Using Riverbank Filtration to Improve Water Quality

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Motivation for Increasing Interest in the U.S.

- Increased regulations on the direct use of surface water. Principal concerns:
  - Disinfection Byproducts (DBPs) (dissolved organic matter in surface waters)
  - *Giardia* and *Cryptosporidium* (resistance to conventional disinfection)
- Potential to reduce treatment costs
- Buffer against spills and terrorist events

Outline

- Site Descriptions
- Part One: Behavior of Natural Organic Matter (NOM) and DBP Precursors during RBF
- Part Two: Behavior of Microorganisms during RBF
- Conclusions

Study Sites

US Rivers
Missouri-American Water at
Parkville, MO (Missouri River)
Indiana-American Water at
Terre Haute, IN (Wabash River)
Indiana-American Water at
Jeffersonville, IN (Ohio River)
W
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S
Key
State
border
River
500 miles
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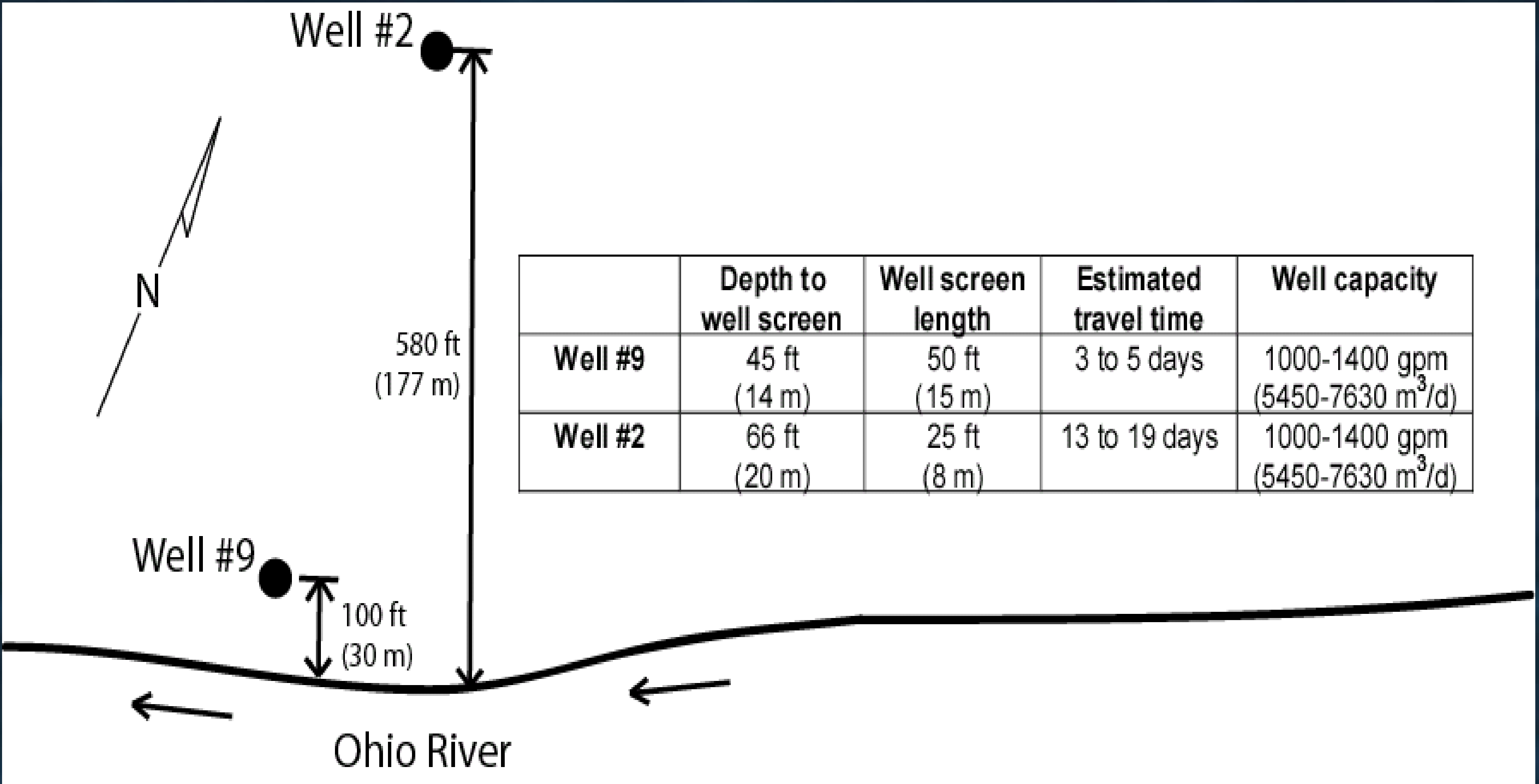
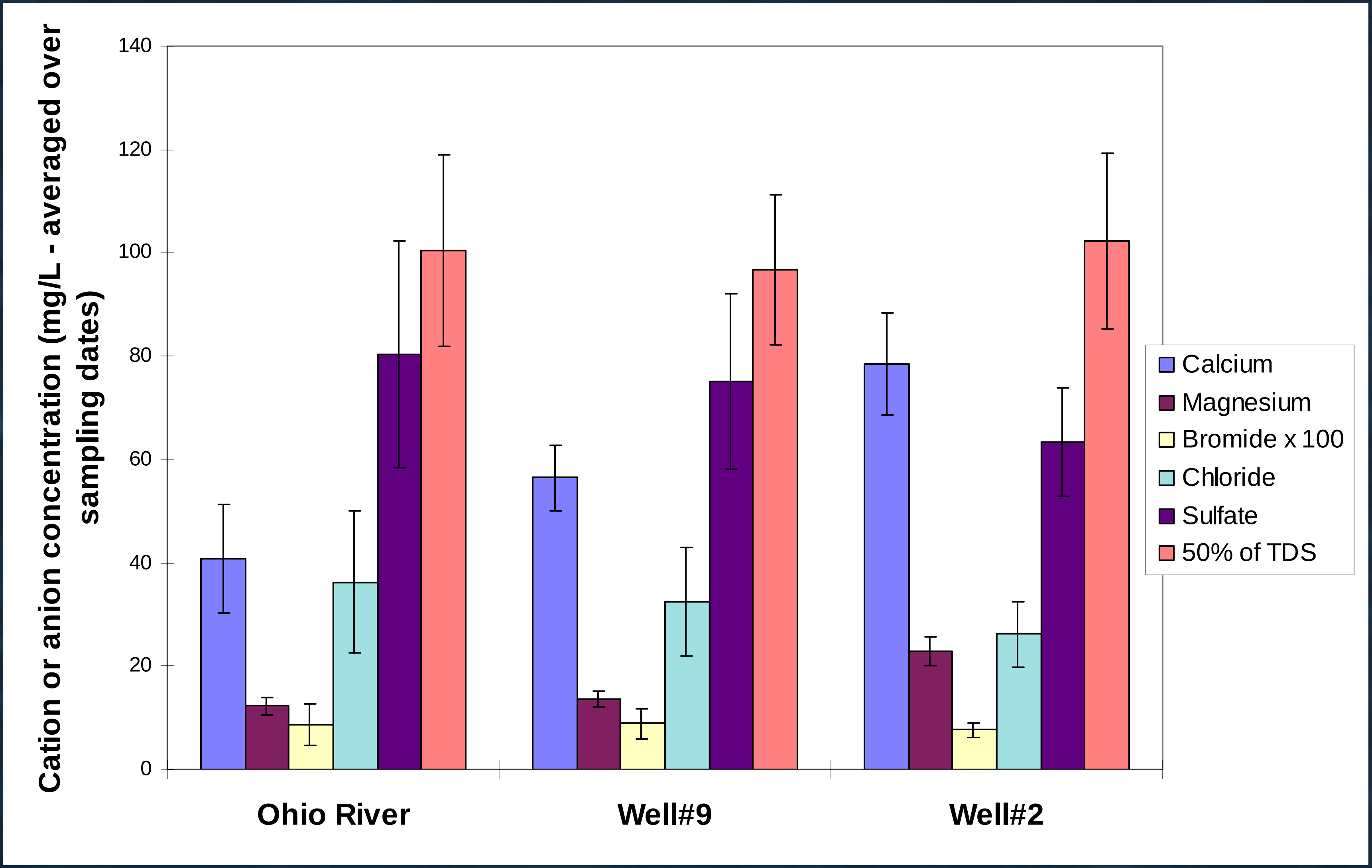
Indiana-American Water at Jeffersonville, IN



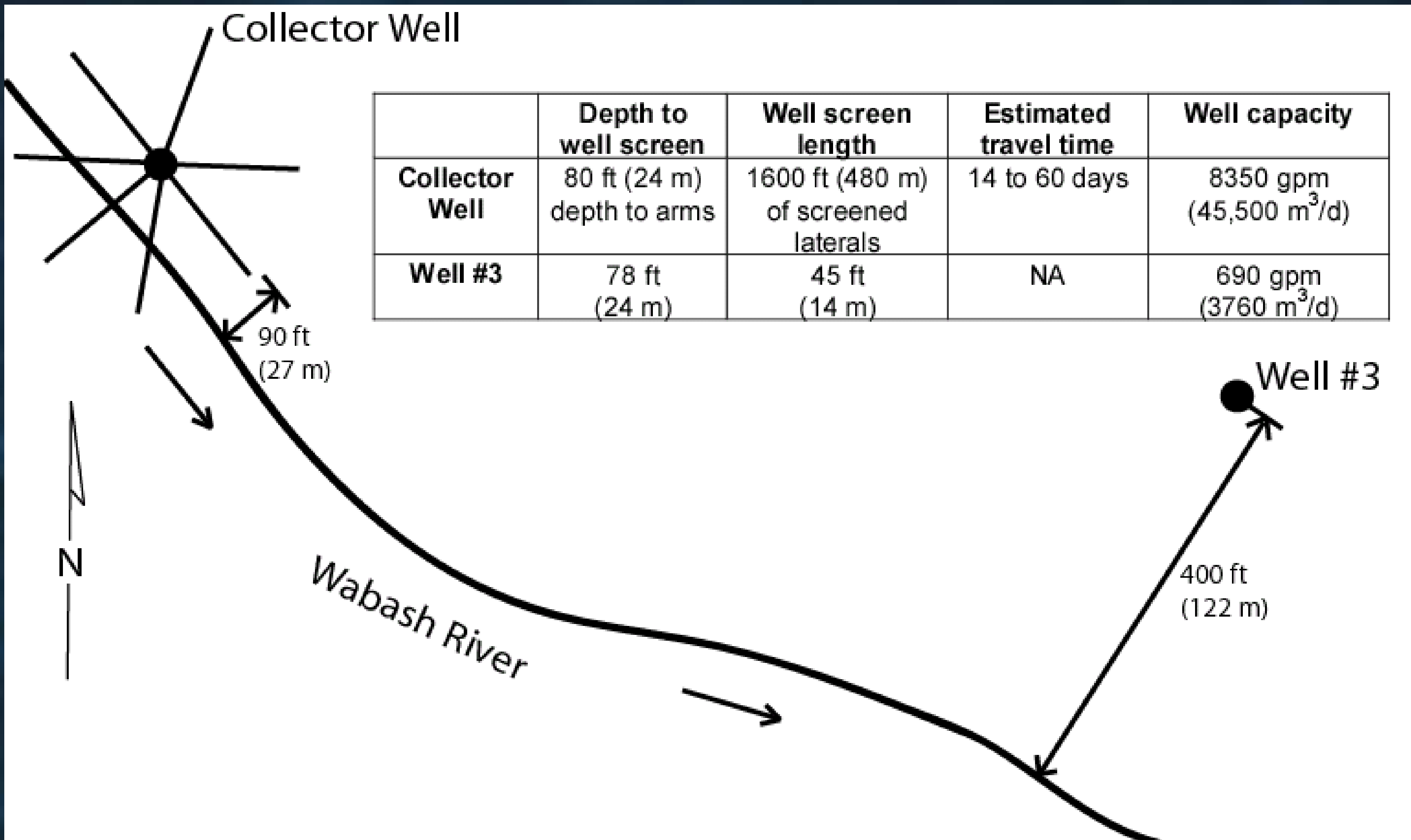
	Depth to well screen	Well screen length	Estimated travel time	Well capacity
Well #9	45 ft (14 m)	50 ft (15 m)	3 to 5 days	1000-1400 gpm (5450-7630 m^3/d)
Well #2	66 ft (20 m)	25 ft (8 m)	13 to 19 days	1000-1400 gpm (5450-7630 m^3/d)

Jeffersonville Inorganics

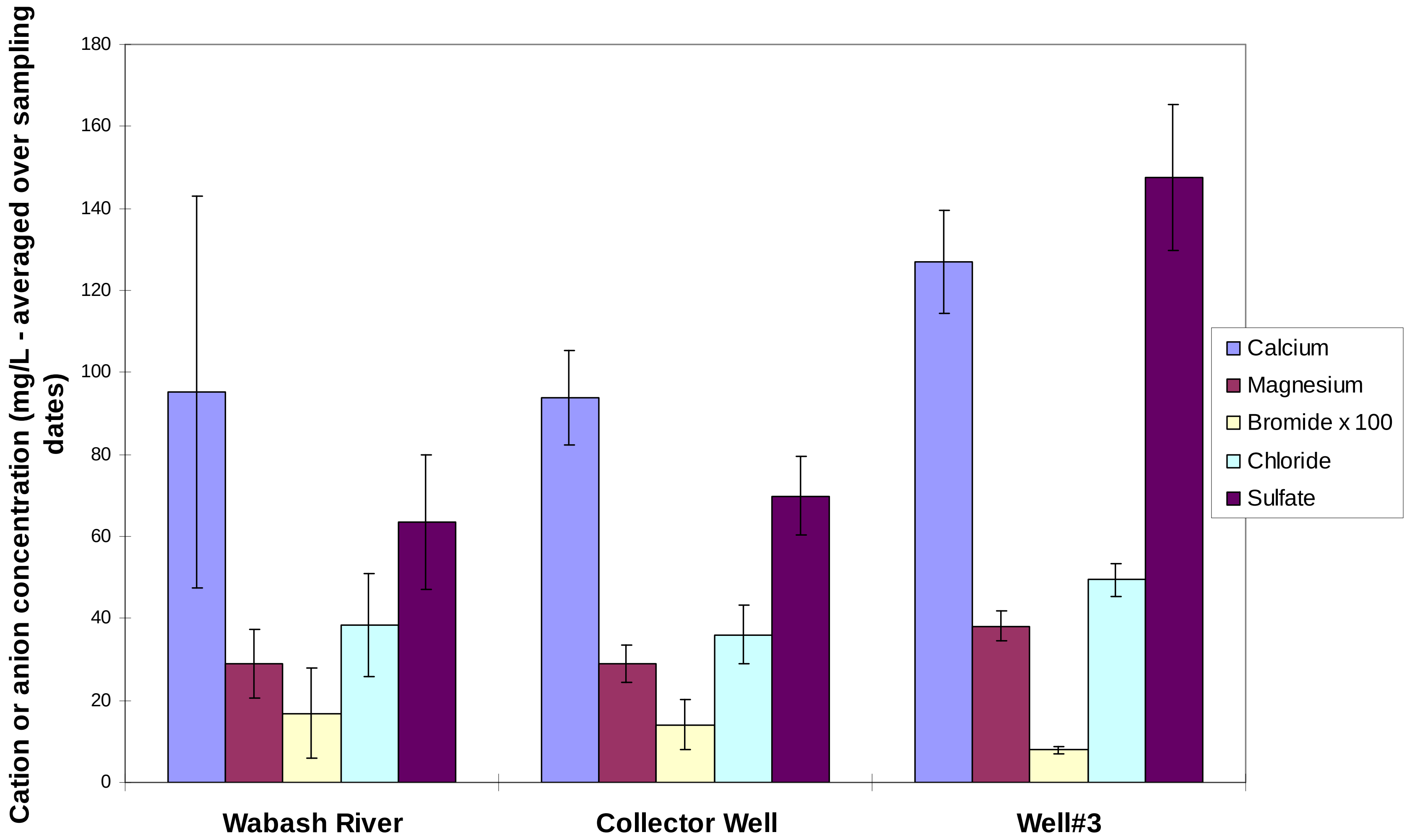


Indiana-American Water at Terre Haute, IN

	Depth to well screen	Well screen length	Estimated travel time	Well capacity
Collector Well	80 ft (24 m) depth to arms	1600 ft (480 m) of screened laterals	14 to 60 days	8350 gpm (45,500 m^3/d)
Well #3	78 ft (24 m)	45 ft (14 m)	NA	690 gpm (3760 m^3/d)

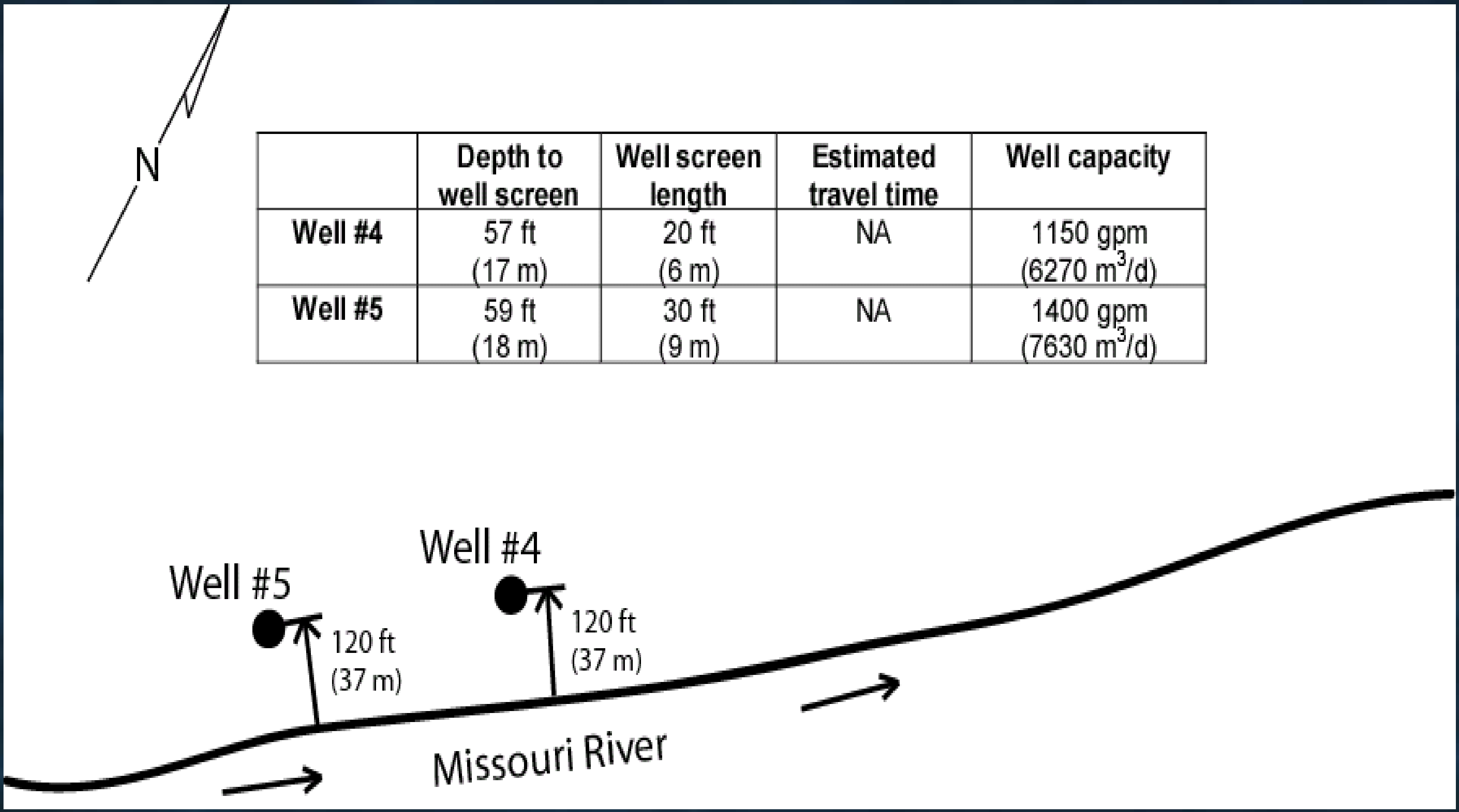


Terre Haute Inorganics

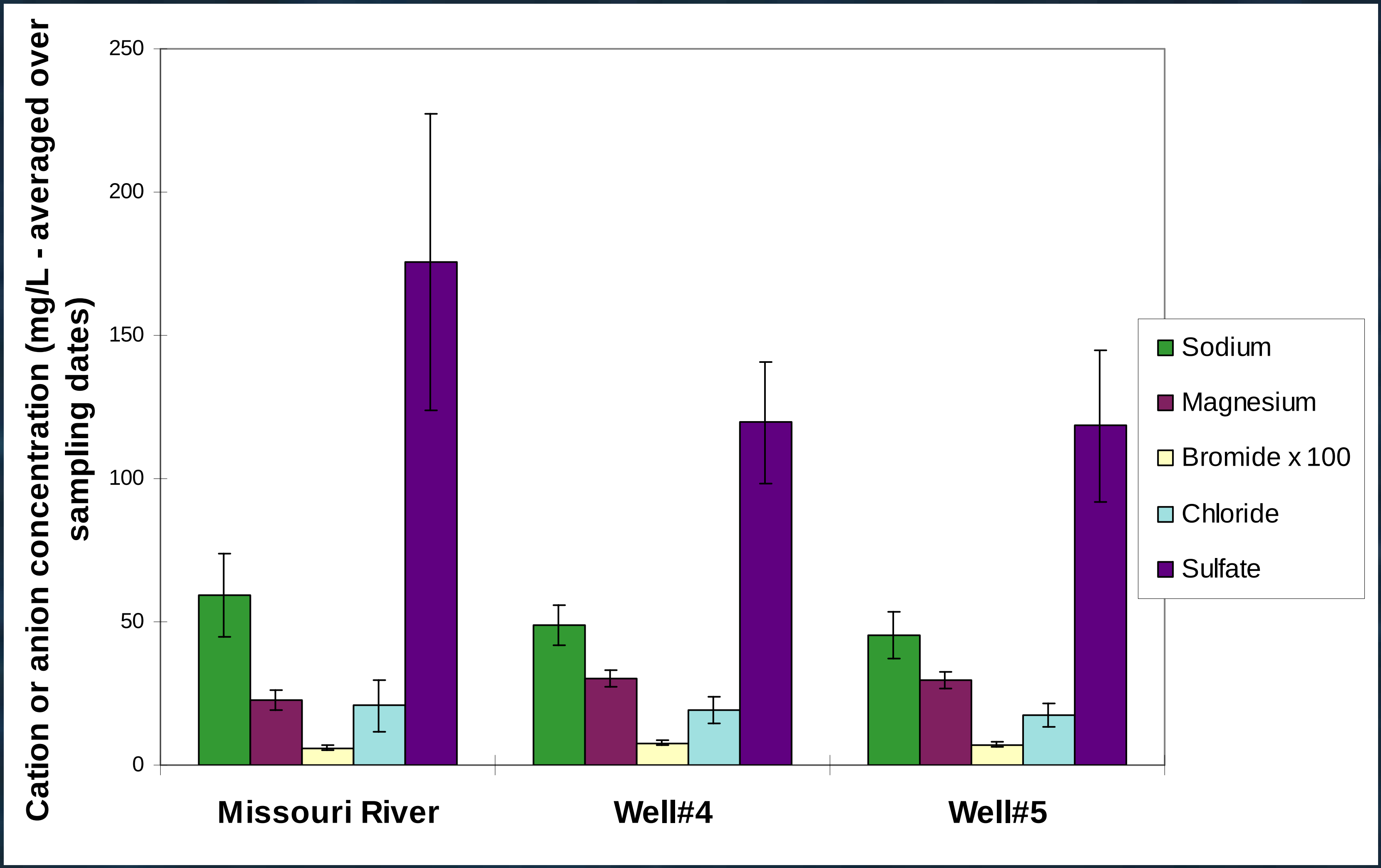


Missouri-American Water at Parkville, MO

	Depth to well screen	Well screen length	Estimated travel time	Well capacity
Well #4	57 ft (17 m)	20 ft (6 m)	NA	1150 gpm (6270 m^3/d)
Well #5	59 ft (18 m)	30 ft (9 m)	NA	1400 gpm (7630 m^3/d)



Parkville Inorganics



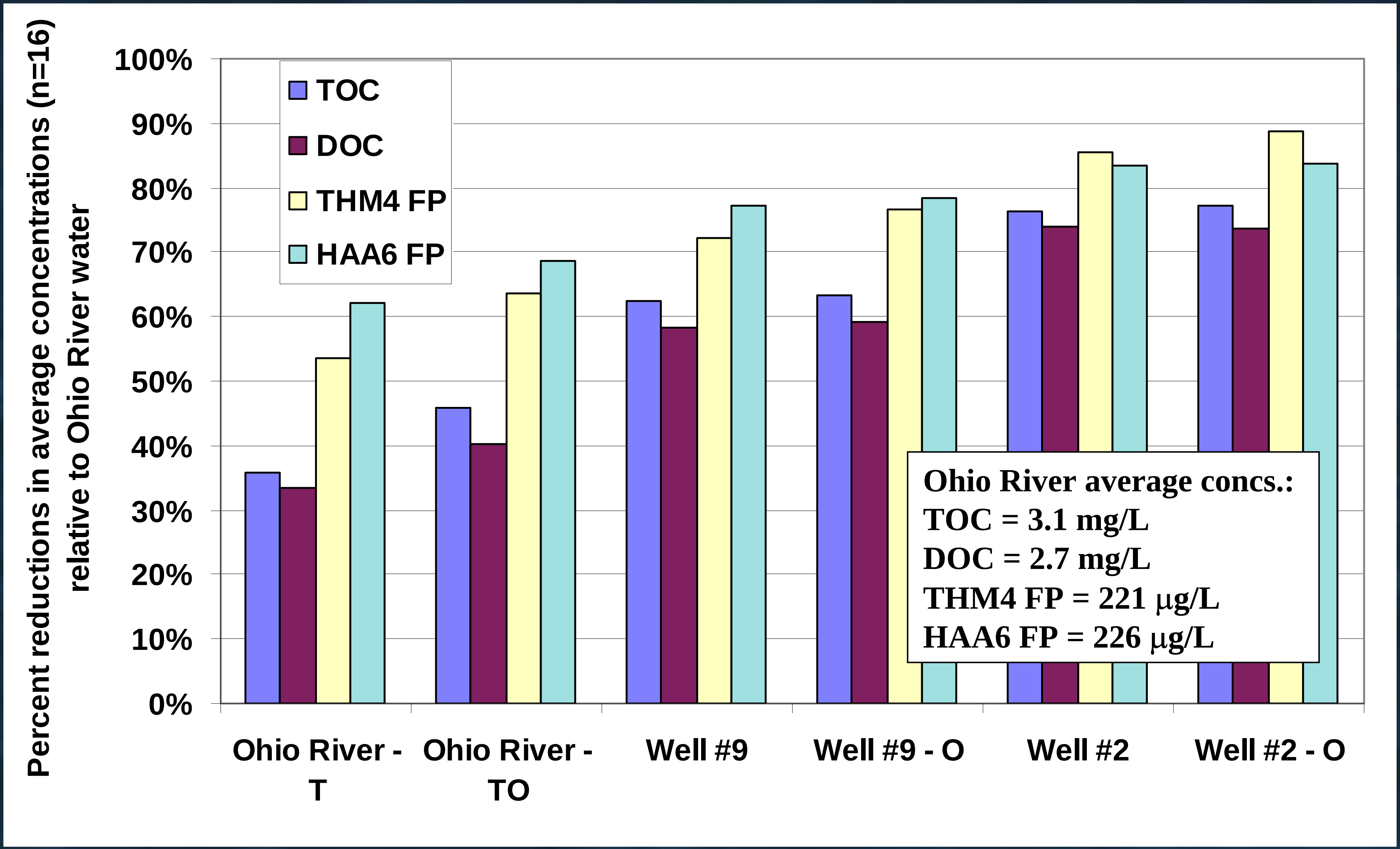
Part One:

Behavior of NOM and DBP Precursors during RBF

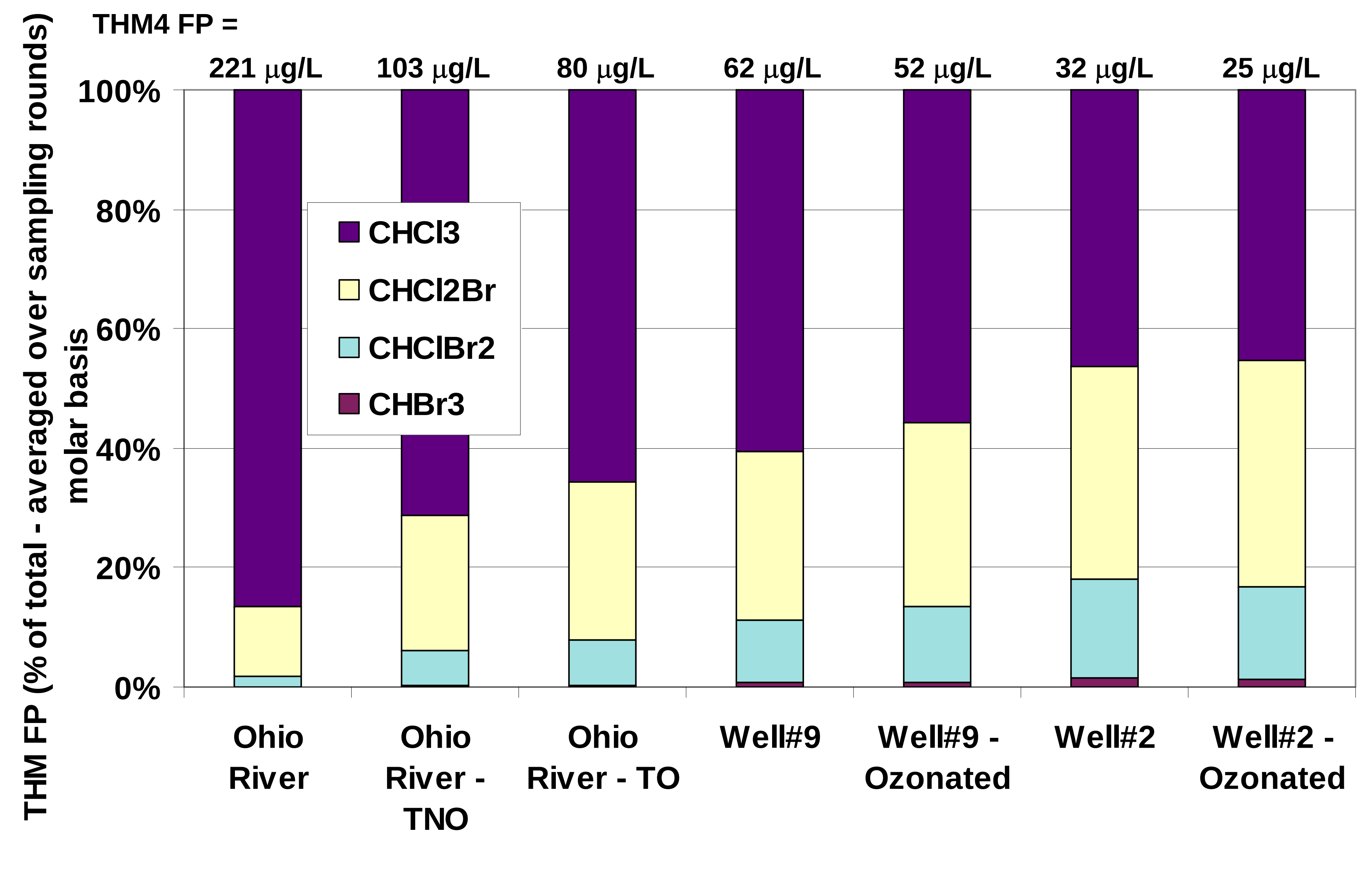
Research Approach

- Monitor performance of 3 different riverbank filtration systems (American Water) with respect to DBP precursors and other water quality parameters
- Compare riverbank filtration with bench-scale conventional treatment trains (coagulation, flocculation, sedimentation, ozonation, and filtration)
- NOM characterization and identification of mechanisms involved in precursor removals

Jeffersonville Reductions Following RBF and Bench-scale Treatment



Jeffersonville THM4 FP Distribution



Results – TOC, DOC, and DBP Formation

- Lower TOC/DOC, THM4 FP, and HAA6 FP with riverbank filtered water
- Shift from chlorinated to brominated DBPs
  - Increased Br/TOC ratio as TOC is removed
  - Brominated compounds have higher associated risk
- THM4 cancer risk calculations indicate reduction in theoretical excess cancer risk upon RBF (higher risk reductions than corresponding bench-scale conventional treatment of river waters)
  - Reduction in risk is not proportional to the reduction in THM4

Results – TOC, DOC, and DBP Formation (cont.)

- Reductions in DBP FPs greater than reductions in TOC
  - Preferential reduction of chlorine-reactive NOM
- Bank filtration provided reductions in TOC, DOC, and DBP precursors greater than or comparable to those achieved following bench-scale conventional treatment
- UFC test results in lower THM4 and HAA6 concentrations, qualitatively similar results
- UFC test results in greater relative amounts of the brominated DBPs

Part One – Conclusions

- RBF as a pretreatment step for DBP control
  - RBF at the three study sites is effective at controlling DBP formation in finished waters by reducing the concentrations of NOM, with a preferential reduction in chlorine-reactive (DBP precursor) material
- RBF performs as well as or better than bench-scale conventional treatment
  - More data are needed comparing RBF with full-scale conventional treatment of the same source water

Part Two:

Behavior of Microorganisms during RBF

Specific Project Goals

- Field studies:
  - Monitor three study sites to evaluate full-scale microbial removal potential of RBF systems
- Column studies with natural riverbank media:
  - Determine the relationship between pathogens and potential surrogate/indicator parameters in RBF-representative systems
  - Evaluate the role of physical and chemical variables (flow rate, pH, ionic strength, organic matter concentration, and microbe size) on pathogen removal and inactivation during flow through riverbank media

Field Monitoring (2002-2003)

- River water samples collected every month from January 2002 through July 2003
- Well water samples collected periodically (closer wells monitored more frequently than distant wells)
- Samples analyzed by personnel at the American Water Belleville laboratory, Belleville, IL

Field Results:
Giardia and *Cryptosporidium*

	Tot Vol. Sampled (L)	*Giardia* Total Counts	*Cryptosporidium* Total Counts
Jeffersonville, IN			
Ohio River	150.76 (n=16)	11	4
Well #9	810 (n=9)	0	0
Well #2	410 (n=5)	0	0
Terre Haute, IN			
Wabash River	117.1 (n=16)	12	2
Collector Well	766 (n=8)	0	0
Well #3	400 (n=4)	0	0
Parkville, MO			
Missouri River	126.91 (n=16)	8	3
Well #4	900 (n=9)	0	0
Well #5	400 (n=4)	0	0

Field Results: Average Conc.

Field monitoring results: January 2002 through July 2003.

	Bacillus **(CFU/L)**	***Clostridium*** **(CFU/L)**	**Total coliforms (MPN/L)**	***E. coli*** **(MPN/L)**
Indiana-American Water Company at Jeffersonville, IN				
Ohio River	8.7×10^4 (n = 17)	7.6×10^2 (n = 17)	1.3×10^6 (n = 18)	1.5×10^4 (n = 18)
Well #9	1.7×10^2 (n = 9)	<0.011 (n = 9)	<5.0 (n = 2)	$<1.0 \times 10^1$ (n = 1)
Well #2	8.0×10^2 (n = 5)	<0.02 (n = 5)	<5.0 (n = 2)	$<1.0 \times 10^1$ (n = 1)
Indiana-American Water Company at Terre Haute, IN				
Wabash River	2.8×10^5 (n = 17)	2.2×10^3 (n = 16)	6.1×10^6 (n = 18)	5.7×10^5 (n = 18)
Collector Well	3.5×10^3 (n = 9)	<0.011 (n = 9)	<5.0 (n = 2)	<5.0 (n = 2)
Well #3	$<2.0 \times 10^2$ (n = 5)	<0.02 (n = 5)	<5.0 (n = 2)	<5.0 (n = 2)
Missouri-American Water Company at Parkville, MO				
Missouri River	4.2×10^5 (n = 17)	8.9×10^2 (n = 17)	6.1×10^5 (n = 17)	3.1×10^4 (n = 17)
Well #4	6.3×10^4 (n = 9)	<0.011 (n = 9)	$<1.0 \times 10^1$ (n = 1)	$<1.0 \times 10^1$ (n = 1)
Well #5	1.1×10^3 (n = 4)	<0.025 (n = 4)	$<1.0 \times 10^1$ (n = 1)	$<1.0 \times 10^1$ (n = 1)

Averages calculated as sum of counts divided by sum of volumes; D.L. calculated as 1 divided by sum of volumes. Number of samples indicated in parentheses.

Field Results: Average Conc. (cont.)

Field monitoring results: January 2002 through July 2003.

	Bacteriophage Male-specific (PFU/L)	Bacteriophage Somatic (PFU/L)	*Cryptosporidium* (oocysts/L)	*Giardia* (cysts/L)
Indiana-American Water Company at Jeffersonville, IN				
Ohio River	4.6×10^{1} (n = 18)	1.7×10^{3} (n = 18)	2.7×10^{-2} (n = 16)	7.3×10^{-2} (n = 16)
Well #9	<1.1 (n = 9)	1.1 (n = 9)	$<1.2 \times 10^{-3}$ (n = 9)	$<1.2 \times 10^{-3}$ (n = 9)
Well #2	<2.0 (n = 5)	<2.0 (n = 5)	$<2.4 \times 10^{-3}$ (n = 5)	$<2.4 \times 10^{-3}$ (n = 5)
Indiana-American Water Company at Terre Haute, IN				
Wabash River	3.6×10^{1} (n = 19)	2.4×10^{3} (n = 19)	1.7×10^{-2} (n = 16)	1.0×10^{-1} (n = 16)
Collector Well	<1.1 (n = 9)	<1.1 (n = 9)	$<1.3 \times 10^{-3}$ (n = 8)	$<1.3 \times 10^{-3}$ (n = 8)
Well #3	<2.0 (n = 5)	<2.0 (n = 5)	$<2.5 \times 10^{-3}$ (n = 4)	$<2.5 \times 10^{-3}$ (n = 4)
Missouri-American Water Company at Parkville, MO				
Missouri River	3.4×10^{1} (n = 18)	2.6×10^{3} (n = 18)	2.4×10^{-2} (n = 16)	6.3×10^{-2} (n = 16)
Well #4	<1.1 (n = 9)	<1.1 (n = 9)	$<1.1 \times 10^{-3}$ (n = 9)	$<1.1 \times 10^{-3}$ (n = 9)
Well #5	<2.5 (n = 4)	<2.5 (n = 4)	$<2.5 \times 10^{-3}$ (n = 4)	$<2.5 \times 10^{-3}$ (n = 4)

Averages calculated as sum of counts divided by sum of volumes; D.L. calculated as 1 divided by sum of the volumes. Number of samples indicated in parentheses.

Field Results:
Log Reductions

Field monitoring results: January 2002 through July 2003.

	Bacillus (CFU/L)	*Clostridium* (CFU/L)	Total coliforms (MPN/L)	*E. coli* (MPN/L)
Indiana-American Water Company at Jeffersonville, IN				
Ohio River	8.7×10^4	7.6×10^2	1.3×10^6	1.5×10^4
Well #9	**2.7**	**>4.8**	**>5.4**	**>3.2**
Well #2	**2.0**	**>4.6**	**>5.4**	**>3.2**
Indiana-American Water Company at Terre Haute, IN				
Wabash River	2.8×10^5	2.2×10^3	6.1×10^6	5.7×10^5
Collector Well	**1.9**	**>5.3**	**>6.1**	**>5.1**
Well #3	**>3.2**	**>5.0**	**>6.1**	**>5.1**
Missouri-American Water Company at Parkville, MO				
Missouri River	4.2×10^5	8.9×10^2	6.1×10^5	3.1×10^4
Well #4	**0.8**	**>4.9**	**>4.8**	**>3.5**
Well #5	**2.6**	**>4.6**	**>4.8**	**>3.5**

Log removals calculated using the average concentrations (determined as sum of counts divided by the sum of volumes sampled; Ò>Óindicates log removal calculated for well water at the detection limit).

Field Results:
Log Reductions (cont.)

Field monitoring results: January 2002 through July 2003.

	Bacterio-phage Male-Specific (PFU/L)	**Bacterio-phage Somatic (PFU/L)**	***Crypto-sporidium* (oocysts/L)**	***Giardia* (cysts/L)**
Indiana-American Water Company at Jeffersonville, IN				
Ohio River	4.6×10^{1}	1.7×10^{3}	2.7×10^{-2}	7.3×10^{-2}
Well #9	**>1.6**	**3.2**	**>1.3**	**>1.8**
Well #2	**>1.4**	**>2.9**	**>1.0**	**>1.5**
Indiana-American Water Company at Terre Haute, IN				
Wabash River	3.6×10^{1}	2.4×10^{3}	1.7×10^{-2}	1.0×10^{-1}
Collector Well	**>1.5**	**>3.3**	**>1.1**	**>1.9**
Well #3	**>1.3**	**>3.1**	**>0.8**	**>1.6**
Missouri-American Water Company at Parkville, MO				
Missouri River	3.4×10^{1}	2.6×10^{3}	2.4×10^{-2}	6.3×10^{-2}
Well #4	**>1.5**	**>3.4**	**>1.3**	**>1.8**
Well #5	**>1.1**	**>3.0**	**>1.0**	**>1.4**

Log removals calculated using the average concentrations (determined as sum of counts divided by the sum of volumes sampled; Ò>Óindicates log removal calculated for well water at the detection limit).

Column Studies

- Columns constructed with sediment collected from the Potomac River in western Maryland (representative system – large, slow-moving river)
- Buffer solutions containing mixtures of microorganisms passed through columns
- Study the relationship between pathogens and potential surrogates upon transport through columns under different physical/chemical conditions
- Variables include flow rate, ionic strength, pH, NOM concentration
- Perturbation studies – simulate flooding and increased pumping events

Microbes and Surrogates

- Viruses:
  - Bacteriophage: MS2 and PRD1
  - Polio virus
- Bacteria: *E. coli* CN13, coliforms, *Bacillus* (aerobic spores), *Clostridium* (anaerobic spores)
- Protozoans: *Cryptosporidium parvum* and *Giardia lamblia*
- Potential surrogate/indicator parameters:
  - Particle counts (latex microspheres and natural river water particles)
  - Turbidity – useful to signal breakthrough in treatment, but probably not a good (quantitative) surrogate

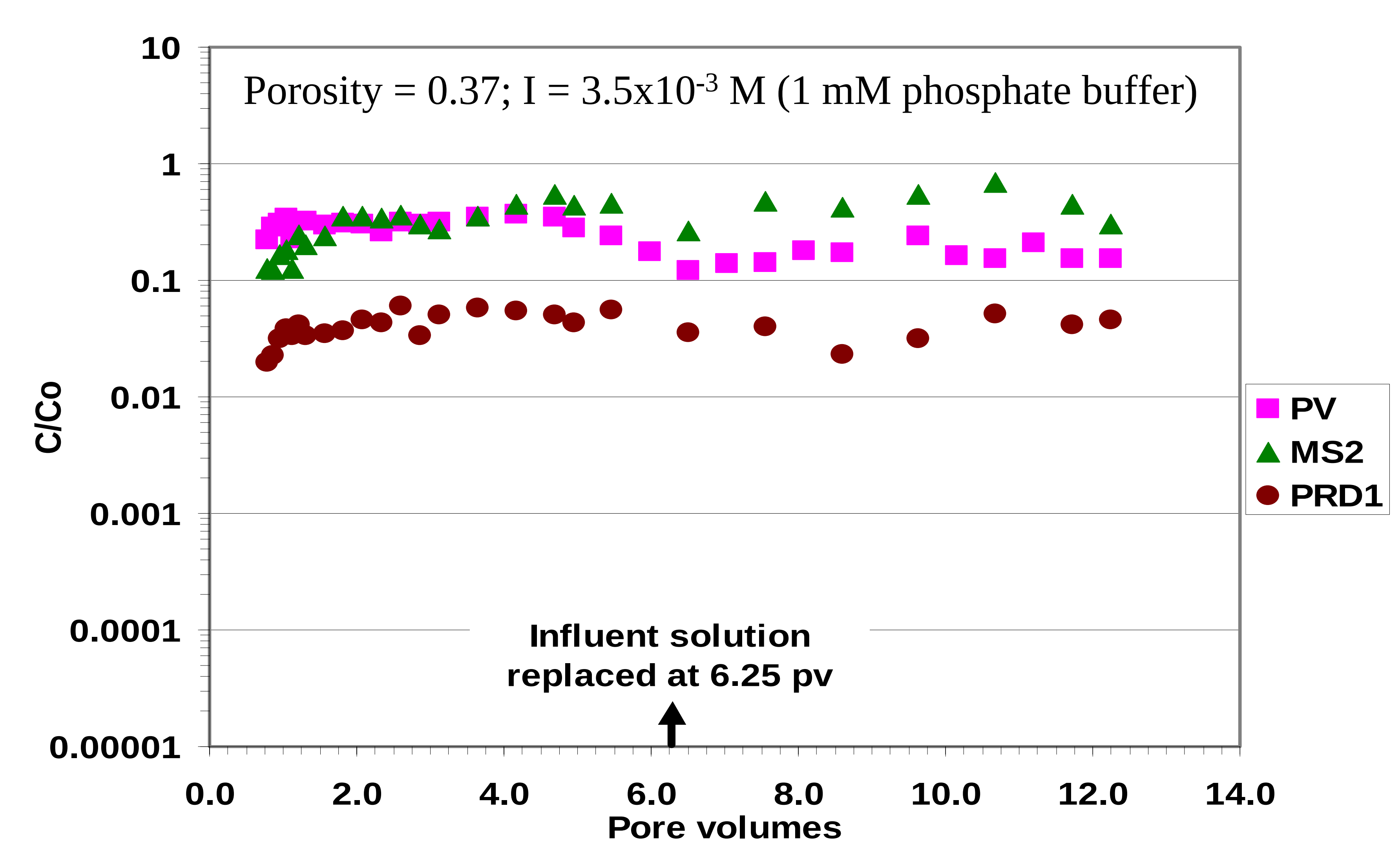
Riverbank Media

- Sediment collected from the Potomac River in western Maryland as "representative" river system
- Sediment was dried in batches in low-heat oven (~80^{o}F)
- Dried sediment was quartered into successively smaller batches
- Ultra-fine (<0.106 μm) and coarse (>1.70 mm) material was sieved out (coating of fine "dust" was not rinsed off)
- No additional treatment/cleaning of sediment was performed
- d_{10} = 0.039 mm
- d_{60} = 0.20 mm

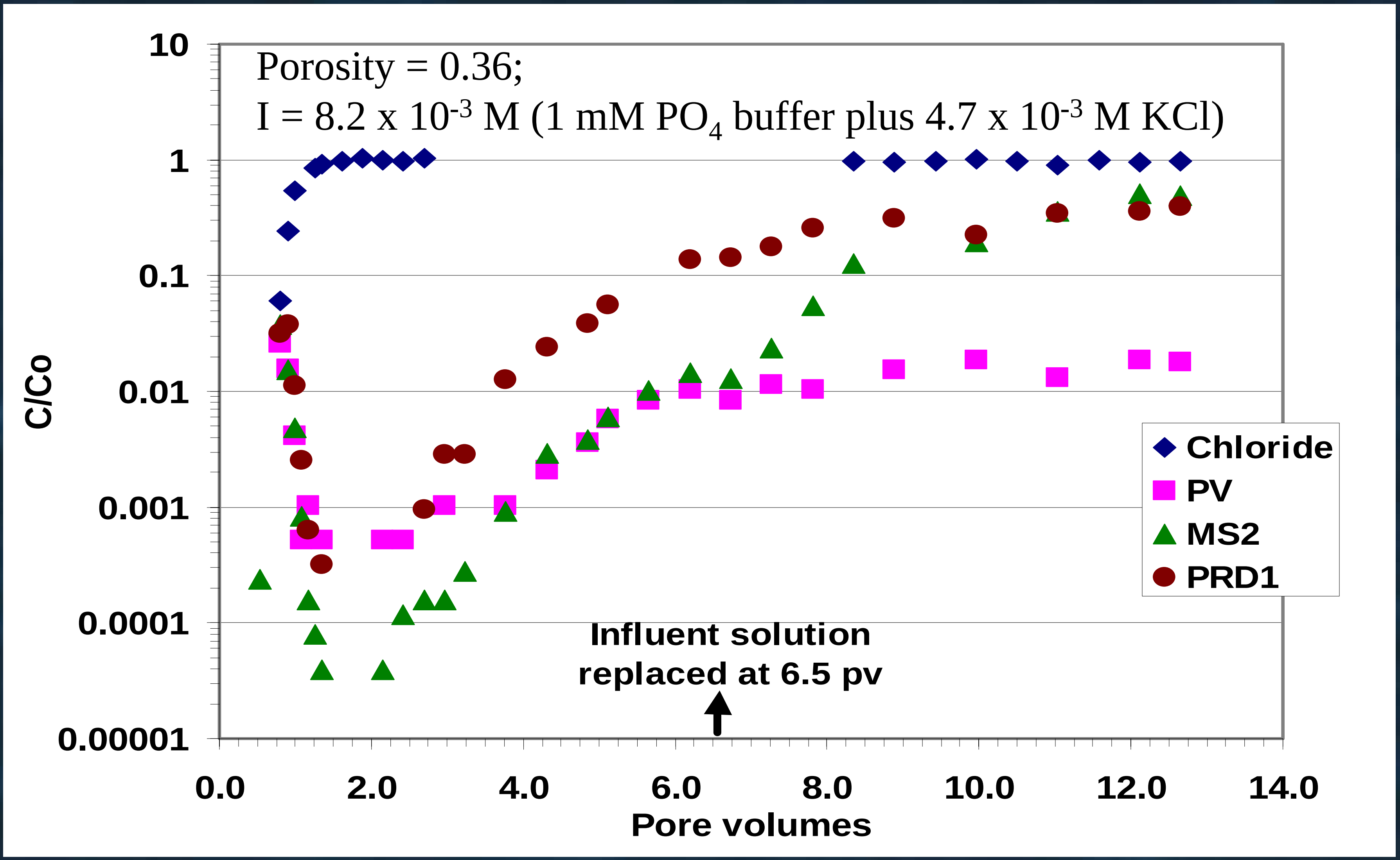
Columns

- Size – 30-cm length, 2.5-cm diameter
- Columns packed with dry sediment, filled with CO_2, then flushed with 1-mM phosphate buffer solution for approximately 10 pore volumes prior to run
- New column used for each experiment
- Base condition – 1 mM phosphate buffer solution (pH = 7; I = 3.5×10^{-3} M) spiked with microorganisms

Column Results – Viruses



Column Results – Viruses (cont.)



Part Two – Preliminary Conclusions and Future Work

- From field-scale results, RBF shows promise as a significant barrier for pathogen transport
- Column studies – Bacteriophage MS2 potentially useful as a conservative indicator for polio virus (this is consistent with Schijven et al., 2003)
  - MS2 also proposed as a “quality-control” parameter for future column studies
- Further research will use column studies to elucidate the relationship between pathogen and surrogate transport in RBF systems and evaluate the effects of certain variables (flow velocity, pH, ionic strength, NOM concentration, temperature) on pathogen transport

Results – BDOC, AOC, SUVA

	BDOC (mg/L) (n=7)	AOC (mg/L) (n=7)	SUVA (L/mg-m) (n=14-17)
Jeffersonville			
Ohio River	0.38 ± 0.17	0.061 ± 0.028	2.7 ± 1.2
Well #9	0.043 ± 0.024 [89%][1]	0.032 ± 0.014 [48%][1]	2.0 ± 0.7 [26%][1]
Well #2	0.025 ± 0.072 [93%][1]	0.021 ± 0.005 [66%][1]	1.7 ± 0.8 [37%][1]
Terre Haute			
Wabash River	0.90 ± 0.59	0.19 ± 0.095	2.7 ± 0.8
Collector Well	0.18 ± 0.19 [80%][1]	0.028 ± 0.011 [85%][1]	2.6 ± 0.8 [4%]
Well #3	0.092 ± 0.22 [90%][1]	0.021 ± 0.013 [89%][1]	2.0 ± 1.5 [26%]
Parkville			
Missouri River	0.41 ± 0.29	0.25 ± 0.093	2.3 ± 1.1
Well #4	0.29 ± 0.22 [29%]	0.25 ± 0.15 [0%]	2.7 ± 1.5 [-17%]
Well #5	0.25 ± 0.19 [39%]	0.21 ± 0.11 [16%]	2.8 ± 2.0 [-22%]

[1]Differences significant at 95% or higher confidence interval.