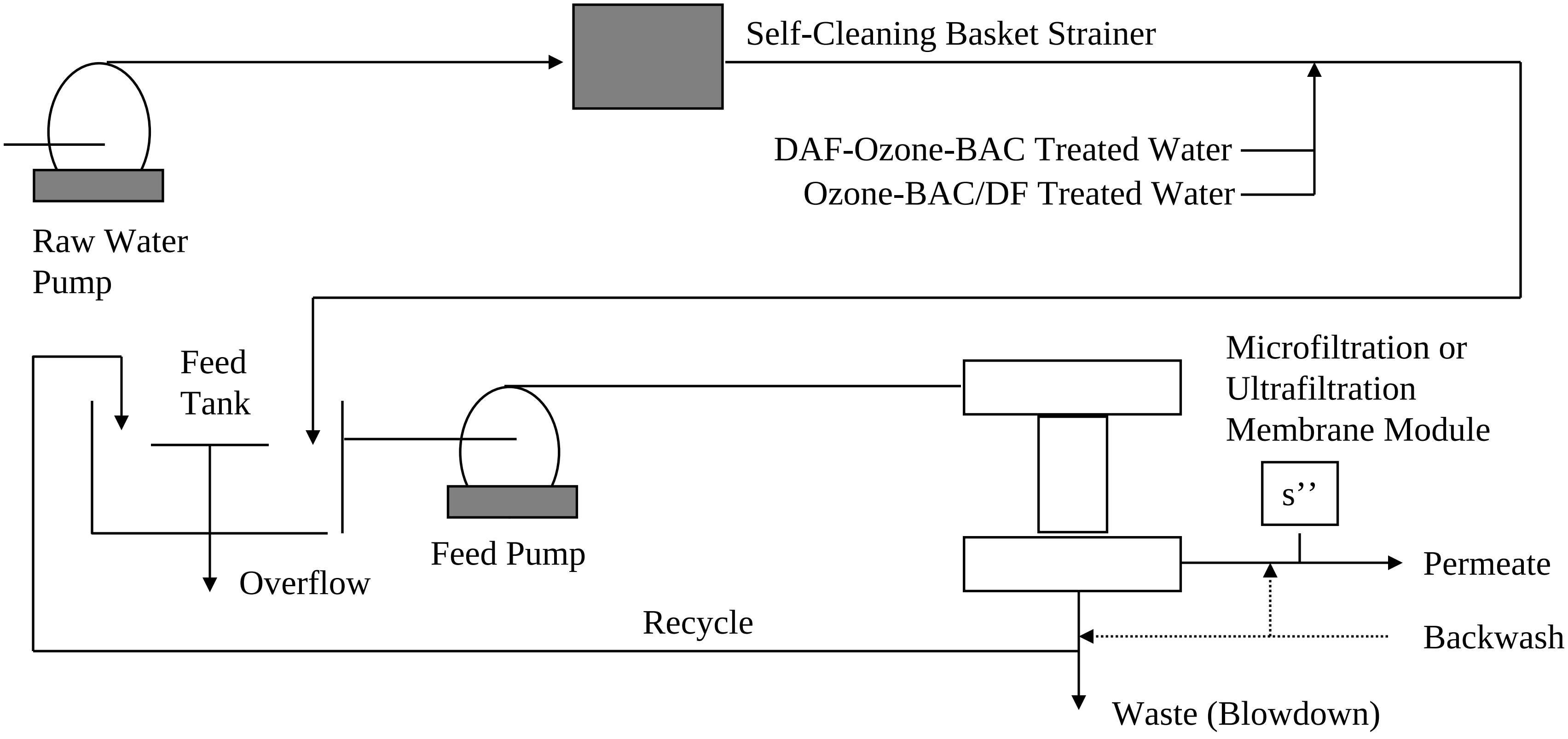
Filtered Water

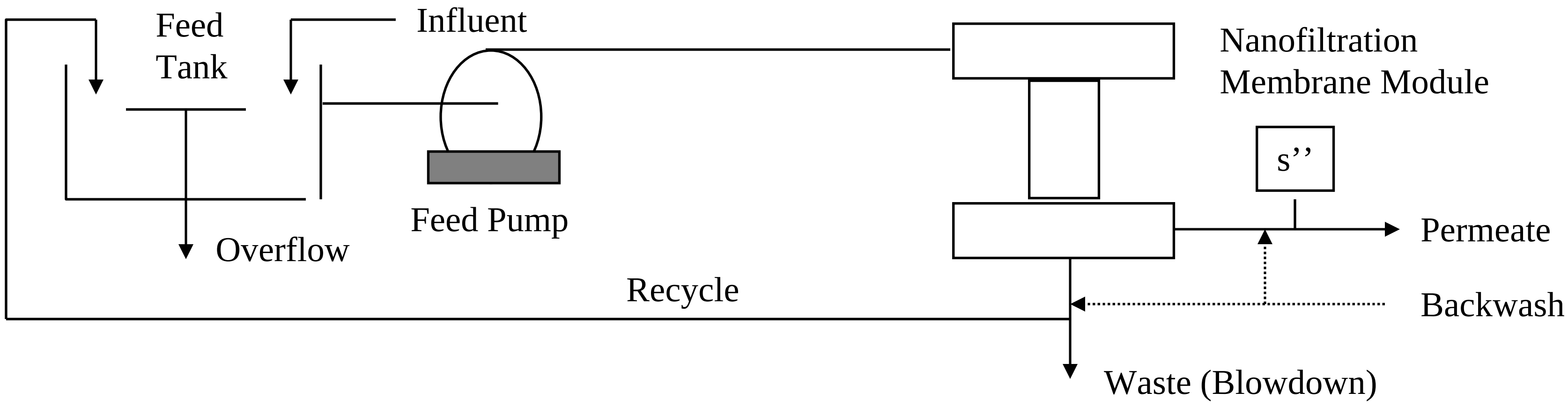
Key:
grainsize (mm) @ loading rate (gpmsf)

Treatment Train No.4

Membrane Filtration

Key:
s’ = 1^o sample
s’’ = 2^o sample





OVERALL RESEARCH OBJECTIVES

Which of the four pilot treatment trains will be most effective in removing the fractions of NOM that are:

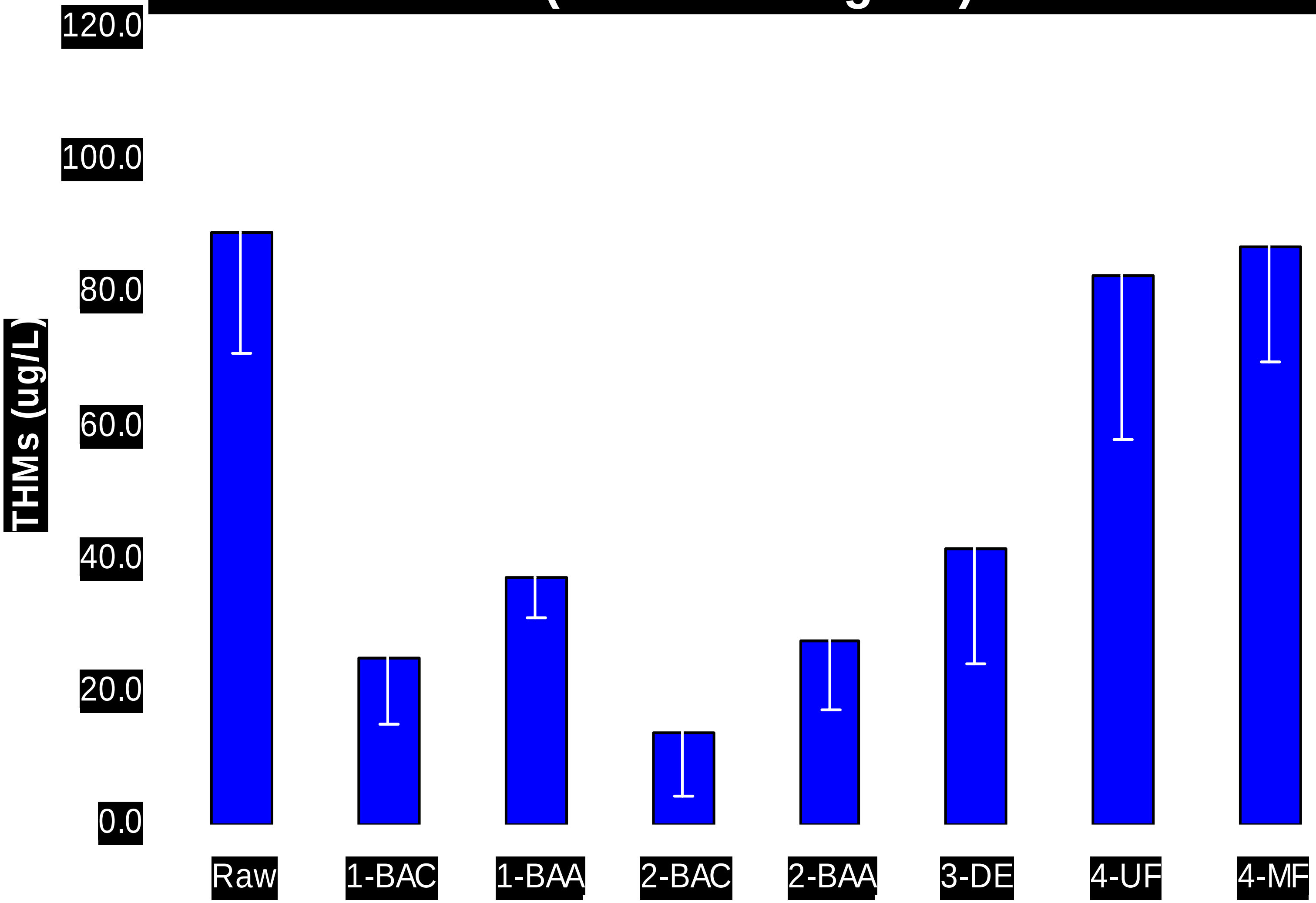
1) Most amenable to reaction with chlorine, i.e. the formation of DBPs

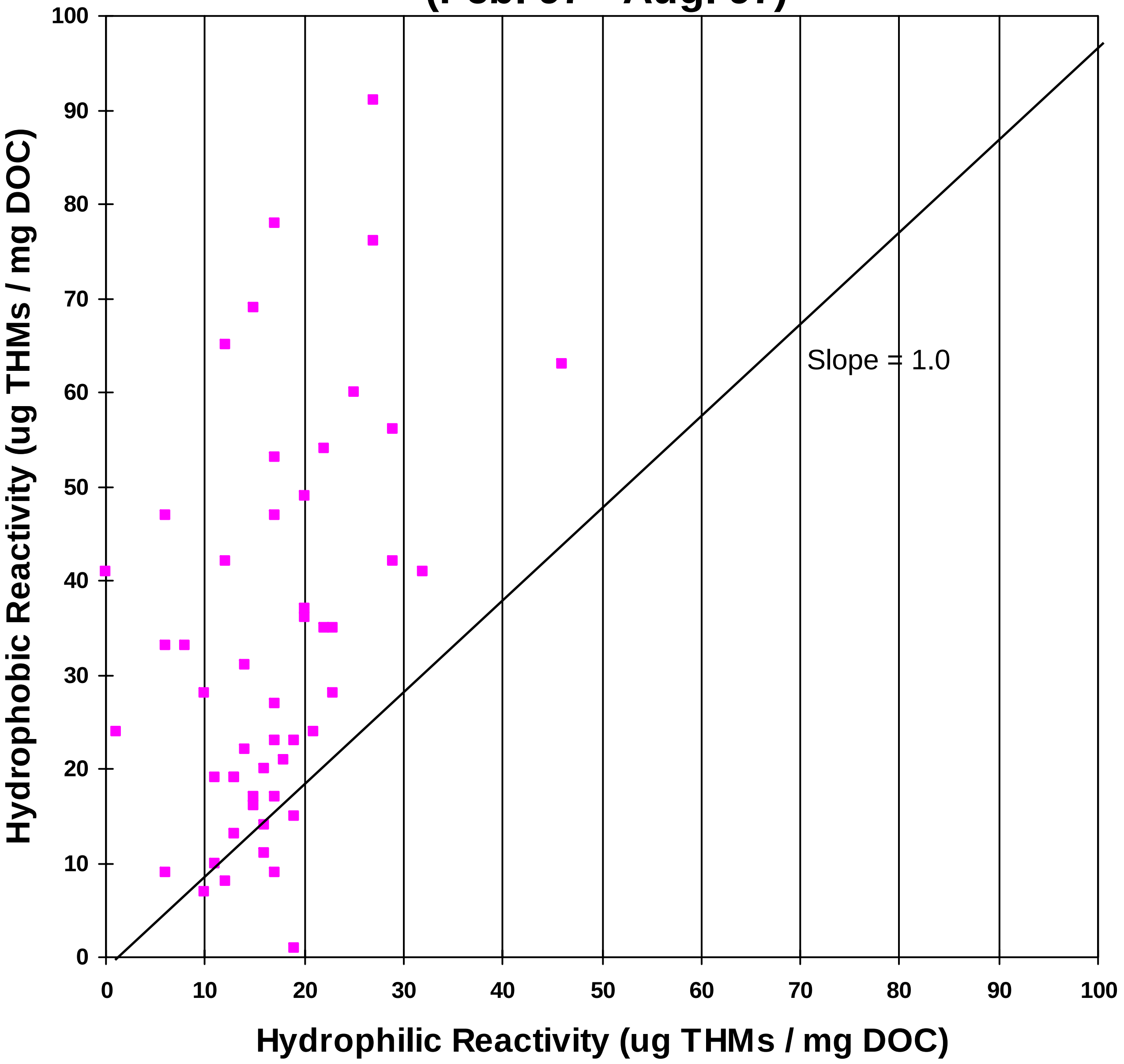
2) Most available for biological activity and subsequent regrowth

OVERALL RESEARCH OBJECTIVES

1) Determine which of the four pilot treatment trains will be most effective in removing the fractions of NOM that are most amenable to reaction with chlorine

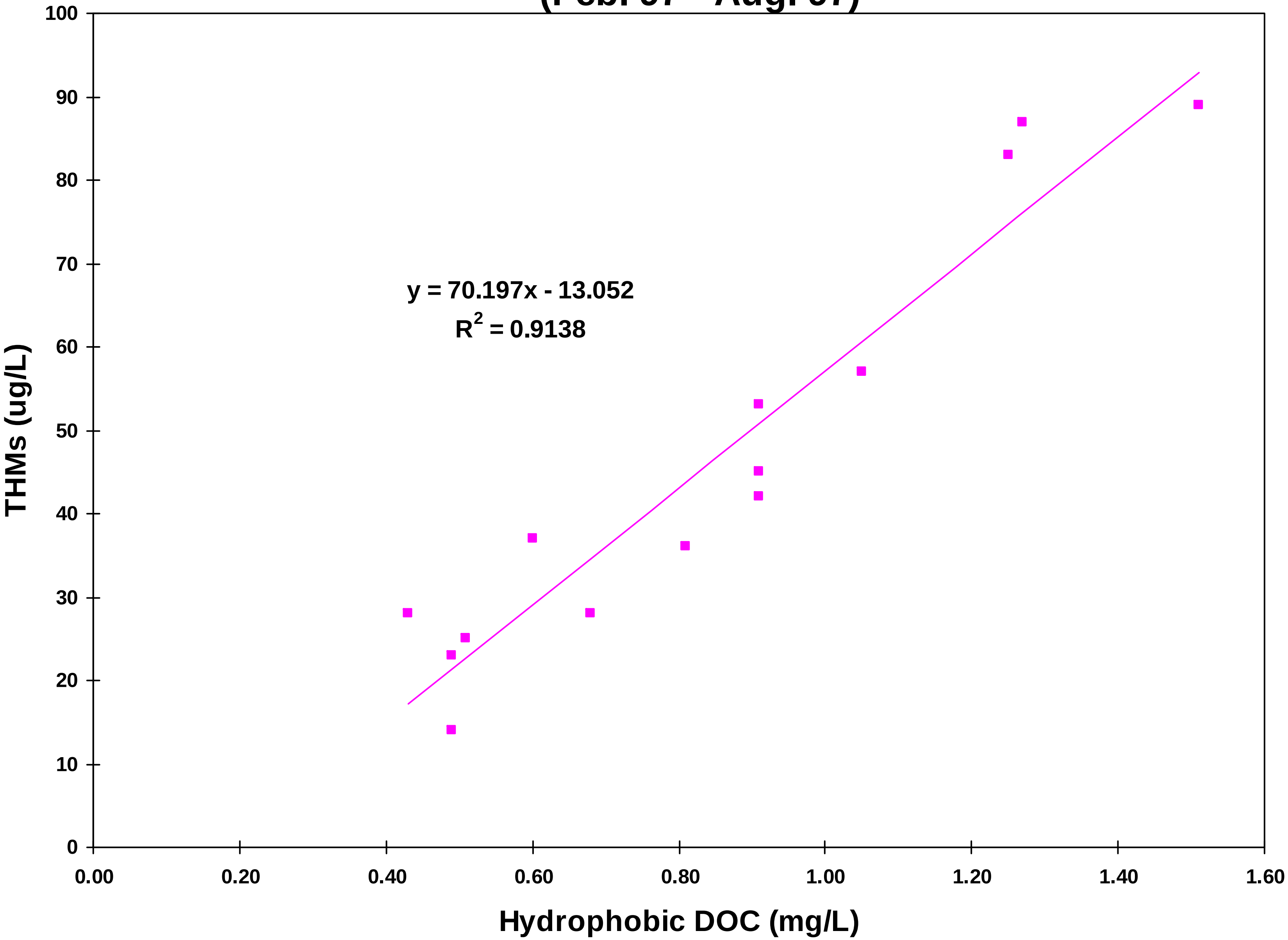
Avg THMs For Each Treatment Train Final Effluent (Feb.'97 - Aug.'97)



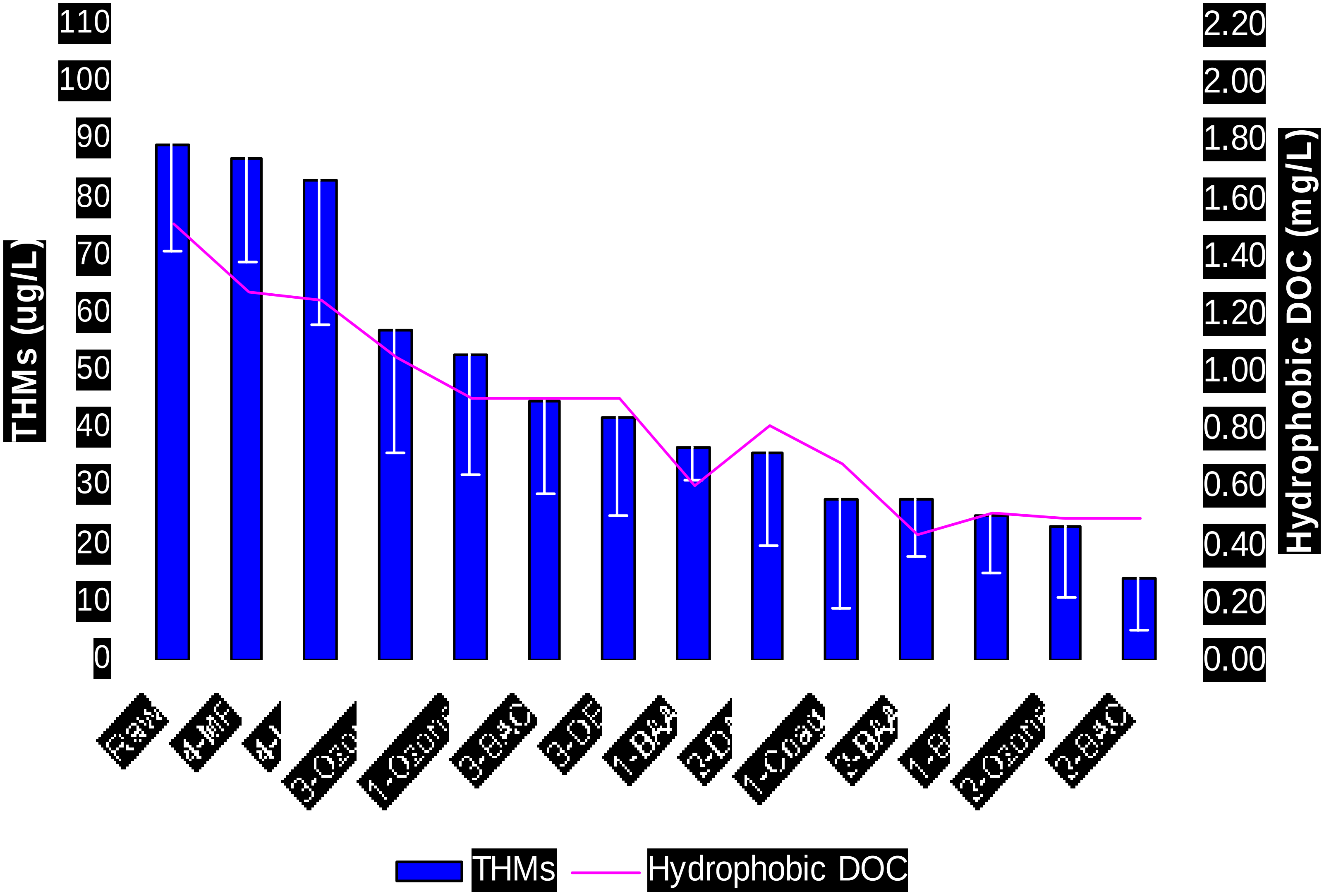


Hydrophobic versus Hydrophilic Reactivity Data (Feb.'97 - Aug.'97)

Avg THMs vs. Avg Hydrophobic DOC Thru Each Unit Operation (Feb.'97 - Aug.'97)

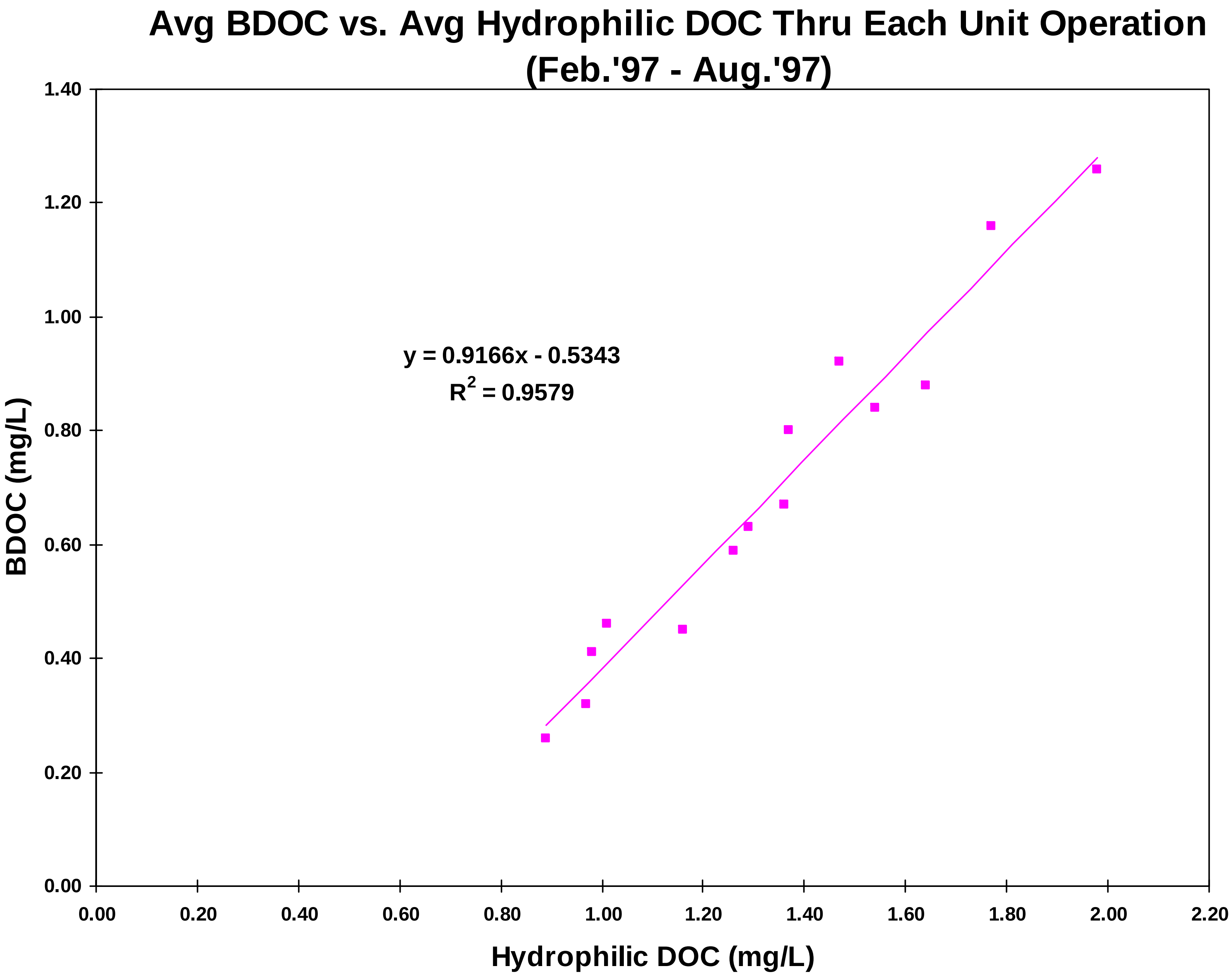


Avg THMs/Phobic DOC Thru Each Unit Operation
(Feb.'97 - Aug.'97)

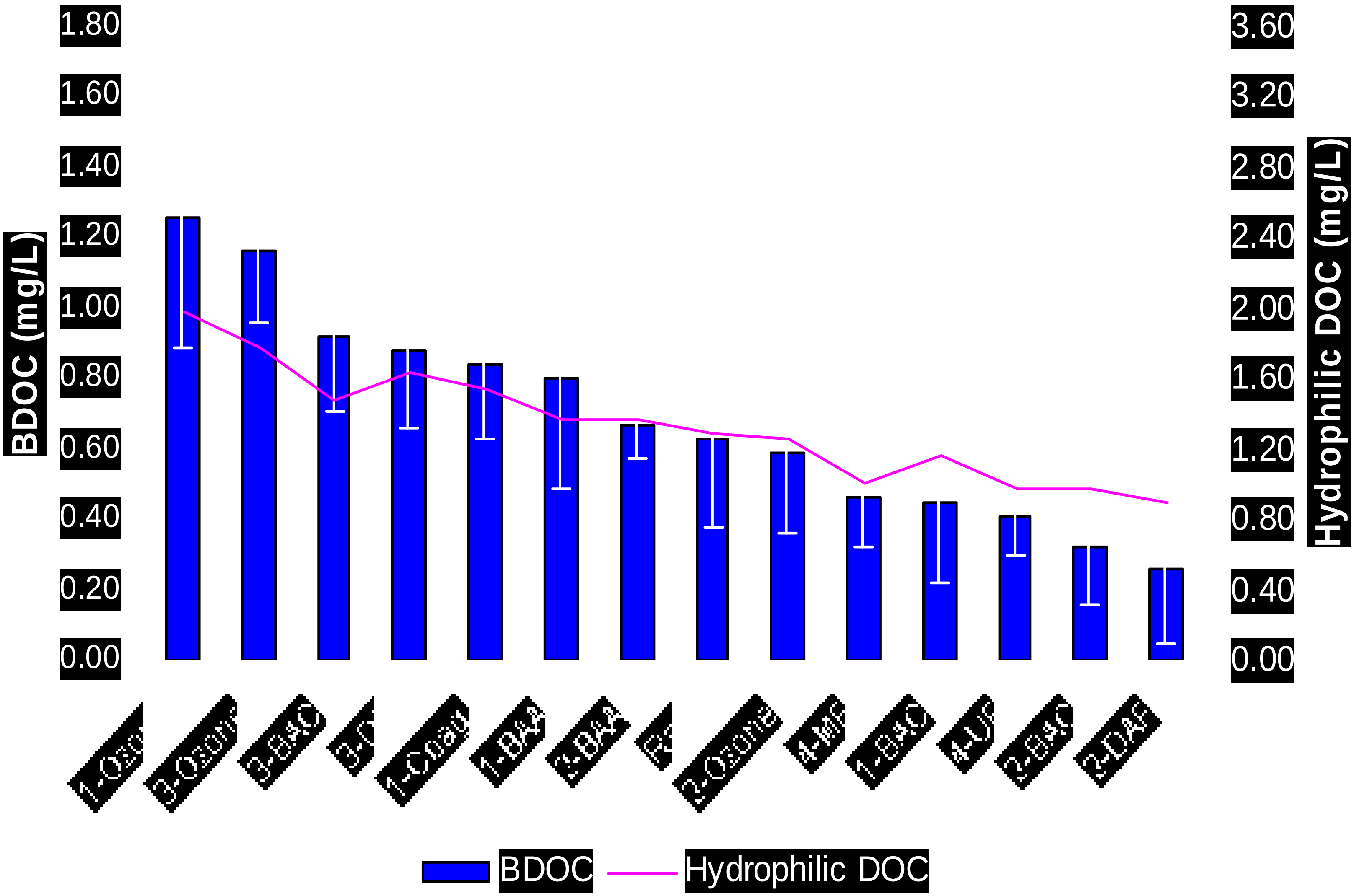


OVERALL RESEARCH OBJECTIVES

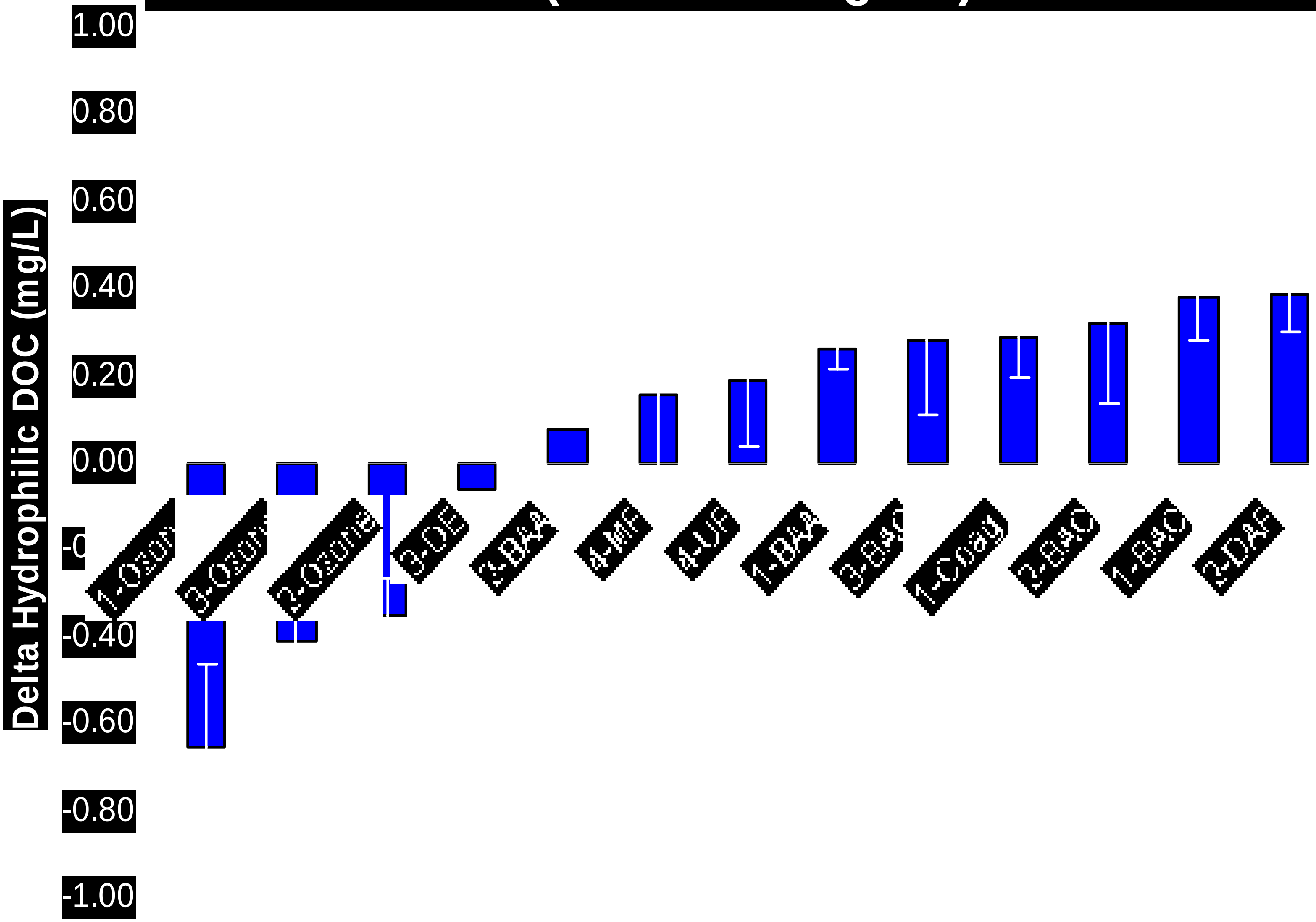
2) Determine which of the four pilot treatment trains will be most effective in removing the fractions of NOM that are most available for biological activity

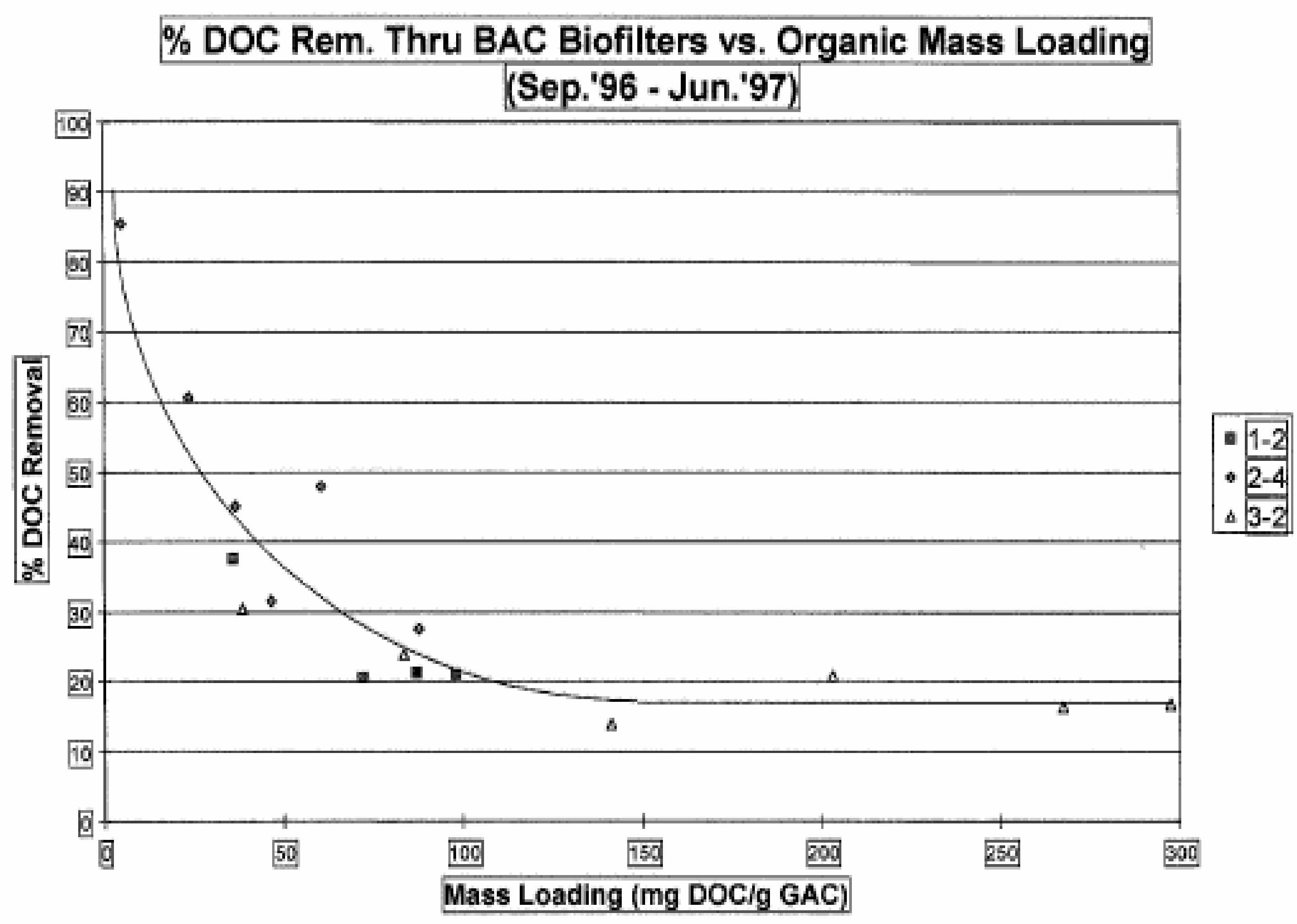

Avg BDOC vs. Avg Hydrophilic DOC Thru Each Unit Operation
(Feb.'97 - Aug.'97)
y = 0.9166x - 0.5343
R2 = 0.9579
BDOC (mg/L)
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
1.60
1.80
2.00
2.20
Hydrophilic DOC (mg/L)

Avg BDOC/Philic DOC Thru Each Unit Operation (Feb.'97 - Aug.'97)



Avg Philic DOC Removal Thru Each Unit Operation
(Feb.'97 - Aug.'97)




% DOC Rem. Thru BAC Biofilters vs. Organic Mass Loading
(Sep.'96 - Jun.'97)
% DOC Removal
100
90
80
70
60
50
40
30
20
10
0
0
50
100
150
200
250
300
Mass Loading (mg DOC/g GAC)
■ 1-2
◆ 2-4
△ 3-2

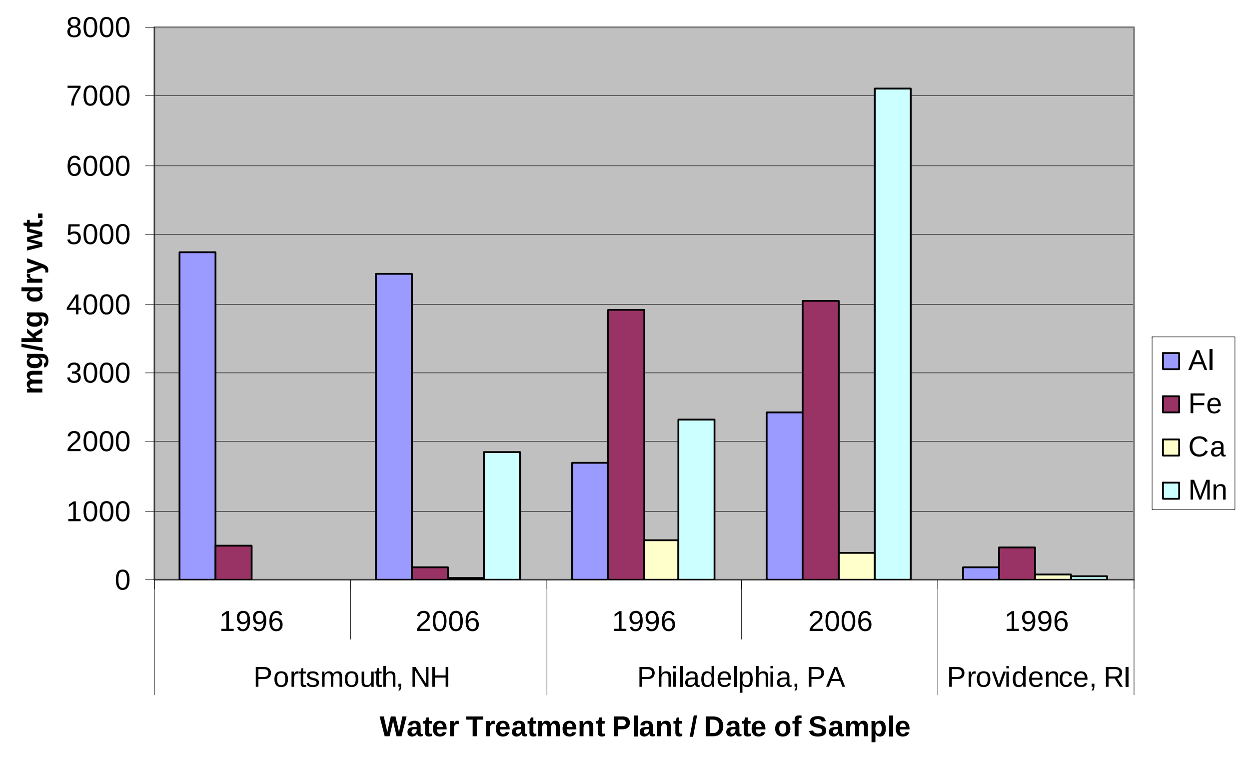
BAC STUDY - CONCLUSIONS

- The treatment trains that removed the most organic precursor material were the DF and DAF Trains.
- The unit operations which resulted in the greatest reduction of THM formation were ozonation and coagulation.
- The DF and DAF Trains with BAC biofiltration produced the least biodegradable final effluents.
- The most effective unit operations for reducing biological regrowth potential were BAC biofiltration and coagulation.

Filter Media

Portsmouth, NH Philadelphia, PA Providence, RI

Average Metal Coating Content of Selected Rapid Sand Filters



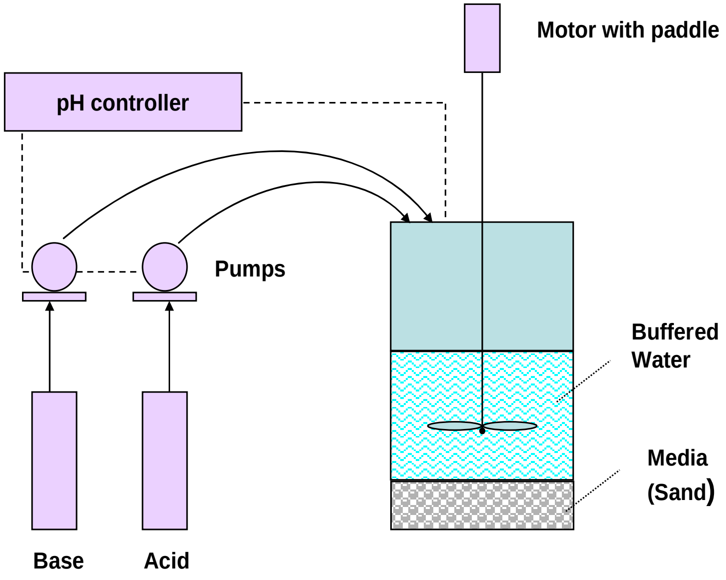
RESEARCH OBJECTIVES

Explore the NOM removal potential of ‘naturally’ coated, regenerable sand filter media.

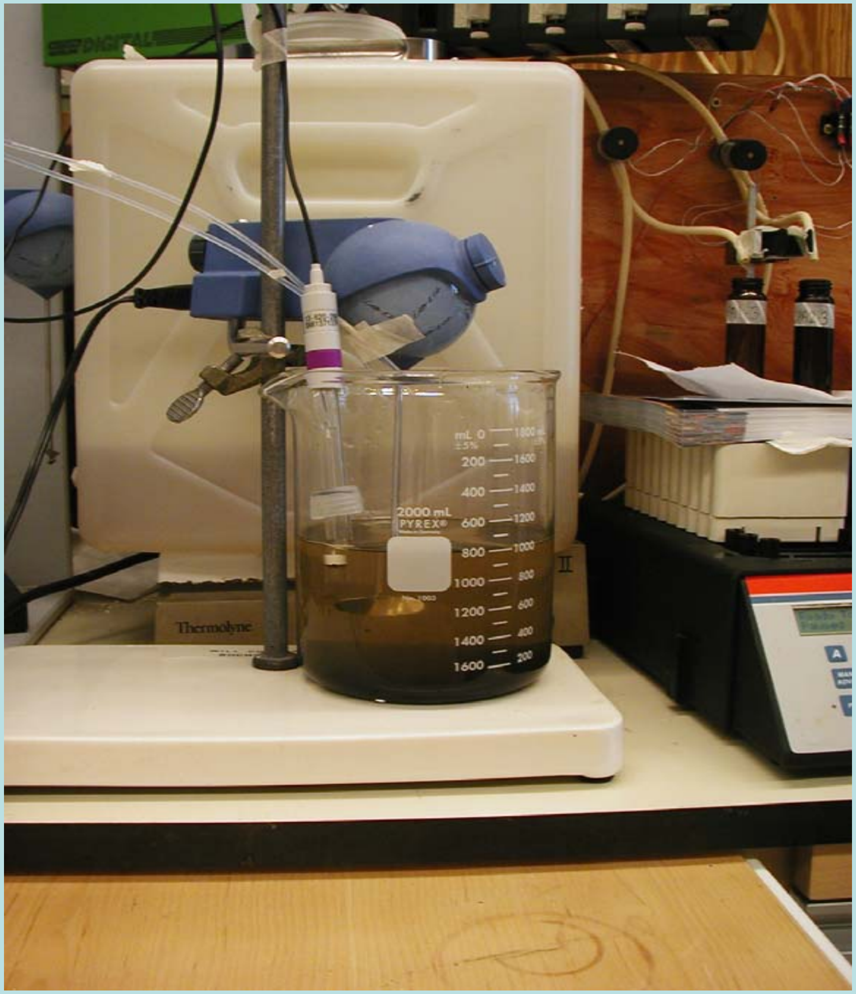
1) Assess coating characteristics of ‘aged’ rapid sand filter media.
2) Evaluate optimum initial cleaning/backwashing conditions.
3) Quantify NOM & Arsenic removal potentials using ‘natural’ Al or Fe oxide coatings on sand filter media.

4) Evaluate interferences associated with the adsorption capacity of the metal oxide coating.

Backwash/Regeneration Set-Up

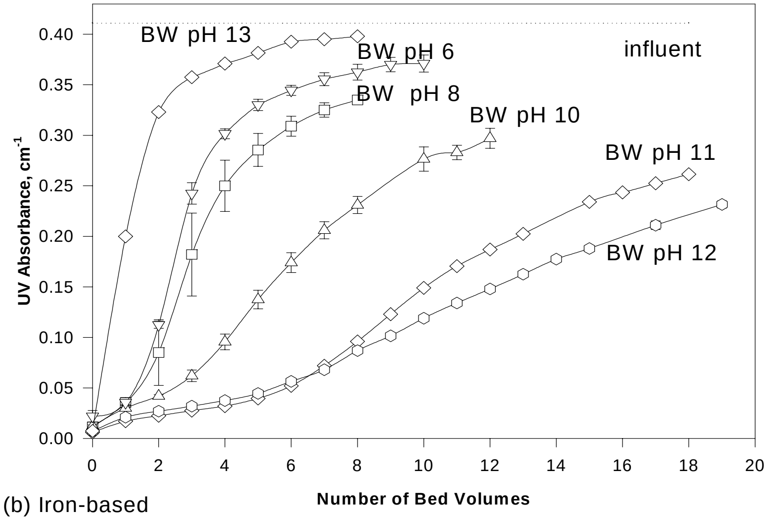


BACKWASH SET-UP

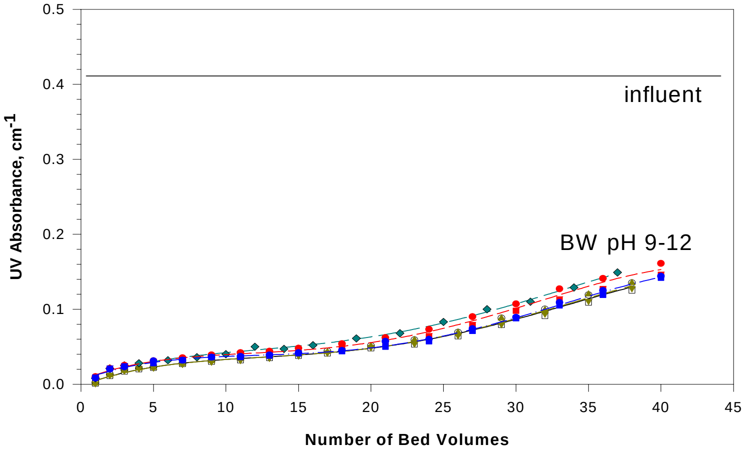


Effect of BW Regeneration pH on NOM Removal at pH 6 Challenges
(a) Aluminum-based coating and (b) Iron-based coating

(a) Aluminum-based



(b) Iron-based



RESEARCH OBJECTIVES

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1) Assess coating characteristics of ‘aged’ rapid sand filter media.
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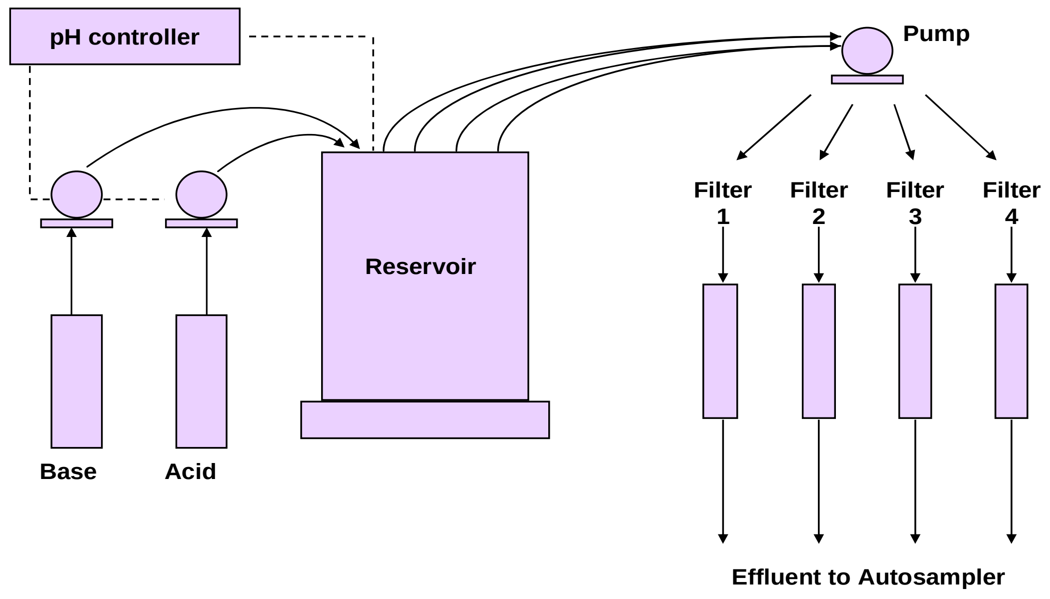
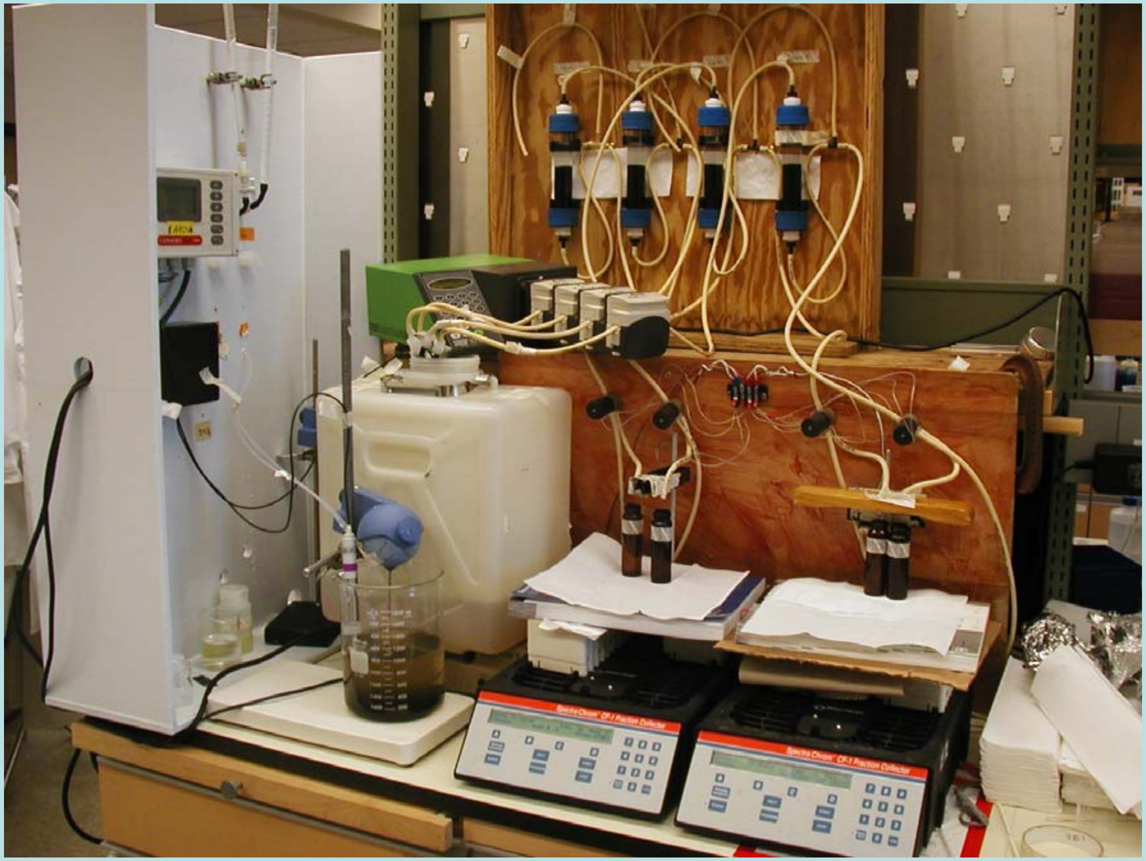
4) Evaluate inorganic interferences regarding the adsorption capacity of the metal oxide coating.

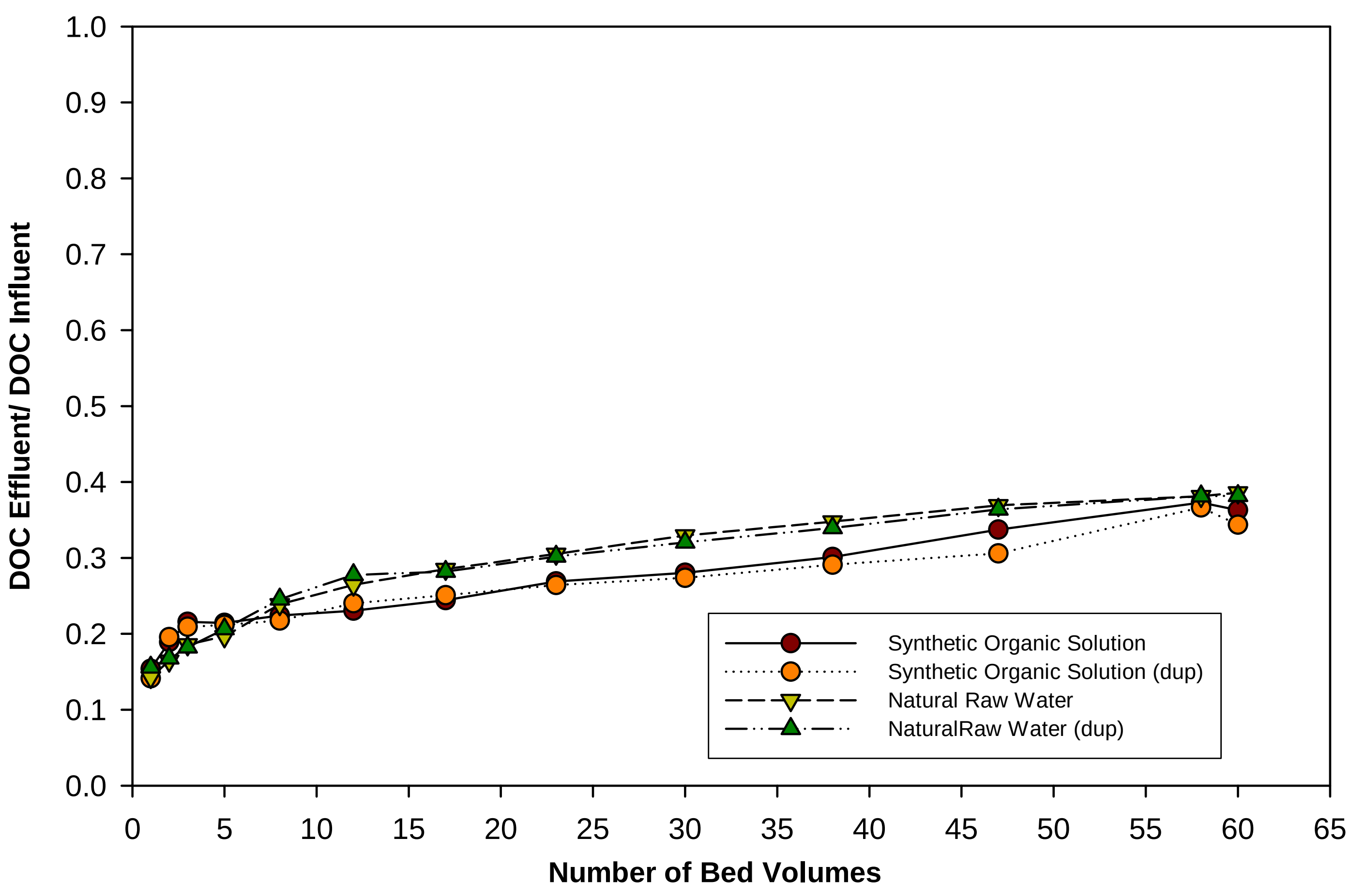
Challenge Set-Up



CHALLENGE SET-UP



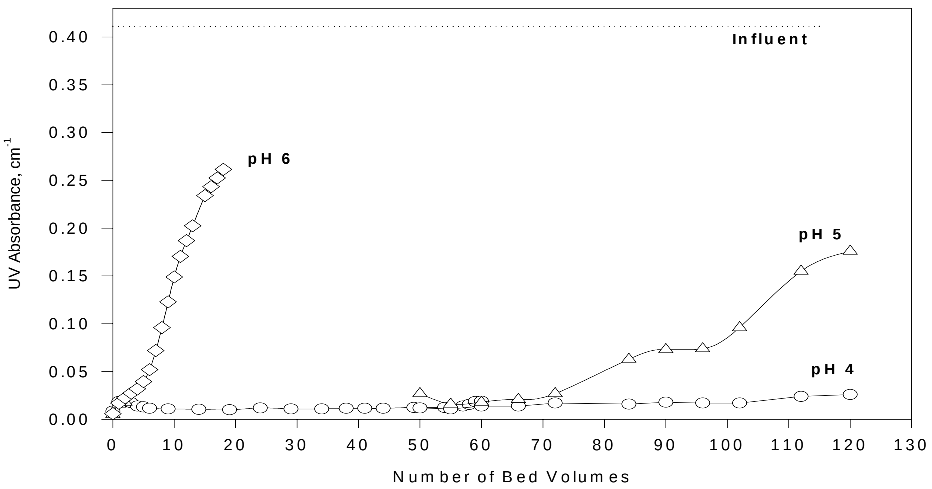
Comparison of Synthetic and Natural DOC Challenge Solutions at pH 6 after Regeneration at pH 11 of Iron-Coated Sand



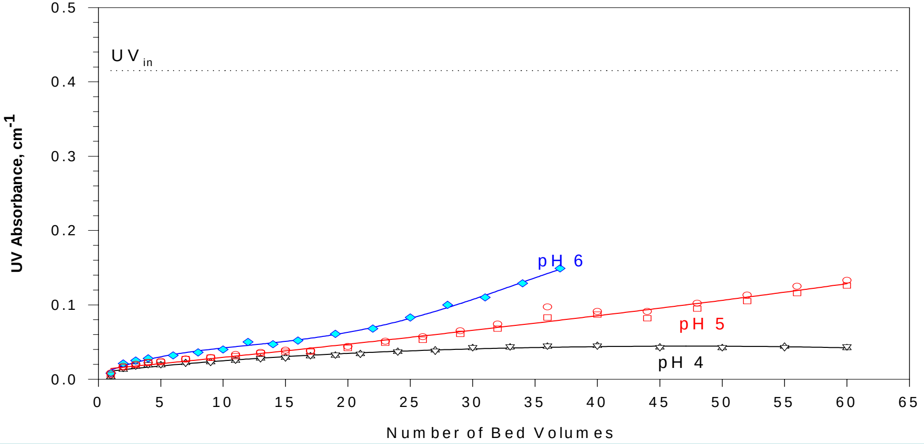
Effect of Challenge Solution pH on NOM Removal after Regeneration at pH 11

(a) aluminum-based coating and (b) iron-based coating

(a) Aluminum-based



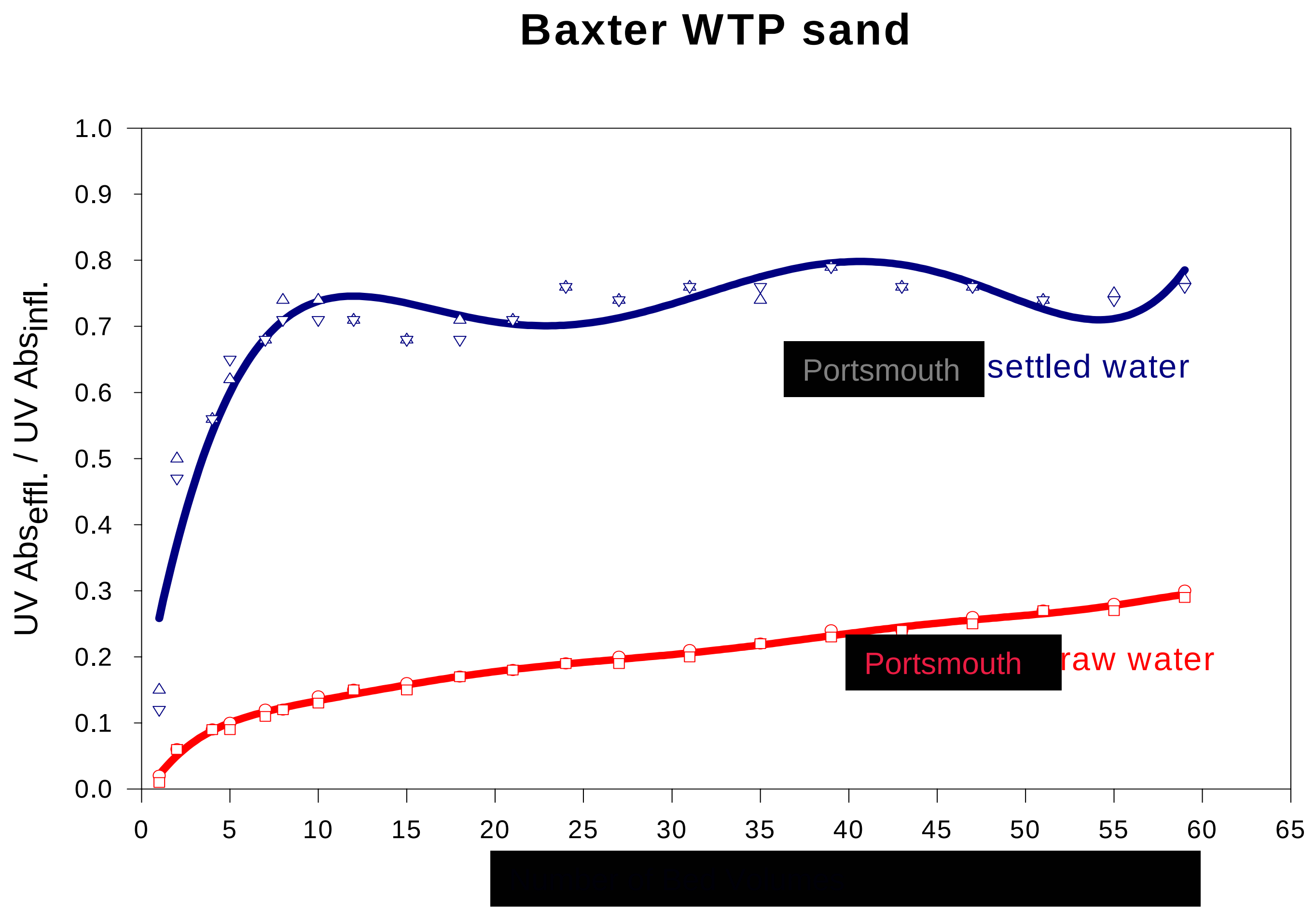
(b) Iron-based



Relating 60 Bed Volumes to Filter Run Times (hr)

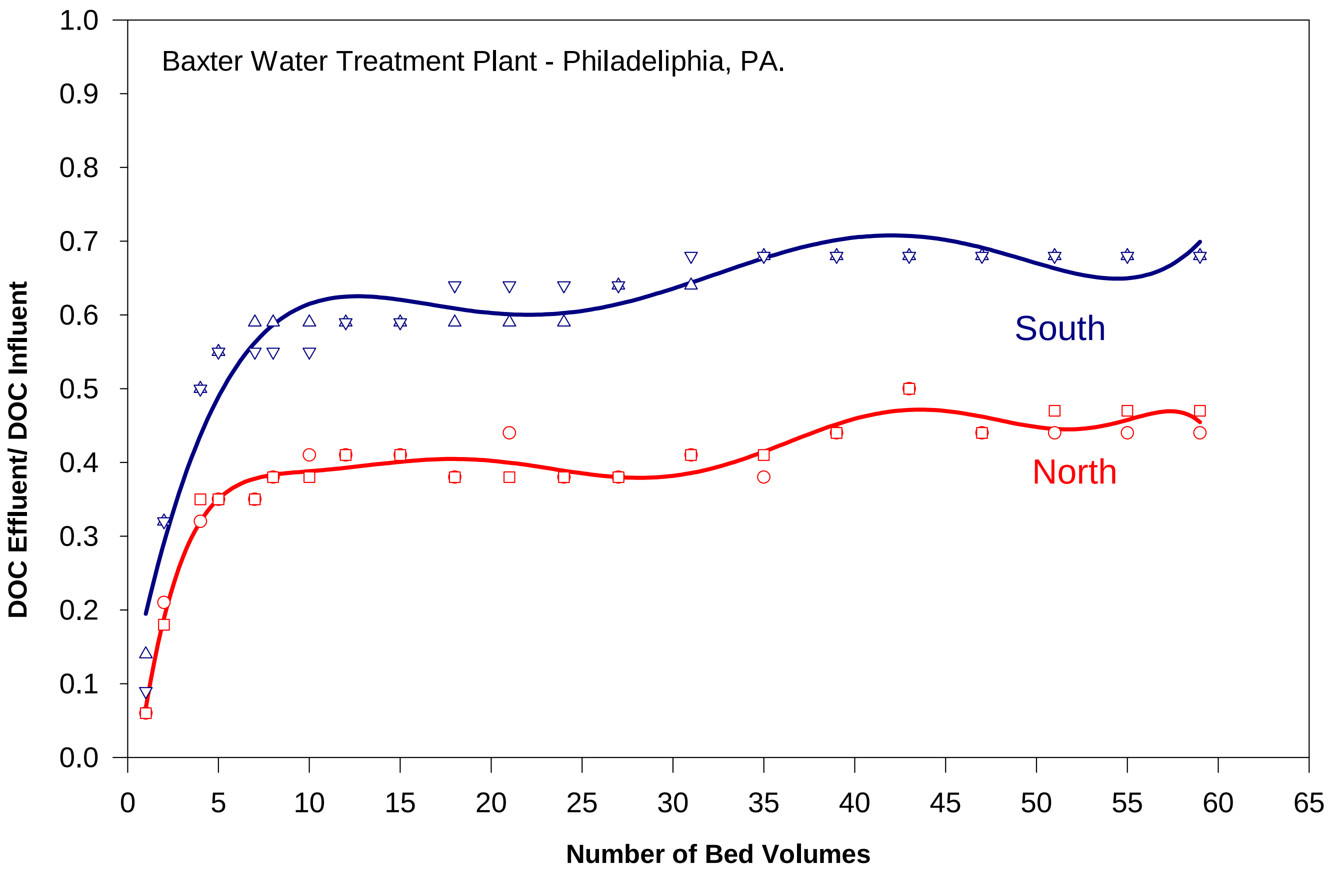
	Filter Bed Depth, ft		
Q, gpm/ft²	2	4	6
2	**7.5**	15.0	22.4
4	3.7	**7.5**	11.2
6	2.5	5.0	**7.5**

Influence of Source Waters Adjusted to pH 5 on Organic Matter Removals after Regeneration of Iron-coated Sand at pH 11

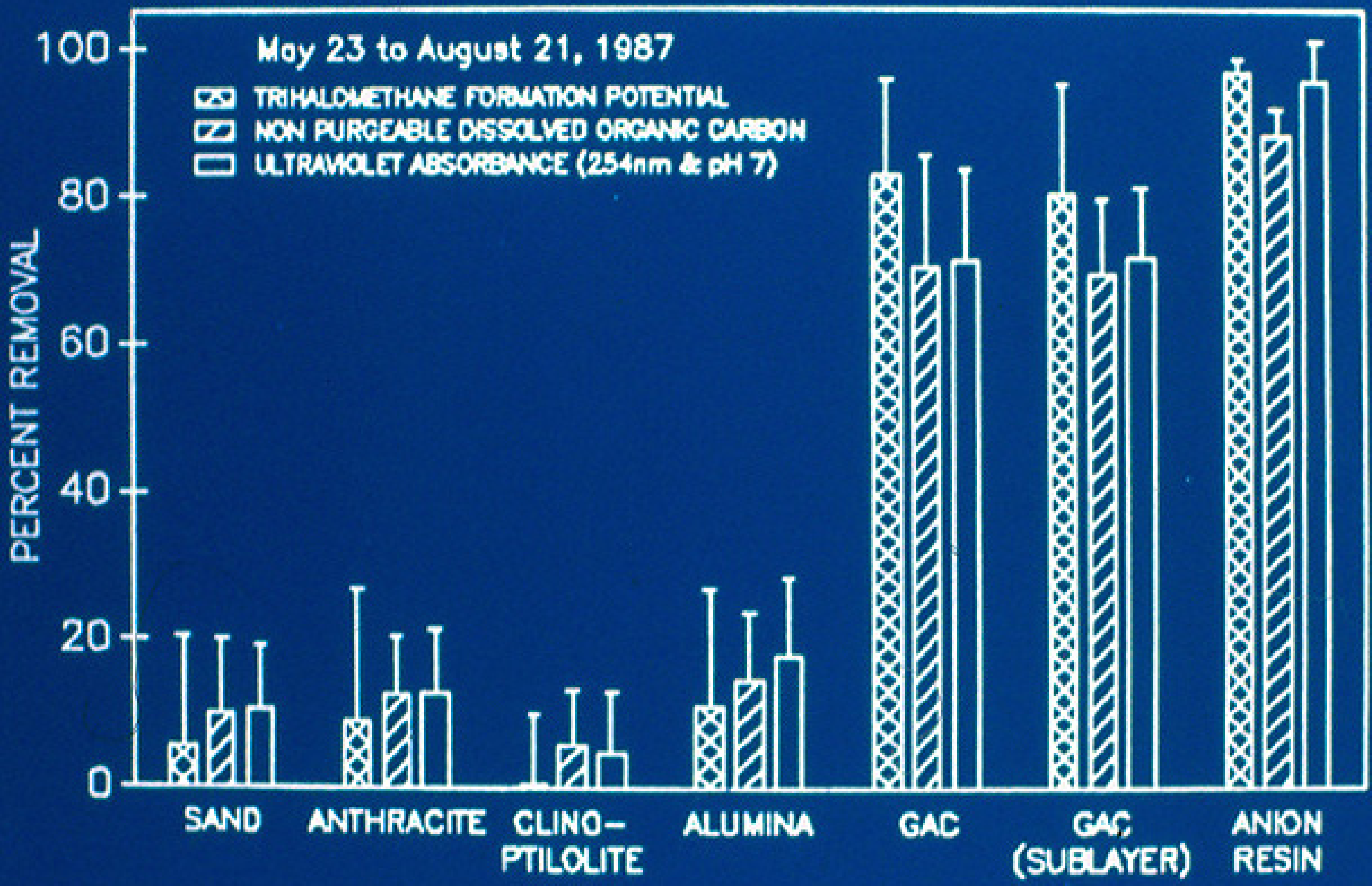


Baxter WTP sand

DOC Removals from a Clarified Source Water adjusted to pH 5 after Regeneration at pH 11 of an Iron-Coated Sand

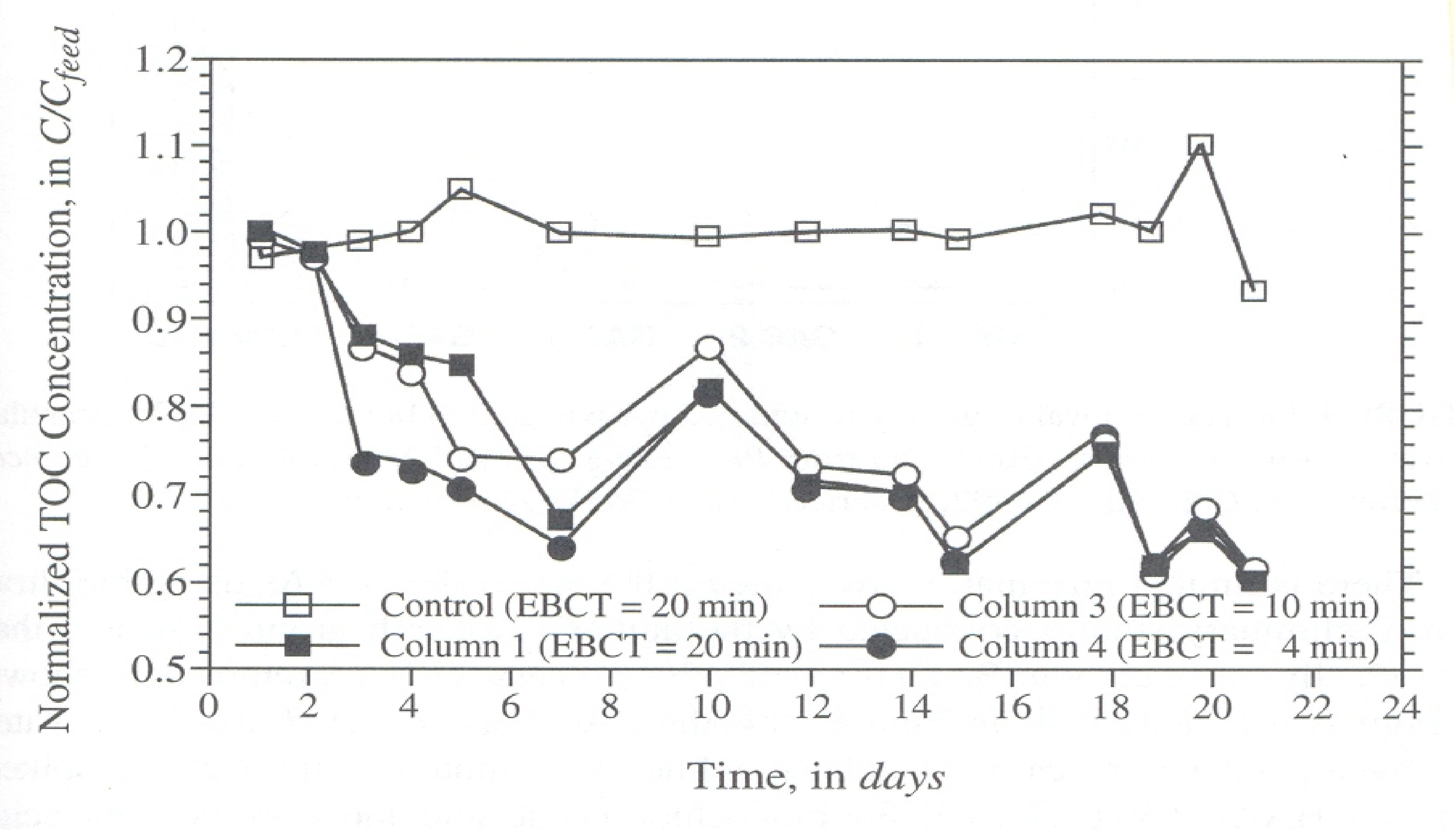


Anionic Exchange Resins


May 23 to August 21, 1987
TRIHALOMETHANE FORMATION POTENTIAL
NON PURGEABLE DISSOLVED ORGANIC CARBON
ULTRAVIOLET ABSORBANCE (254nm & pH 7)
PERCENT REMOVAL
100
80
60
40
20
0
SAND
ANTHRACITE
CLINO-PTILOLITE
ALUMINA
GAC
GAC (SUBLAYER)
ANION RESIN

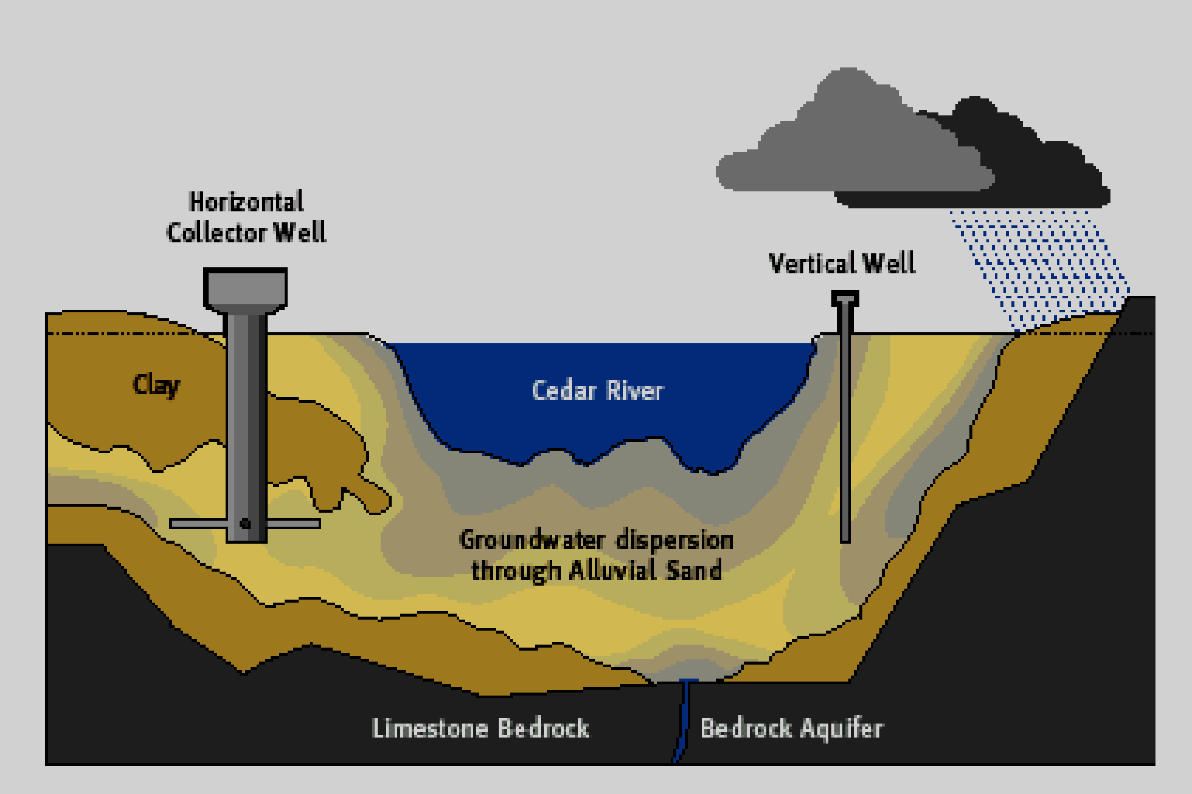
Biodegradation with and without Enhanced Biofiltration and BAC

Biofiltration for DBP precursor removal

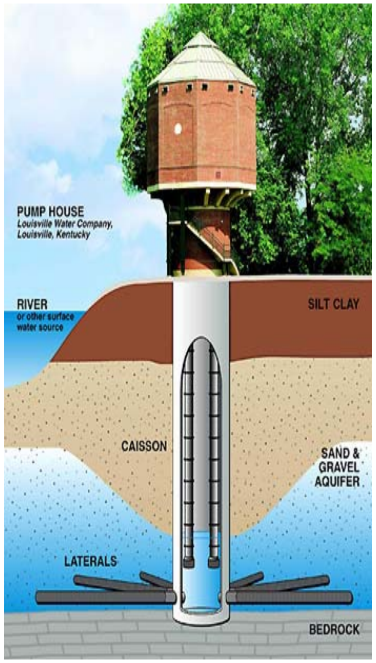


(Hozalski & Bouwer)

Typical Layout of a RBF Well

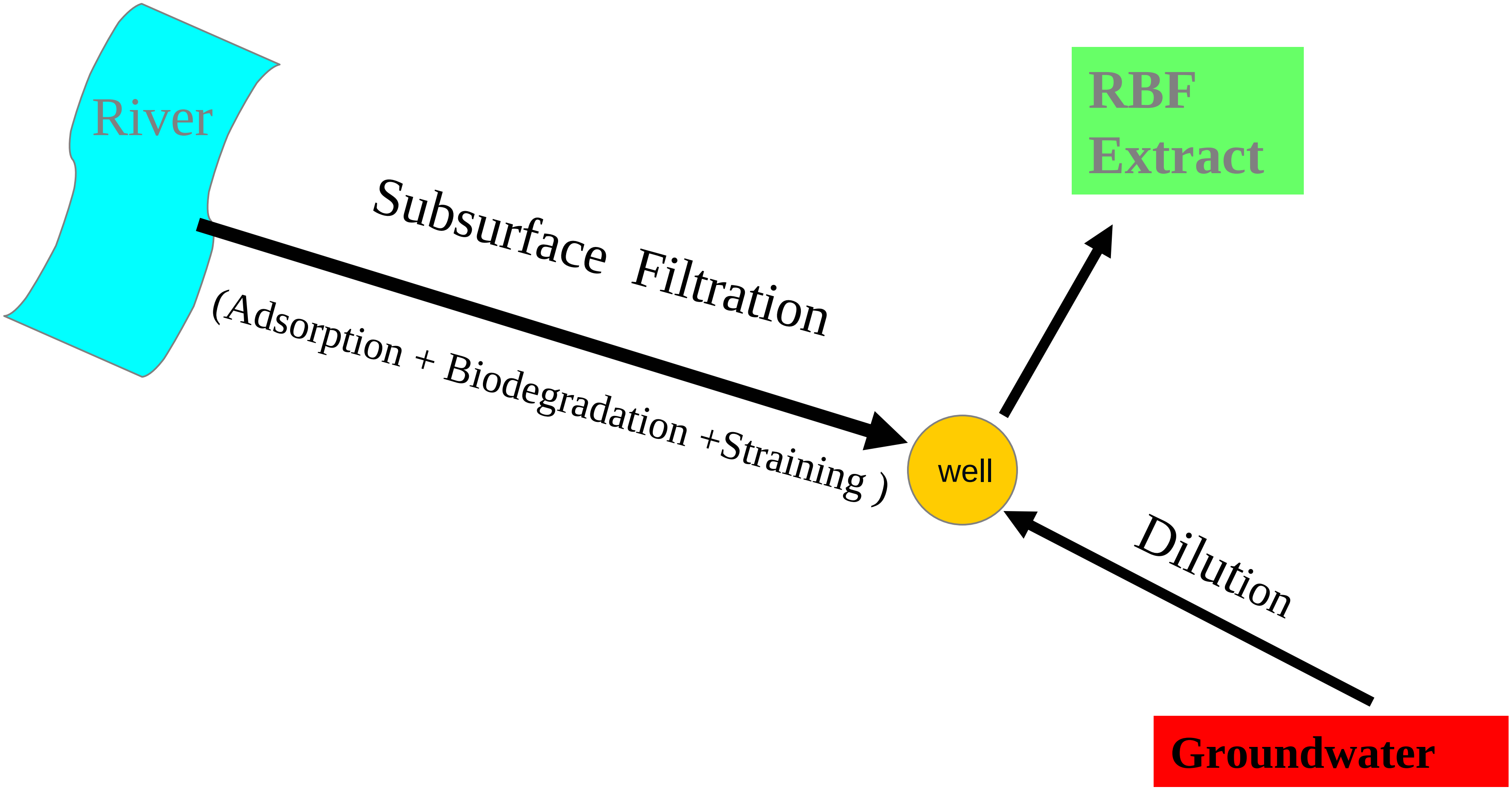


Cedar Rapids, IA



Louisville, KY

Removal Processes Taking Place at an RBF Site



River

Subsurface Filtration

(Adsorption + Biodegradation +Straining)

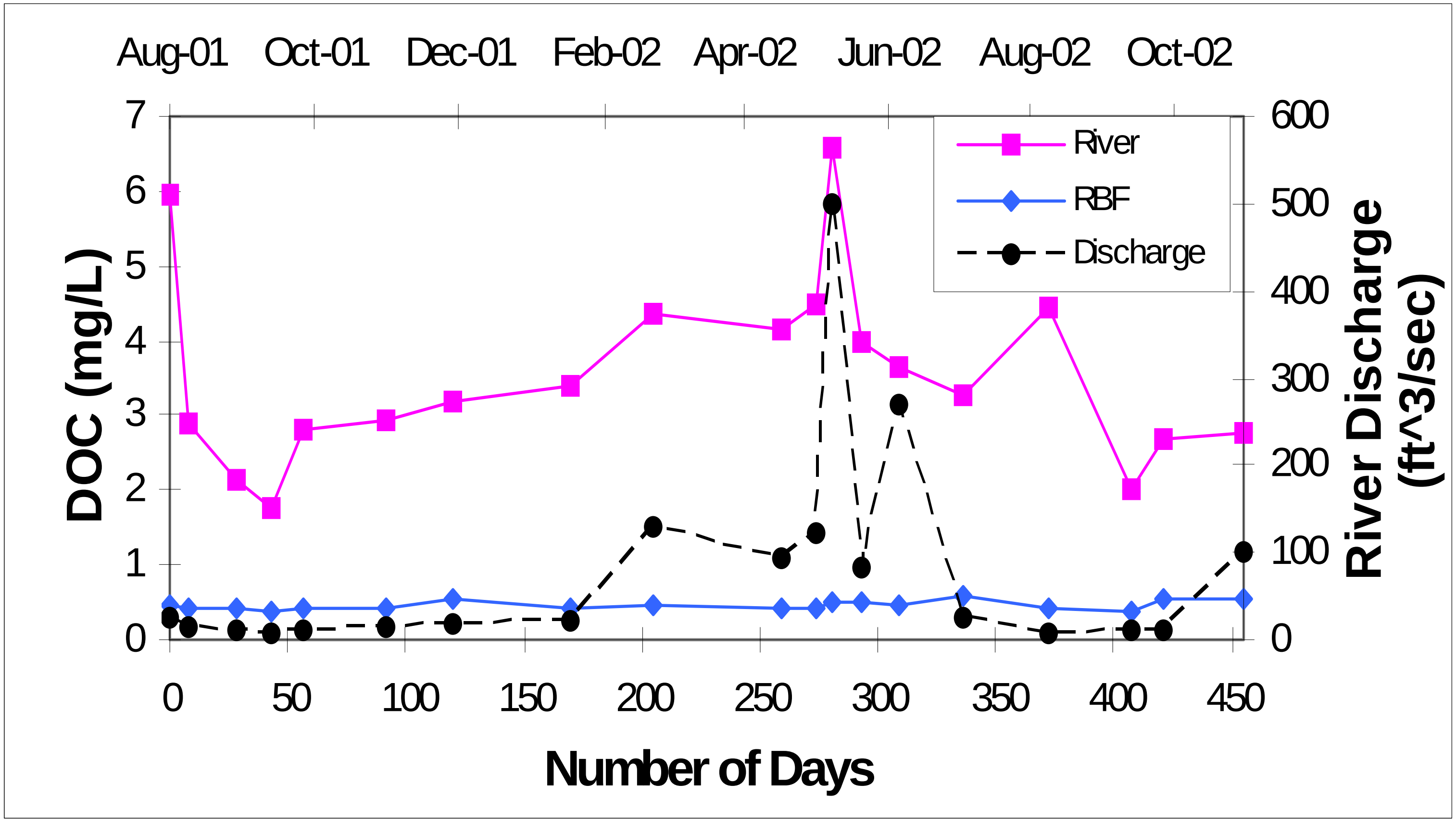
well

RBF Extract

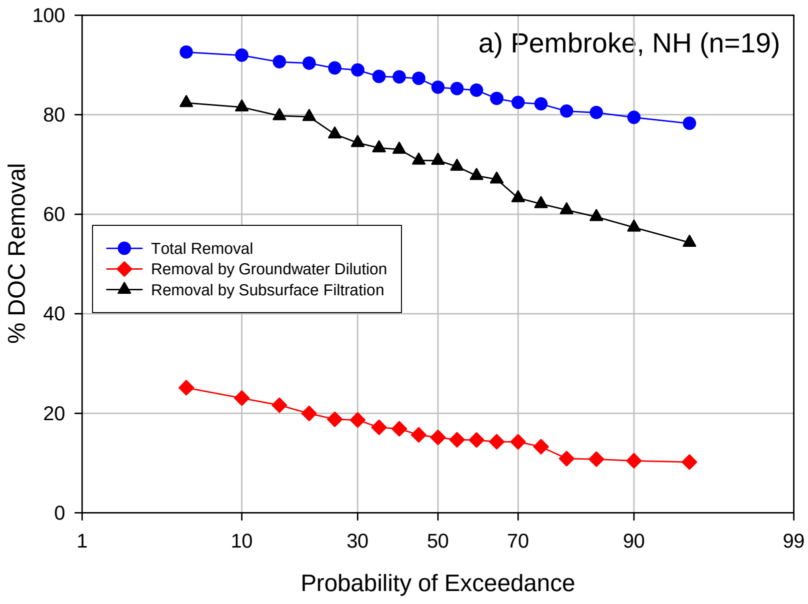
Dilution

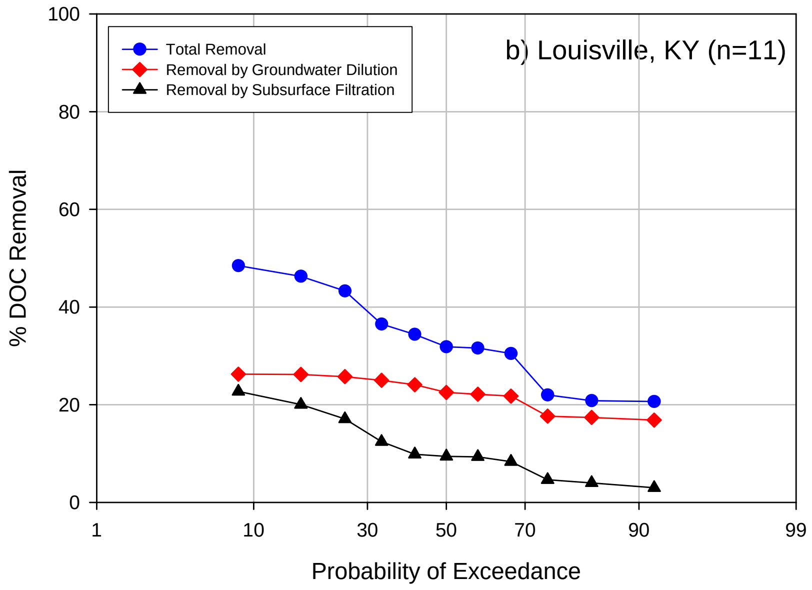
Groundwater

Typical DOC variations as a function of river discharge in Pembroke, NH including groundwater dilution impacts.

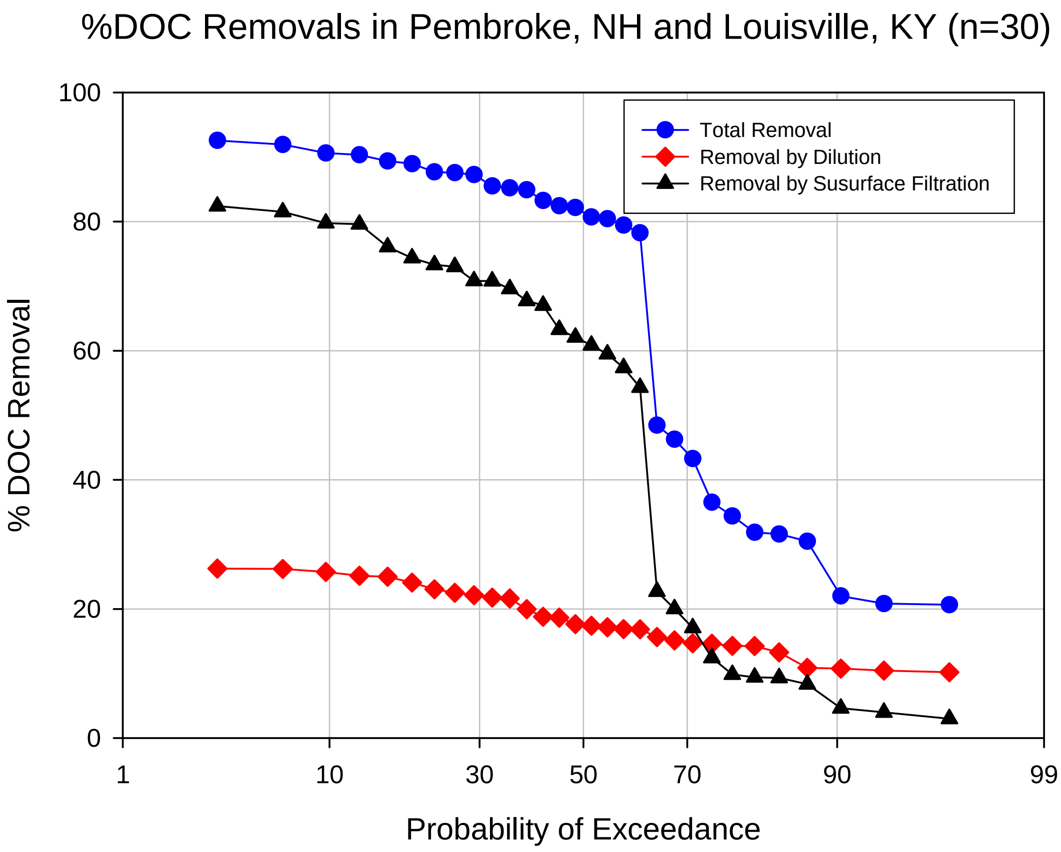


DOC Removals versus Probability of Exceedance in Pembroke, NH and Louisville, KY





DOC removal capability of exceedance comparison between Pembroke, NH and Louisville, KY

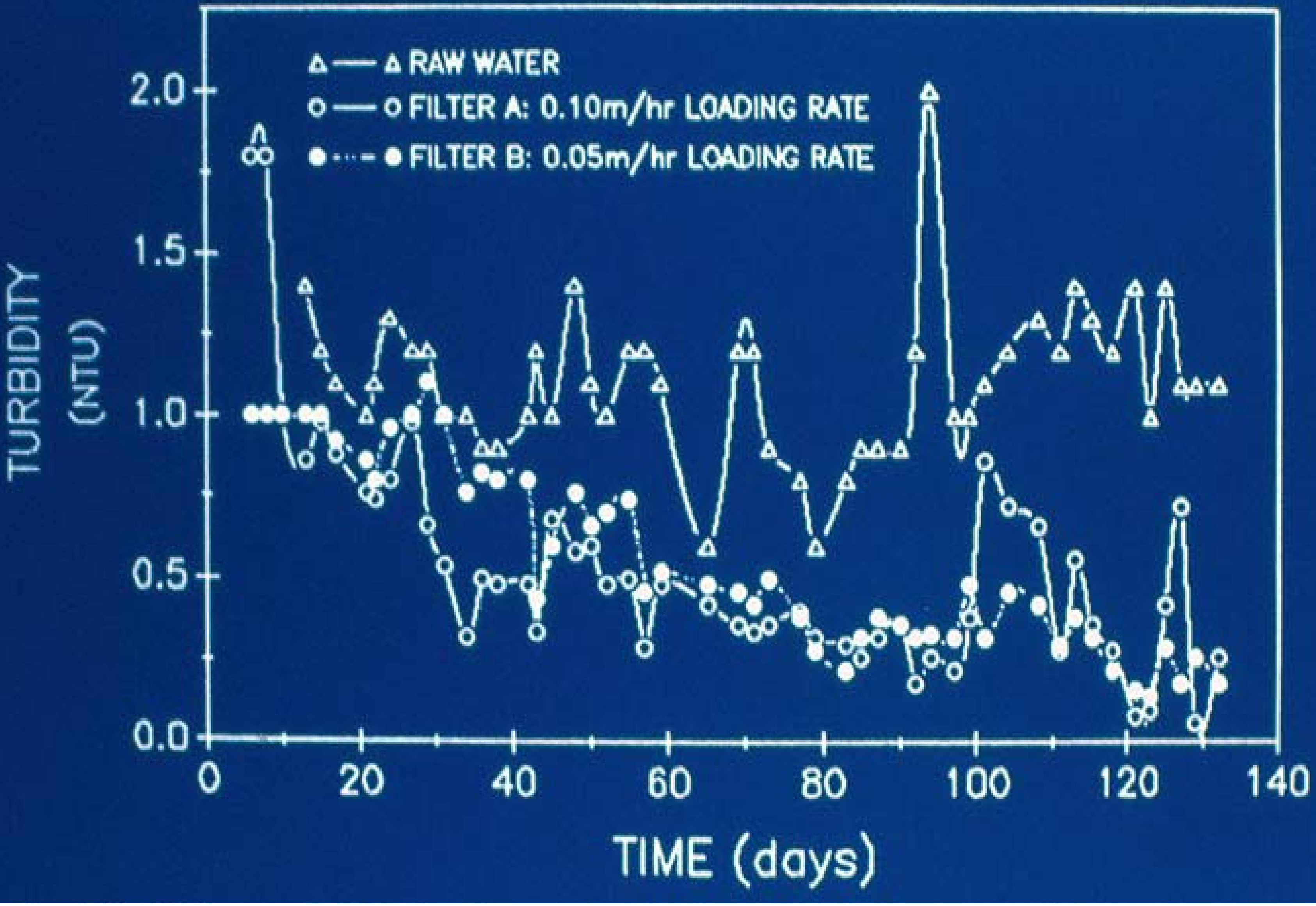


Site Specific RBF Parameters Influencing DOC Removals

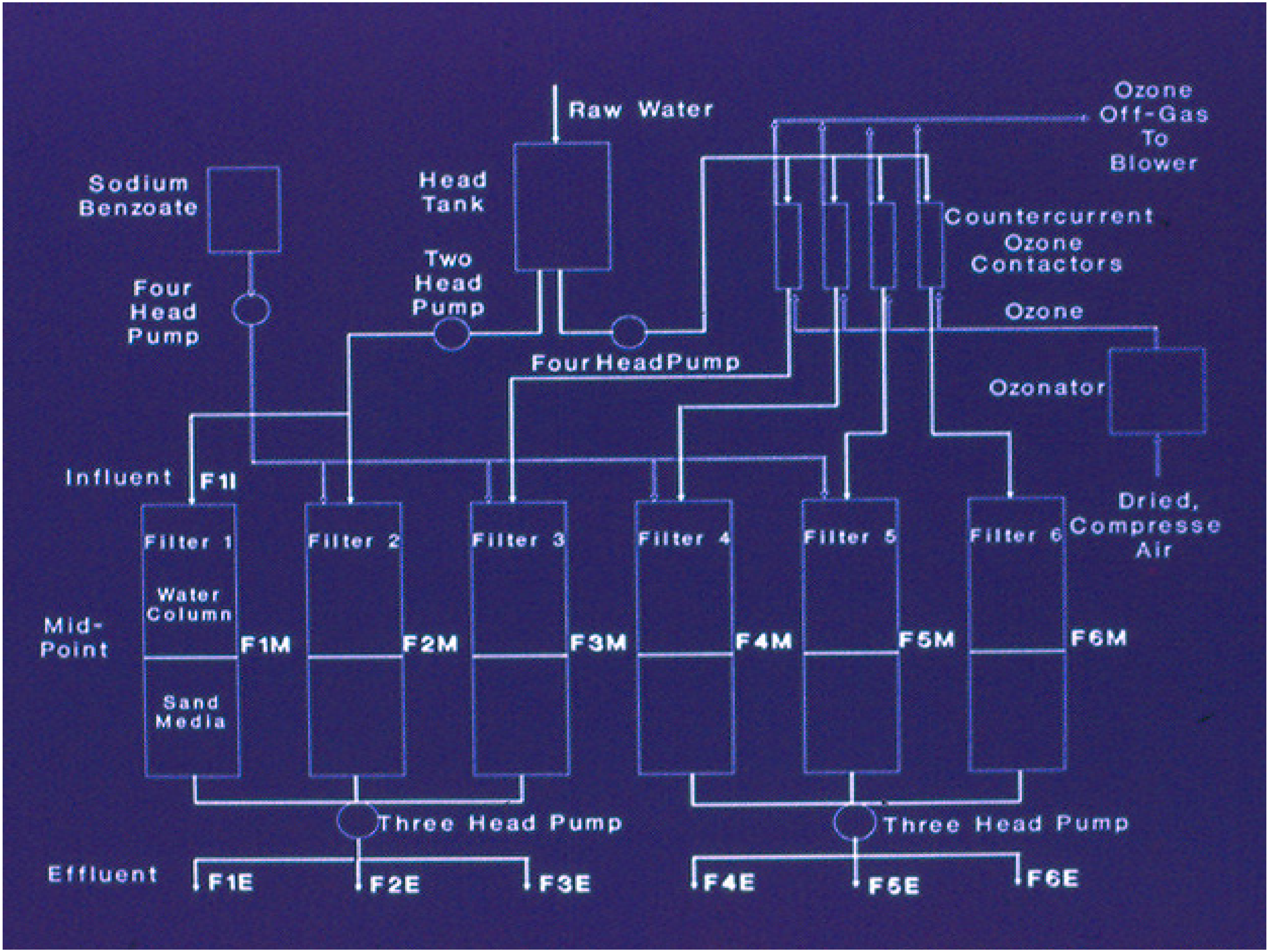
- Initial DOC Concentration & Biodegradability
- Hydraulic Residence/Travel Time
- Aquifer Transmissivity
- Extent of Groundwater Dilution
- Composition of Subsurface Material
- Aerobic vs Anaerobic Subsurface Conditions
- Intermittent vs Continuous Operations

TURBIDITY VALUES
VERSUS TIME

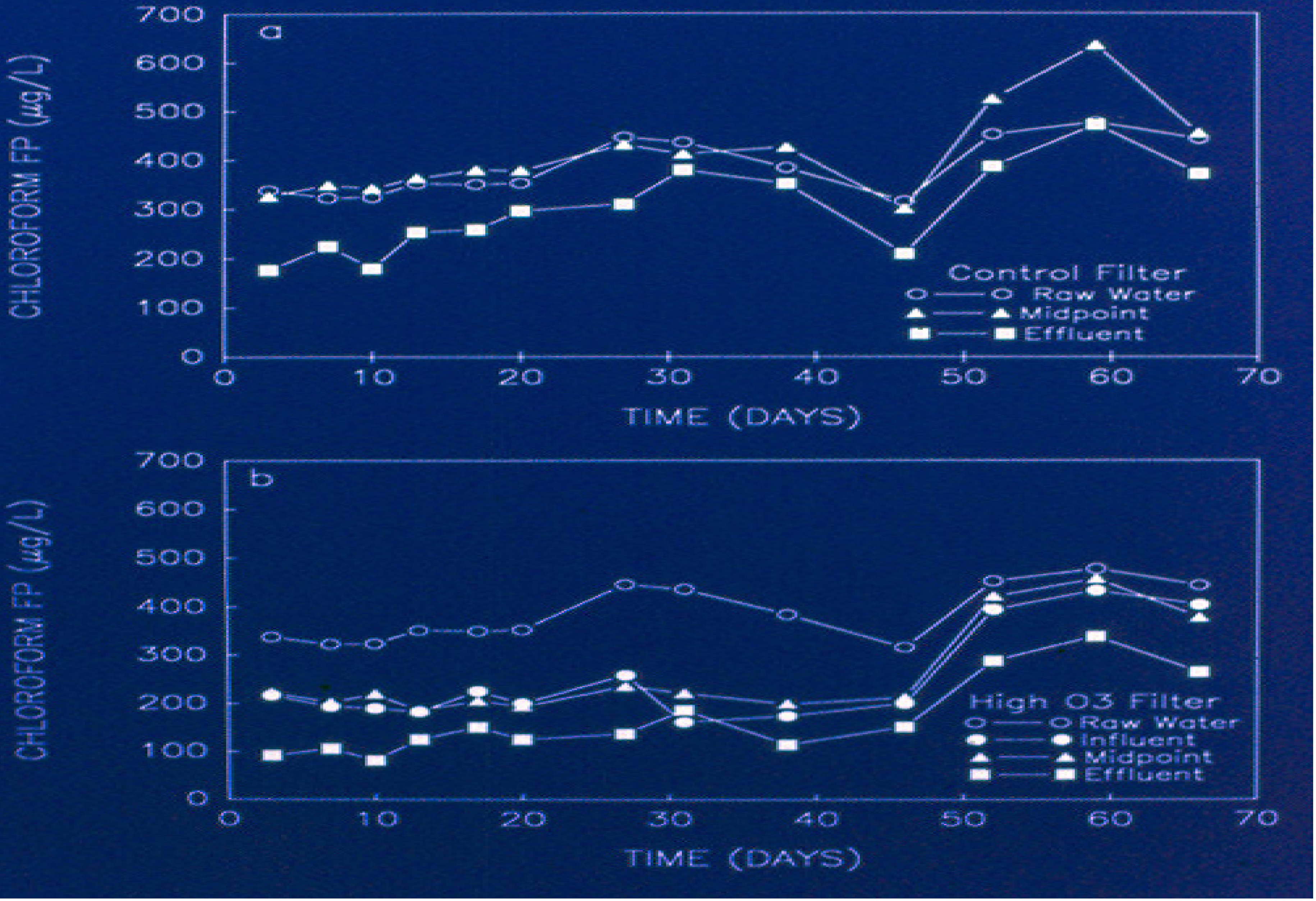
ASHLAND, NH, July 29 to December 8, 1987



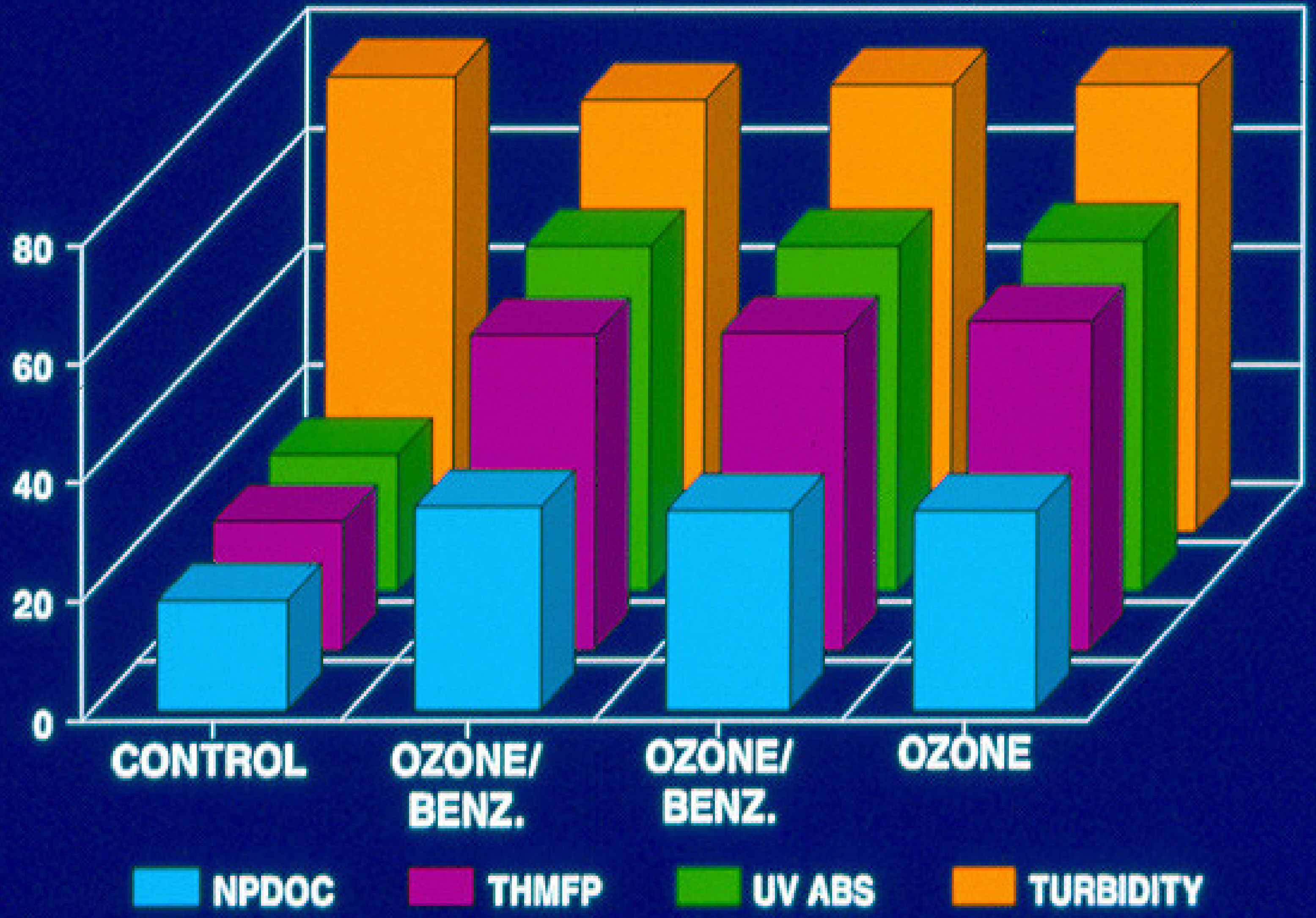

National Bureau of Standards
Washington, D. C. 20234
Filter #3
CONTROL


Raw Water
Ozone Off-Gas To Blower
Sodium Benzoate
Head Tank
Countercurrent Ozone Contactors
Four Head Pump
Two Head Pump
Ozone
Four Head Pump
Ozonator
Influent
F1I
Dried, Compresse Air
Filter 1
Filter 2
Filter 3
Filter 4
Filter 5
Filter 6
Water Column
Mid-Point
F1M
F2M
F3M
F4M
F5M
F6M
Sand Media
Three Head Pump
Three Head Pump
Effluent
F1E
F2E
F3E
F4E
F5E
F6E

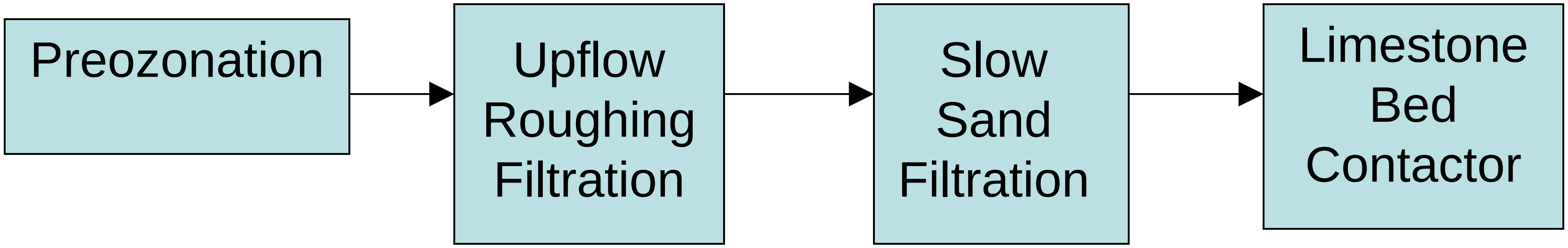
PORTSMOUTH OZONE EFFECTS: THMFP



AVERAGE PERCENT REMOVALS
RUN 2



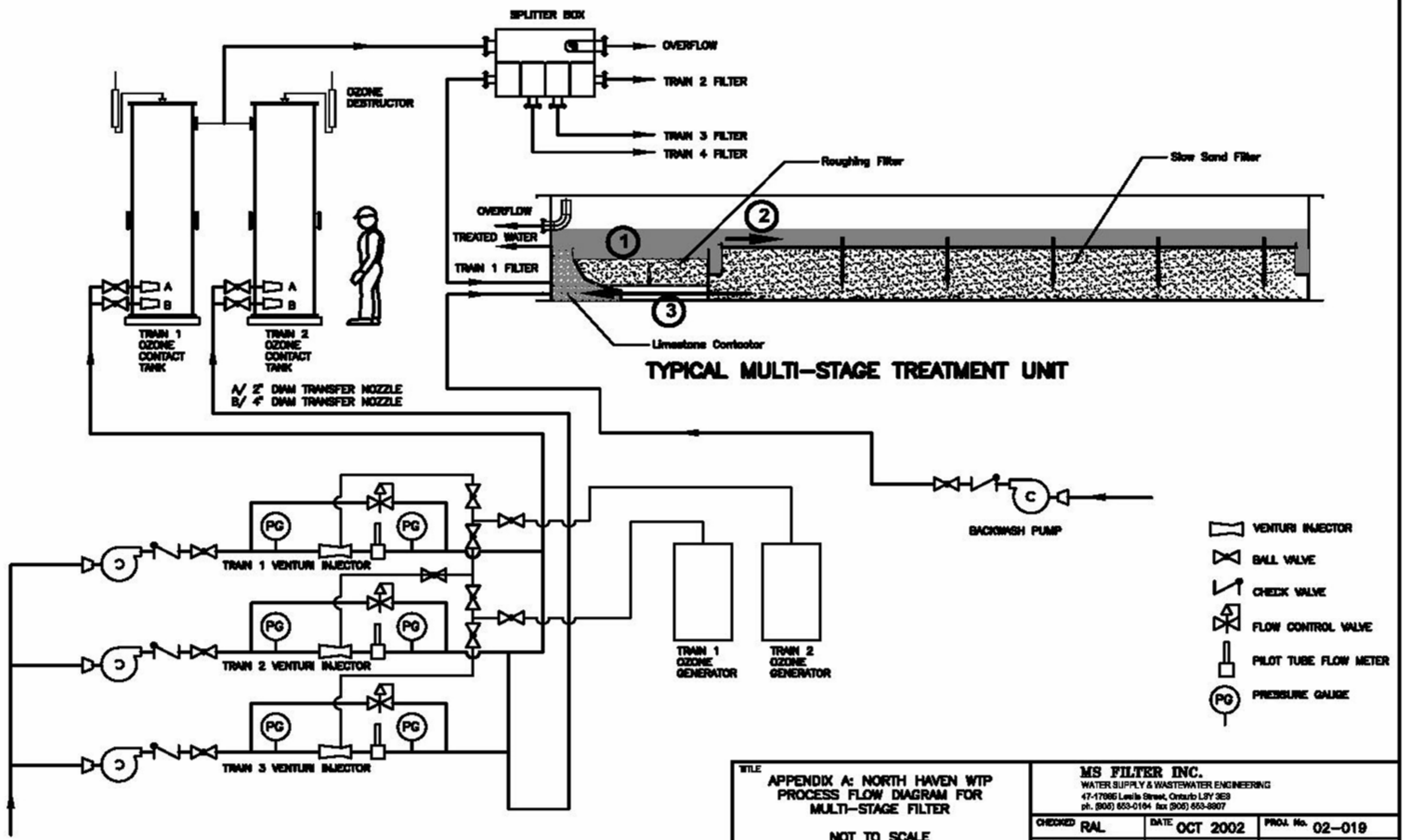
Selected “Multi-stage” Prefabricated Treatment System


Preozonation

Upflow Roughing Filtration

Slow Sand Filtration

Limestone Bed Contactor



TITLE

APPENDIX A: NORTH HAVEN WTP
PROCESS FLOW DIAGRAM FOR
MULTI-STAGE FILTER

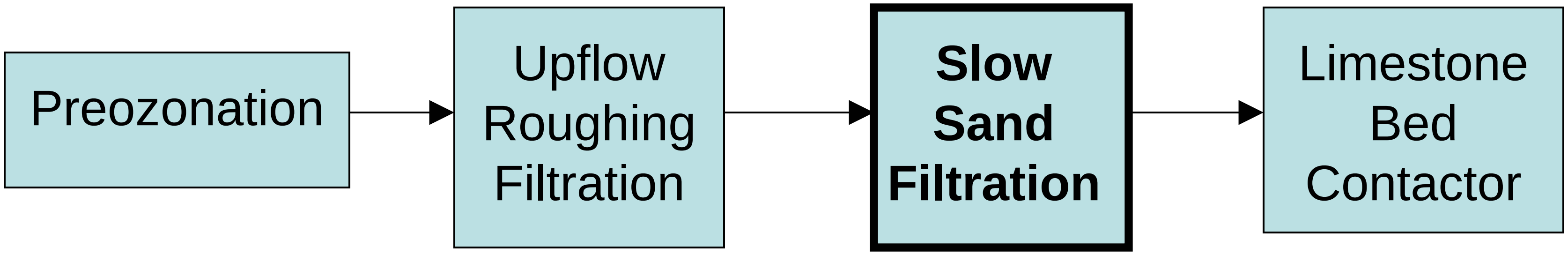
NOT TO SCALE

MS FILTER INC.
WATER SUPPLY & WASTEWATER ENGINEERING
47-17665 Leslie Street, Ontario L3Y 3E3
ph. (905) 853-0164 fax (905) 853-8807

CHECKED RAL	DATE OCT 2002	PROJ. No. 02–019
DRAWN FJA	SCALE NTS	FIGURE No. A1


EXIT

Design Parameters


Preozonation

Upflow Roughing Filtration

Slow Sand Filtration

Limestone Bed Contactor

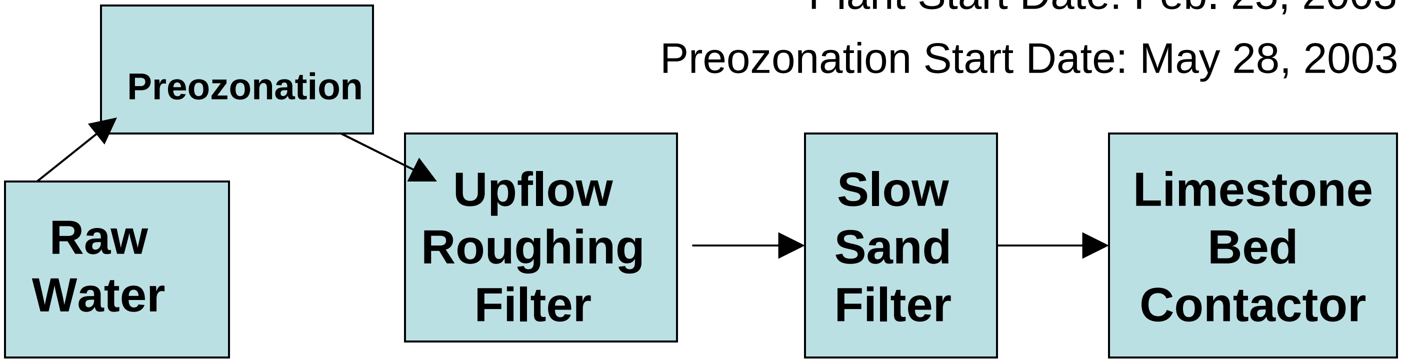
	Peak Day	**Average Summer Day**	**Average Winter Day**
Flow Rate, gpd	250,000	125,000	80,000
Slow sand filtration rate, gpm/ft^2	0.12	0.06	0.04
Slow sand filter empty bed contact time, minutes	324	648	1,010

Operational Summary

(5/28/03 – 6/12/03)

Plant Start Date: Feb. 25, 2003

Preozonation Start Date: May 28, 2003



Preozonation

Raw Water

Upflow Roughing Filter

Slow Sand Filter

Limestone Bed Contactor

Turbidity (NTU)	0.8	0.3	0.2	----
Color (CU)	25	----	5	----
UV Abs. (cm-1)	0.489	0.202	0.187	0.185
TOC (mg/L)	9.89	7.10	6.36	6.27

“NEW” Modifications to SSF

- Replace limestone bed contactor with GAC or anionic resin with separate regeneration system
- Utilize an anionic resin “mat/quilt” on top of limestone bed contactor
- Use iron additions (<0.1ppm) to enhance NOM adsorption by iron-coated sand media

Membrane Filtration (Nanofiltration)

Membrane Process	MWCO (daltons)[a] or Pore Size (μm)[b]	Operating Pressures	Recovery	Trans-membrane Flux	Primary Application
Microfiltration	0.05-5[b]	5 to 30 psi	95 to 98%	100 to 1,000 gfd	Particle Removal Disinfection
Ultrafiltration	1,000-500,000[a]	7 to 60 psi	80 to 95%	20 to 300 gfd	Partical Removal Disinfection
Nanofiltration	200-1,000[a]	50 to 120 psi	70 to 90%	15 to 25 gfd	Softening NOM Removal
Reverse Osmosis	<200[a]	200 to 1,500 psi	50 to 85%	3 to 20 gfd	Desalting, SOC IOC Removal

Membranes for DBP precursor removal

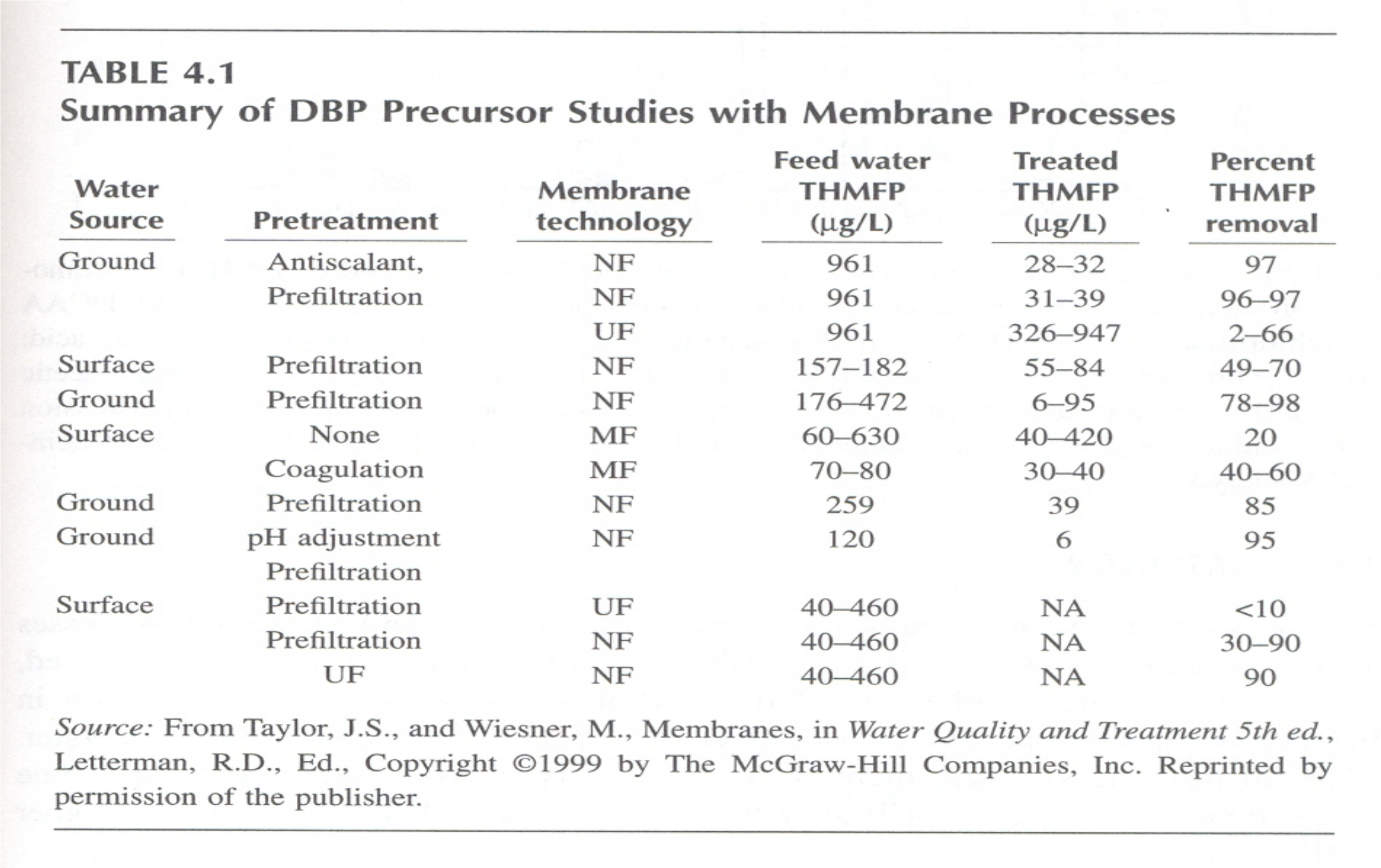


TABLE 4.1
Summary of DBP Precursor Studies with Membrane Processes

Water Source	Pretreatment	Membrane technology	Feed water THMFP (µg/L)	Treated THMFP (µg/L)	Percent THMFP removal
Ground	Antiscalant,	NF	961	28–32	97
	Prefiltration	NF	961	31–39	96–97
		UF	961	326–947	2–66
Surface	Prefiltration	NF	157–182	55–84	49–70
Ground	Prefiltration	NF	176–472	6–95	78–98
Surface	None	MF	60–630	40–420	20
	Coagulation	MF	70–80	30–40	40–60
Ground	Prefiltration	NF	259	39	85
Ground	pH adjustment Prefiltration	NF	120	6	95
Surface	Prefiltration	UF	40–460	NA	<10
	Prefiltration	NF	40–460	NA	30–90
	UF	NF	40–460	NA	90

Source: From Taylor, J.S., and Wiesner, M., Membranes, in *Water Quality and Treatment 5th ed.*, Letterman, R.D., Ed., Copyright ©1999 by The McGraw-Hill Companies, Inc. Reprinted by permission of the publisher.

(Taylor & Wiesner)

Other Approaches to Reducing DBPs in Drinking Water

- Utilize “best” quality source water
  - Multilevel draw-offs from stratified reservoirs
  - Reduce exposure to algal blooms
  - Utilize selective pretreatment options, e.g. riverbank filtration, infiltration galleries, gravel roughing filters

- Minimize the use of chlorine
  - Replace chlorine with other disinfectant(s), e.g. UV+chloramination

- Utilize separate water system for residents close to WTP for CT purposes
- Reduce distribution system residence time from a single chlorination point by using disinfectant booster stations
- Reduce chlorine demand in distribution system by
  - Replacing old water mains
  - Initiating a strong flushing program

General Comparison

	BAC	SSF	RBF	AR/SAT
Turbidity (NTU)	≤ 1 NTU	≤ 1 NTU	≤ 1 NTU	≤ 1 NTU
DOC Removal	≥ 15 %	≥ 10 %	≥ 30 %	≥ 50 %
Biostability: BDOC Removal	50 %	50 %	< MDL	< MDL

General Comparison - cont

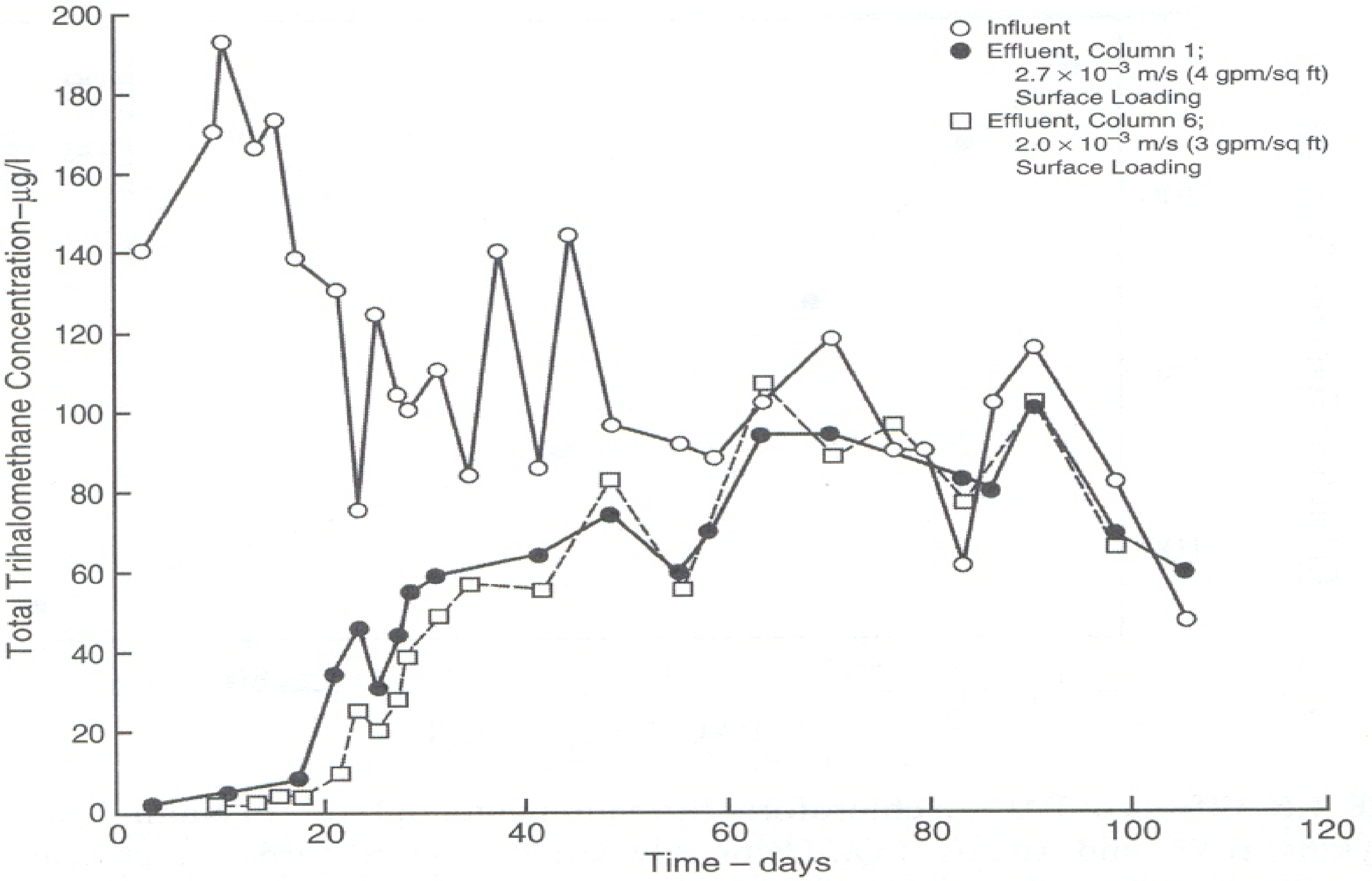
	BAC	SSF	RBF	AR/SAT
Effective Turbidity Removal	✓✓	✓✓	✓✓	✓✓
Effective DOC Removal	✓ (15-35%)	✓ (10-30%)	✓✓ (12-93+%)	✓✓ (10-93+%)
Biostability	✓✓	✓✓	✓✓	✓✓

Biodegradation of Disinfection By-Products

DBP removal

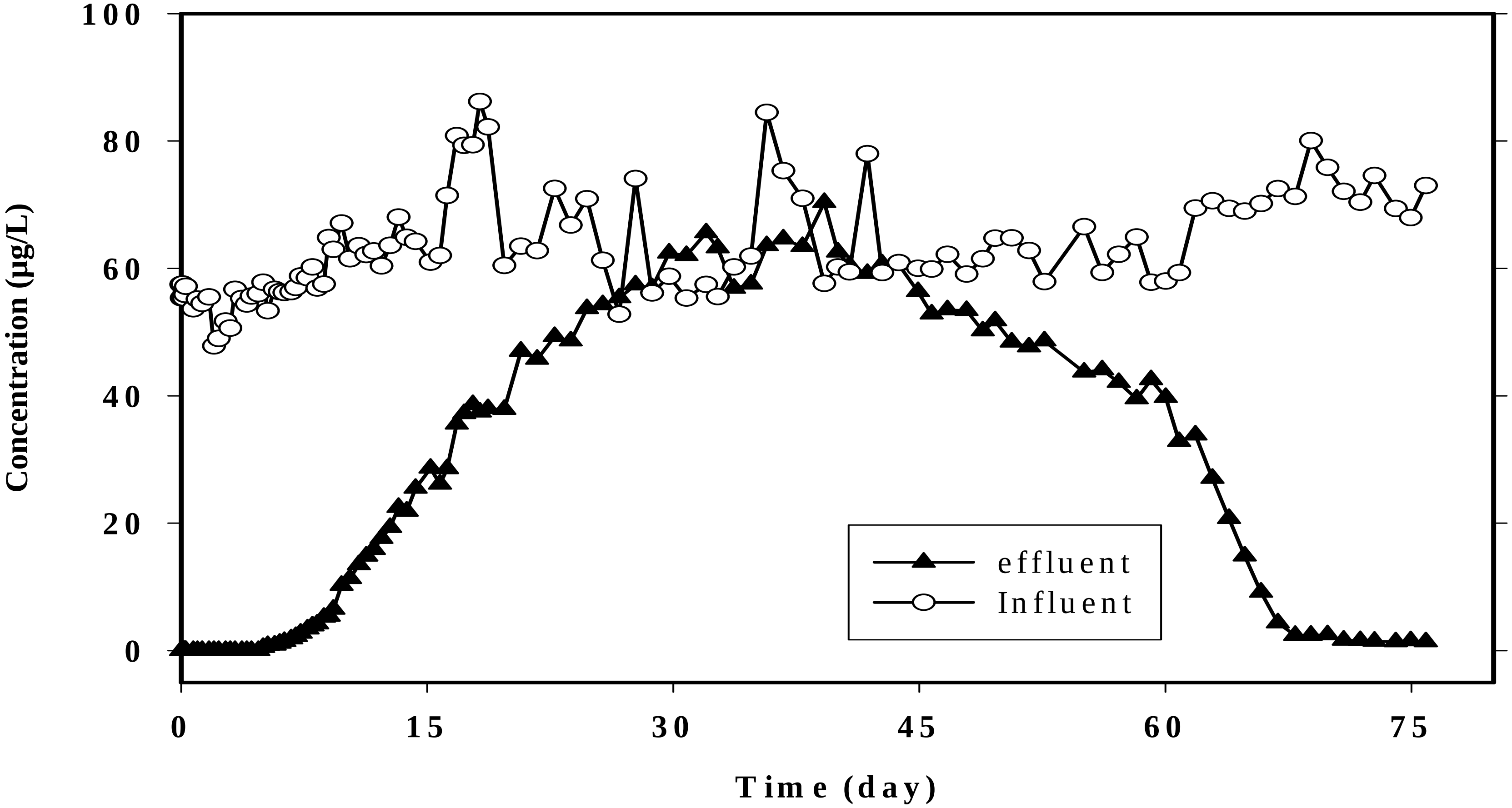
- GAC adsorption
  - Low carbon capacity
- Membranes
  - RO filtration; excellent for HAAs; OK for THMs
- Biofiltration
  - Biologically active carbon; HAAs not THMs
- Aeration
  - THMs, especially chloroform

GAC for THM removal

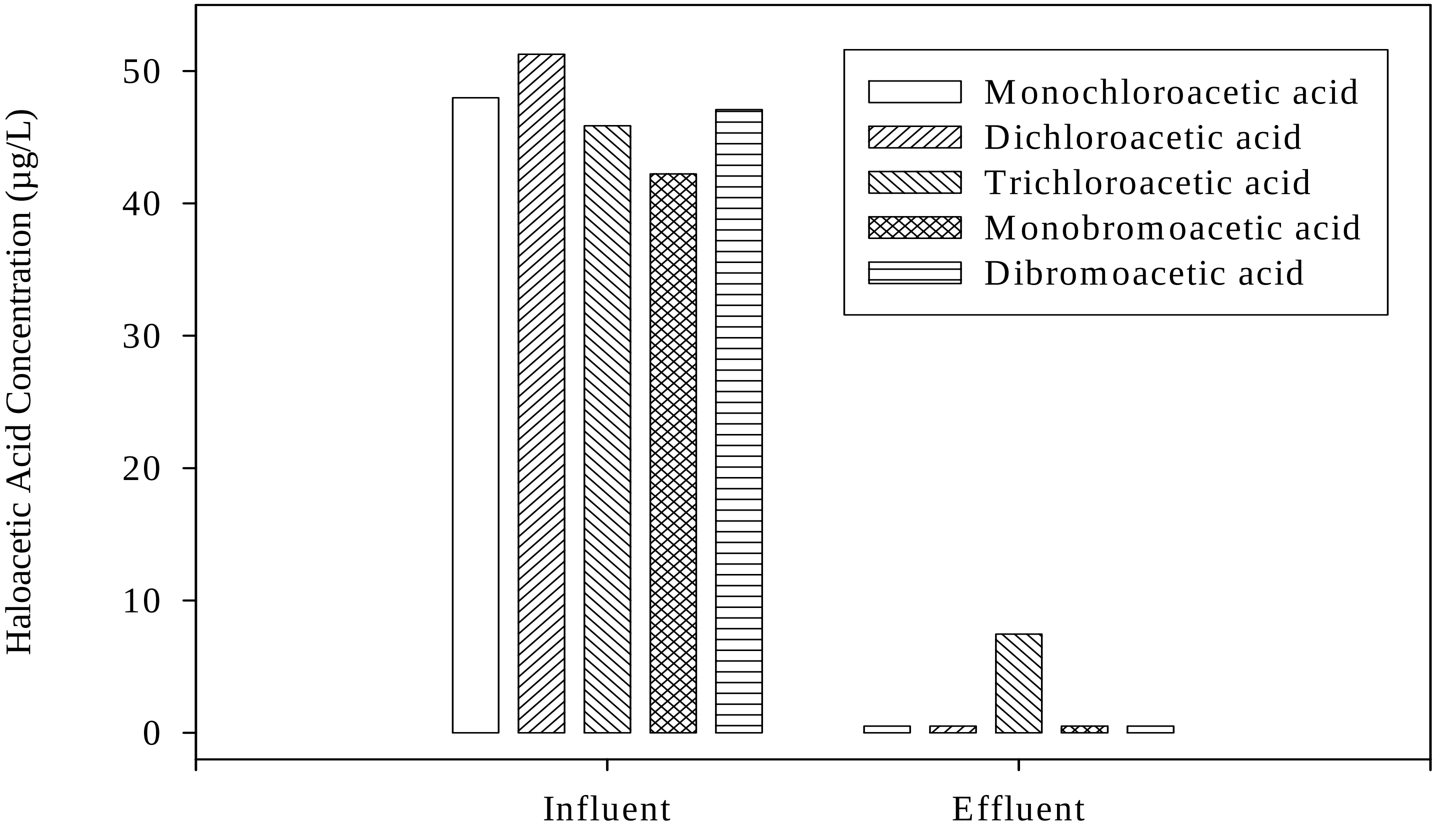


(McGuire & Suffet)

GAC for haloacetic acid removal



BAC filtration on HAAs



BAC filtration on DBPs