Influence of Coagulation Conditions on Particle Size Distributions and Floc Morphology

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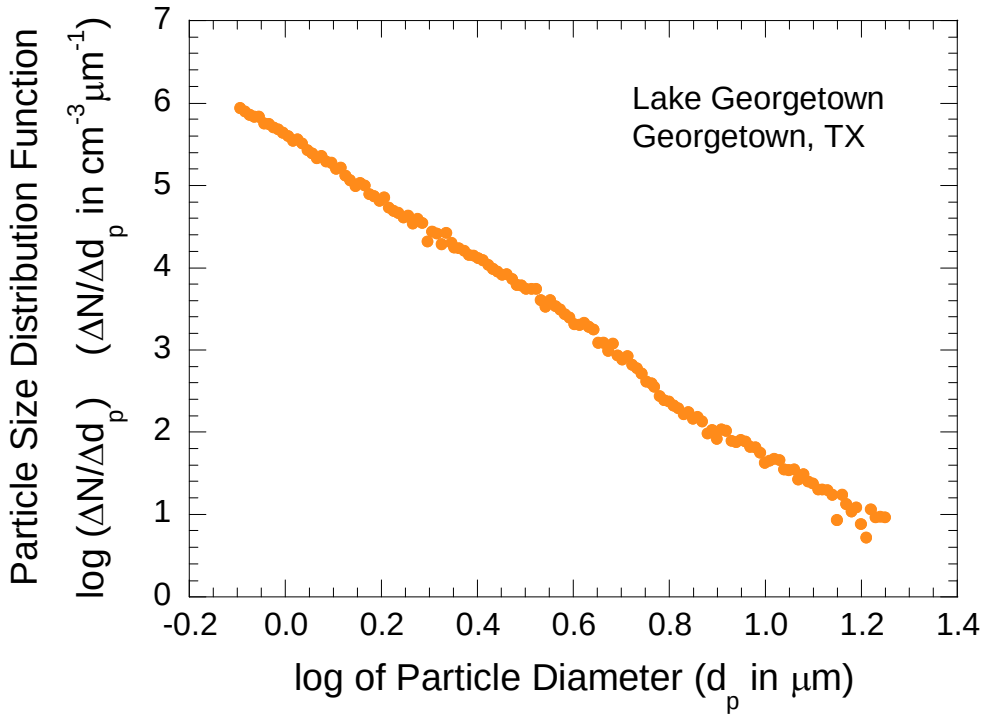
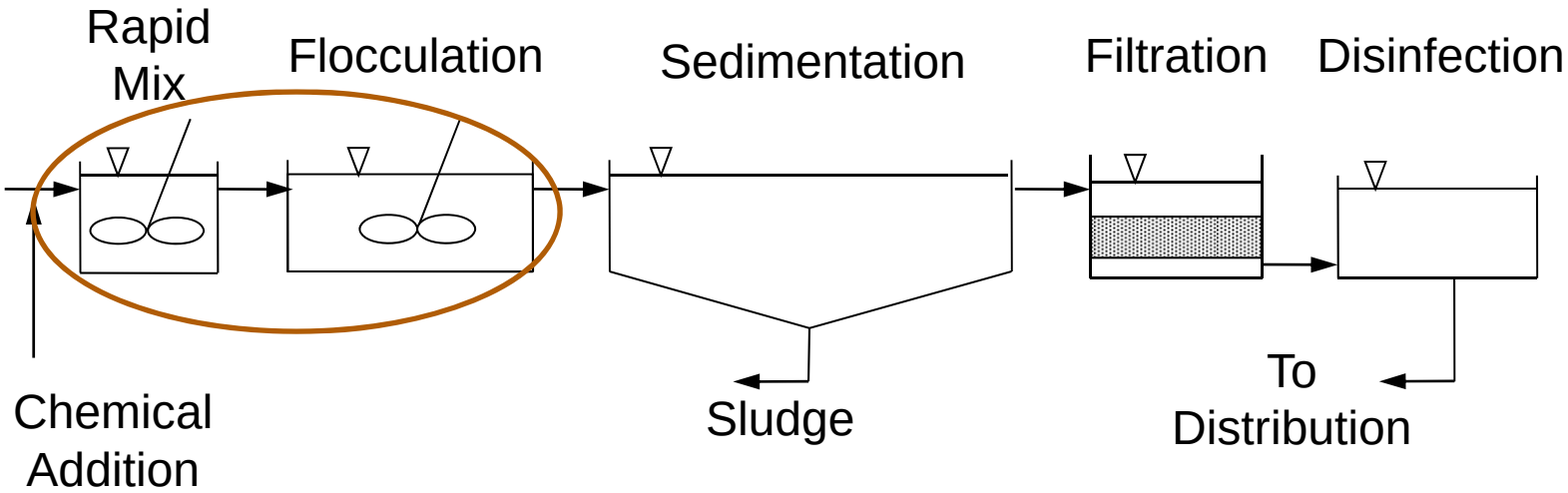
Particle Size Distributions

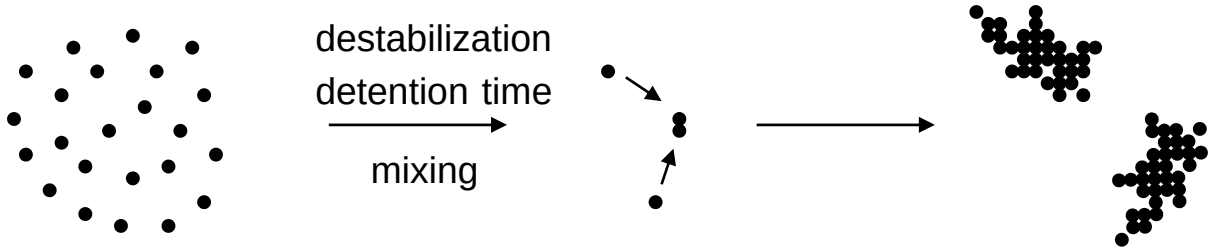
- Typical particle suspensions contain particles from nm to mm in size



Particle Size Distributions

- A primary determinant of removal efficiency
- We can control to a certain degree through coagulation pre-treatment





Motivation

- As we strive to achieve greater efficiency in terms of contaminant removal, energy usage, cost and use of resources **we must take a more holistic and systems approach to designing and operating water treatment facilities**

- Gaining a fundamental and quantitative understanding of how particle size distributions and floc morphology influence treatment process efficiency is critical to this aim.

Example: Coagulation Pre-treatment for Low Pressure Membranes

Background

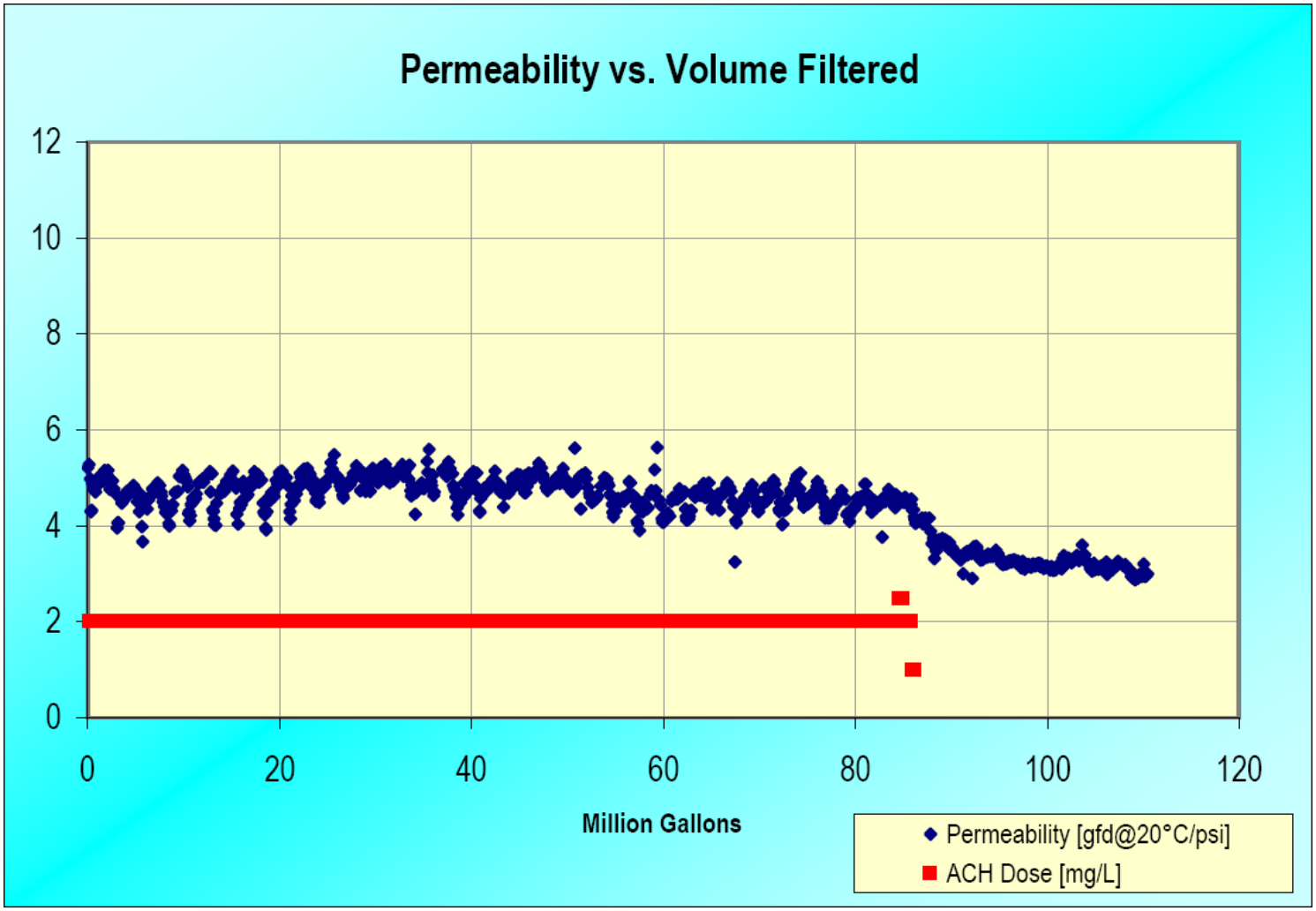
- Low-pressure membranes are increasingly replacing and/or supplementing conventional particle separation processes
  - Physical barrier to particles/pathogens
  - Small footprint
  - Improved materials/lower capital cost
  - Reliability

- Fouling
  - Particulate – deposition of a cake layer on the membrane surface
  - NOM – deposition in pores of the membrane

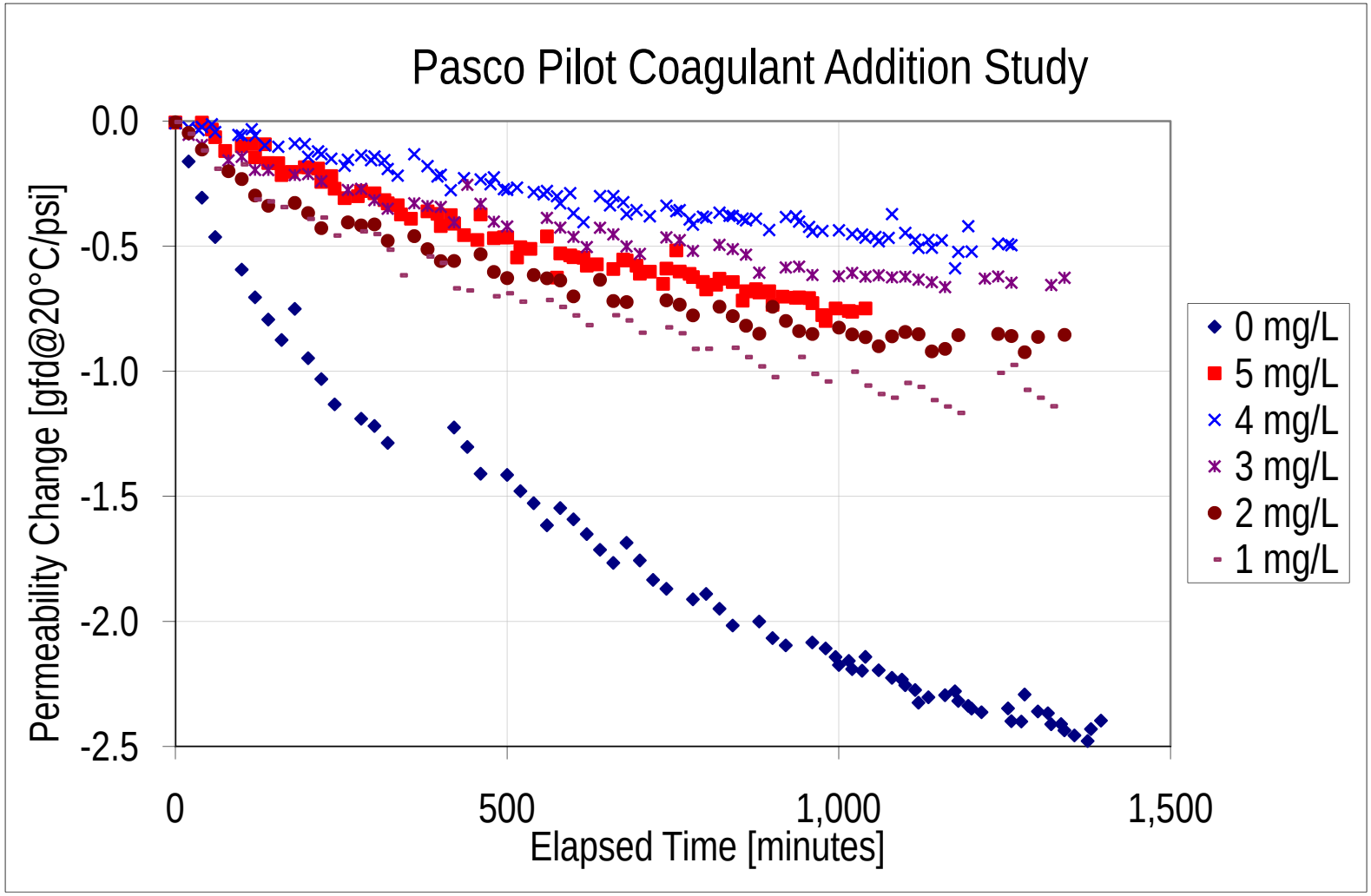
Coagulation Pre-Treatment

- Change the size distribution
- Reduce NOM
  - Prevent fouling by organics
  - Prevent formation of DBPs
- Complex interactions
  - Membrane (material, pore size, configuration)
  - Water Quality
    - Colloids/particles
    - Natural organic matter
  - Coagulant (type and dose)

Albany-Millersburg WTP, Oregon



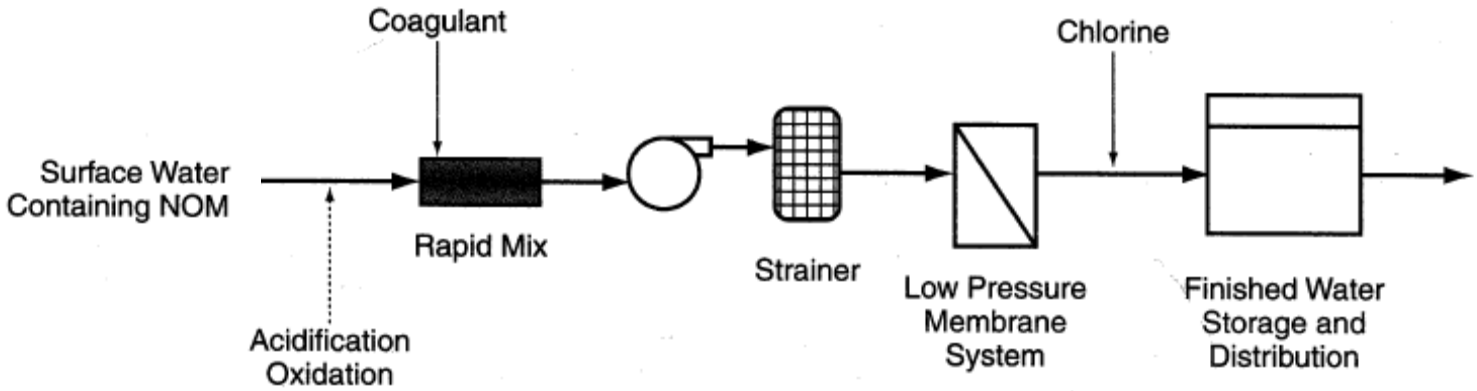
Pasco, WA Pilot Plant



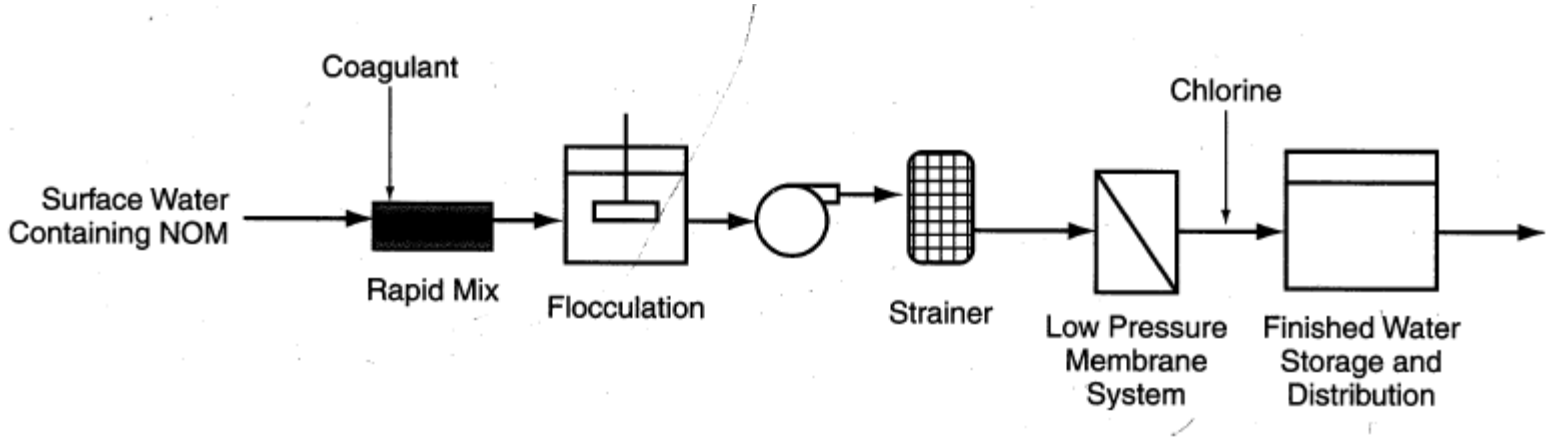
Process Configurations

Source: AWWA Manual 53

- In-line membrane filtration

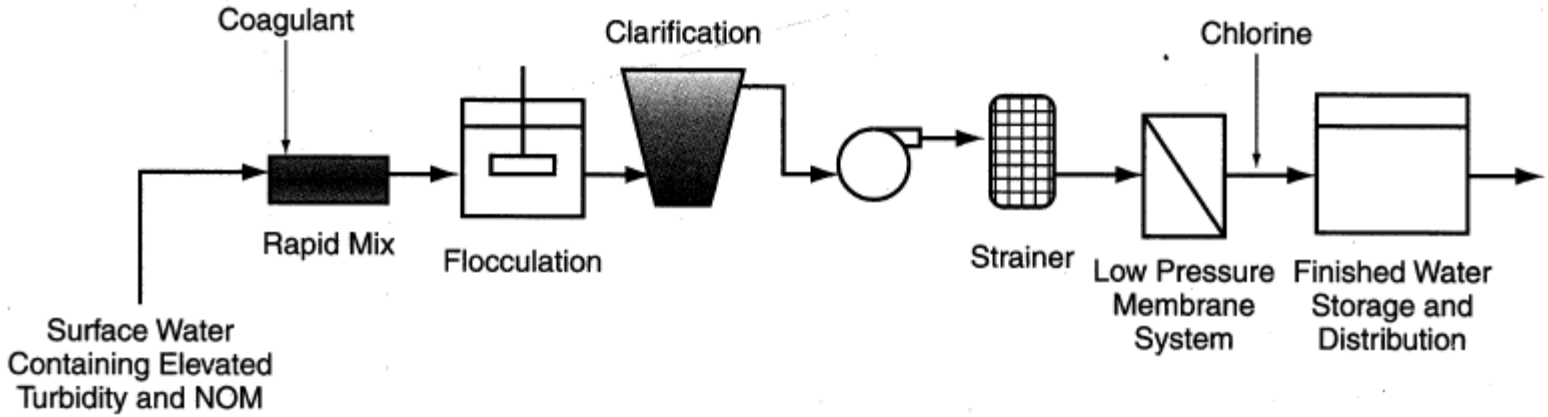


- Direct membrane filtration



Process Configurations (Cont.)

- Conventional pretreatment-membrane filtration



- Submerged vs. Pressure membranes

Knowledge Gap

- Lack of a holistic/systems approach to design and operation of integrated membrane treatment processes
  - No good guidelines exist for membrane pretreatment
- There is a missed opportunity in the information that is traditionally ignored during jar testing
  - PSD
  - Floc Morphology
- Tailoring coagulation conditions and process configurations to optimize NOM removal ***and*** PSD/floc morphology could result in improved performance and lower costs

Project Objective

Develop a framework for optimization of coagulation pre-treatment for low pressure membranes on the basis of **NOM removal** and the **characteristics of the floc** that are formed

Tasks:

- Develop an improved method for characterizing fractal dimensions of floc
- Characterize particle size distributions and fractal dimensions during coagulation
- Relate floc characteristics to particulate fouling of membranes

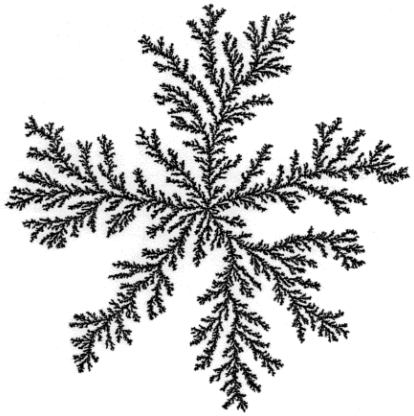
The Fractal

- The porous, irregular nature of floc formed during water treatment can be described using fractal geometry

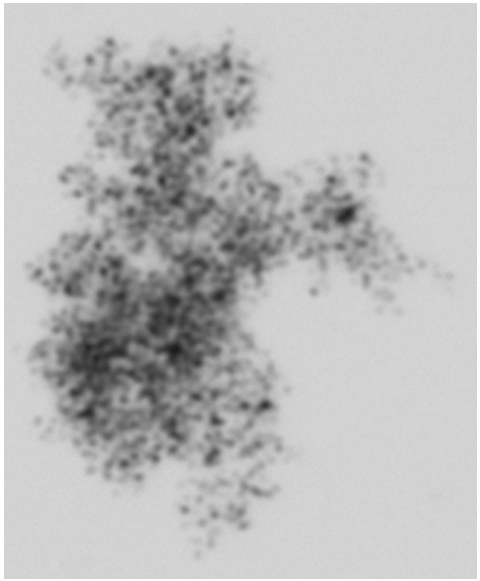
$$V_a \propto d_a^{D_3}$$

- D_3 = 1.4–2.8 (3.0 for sphere)

- Floc porosity increases with decreasing D_3 and increasing aggregate size



http://classes.yale.edu/fractals/Panorama/Physics/DLA/BigDLA1.html



Method Development

Goal: Develop an improved methodology for characterizing floc morphology

- Fast (relatively)
- Limit impact on floc
- Characterize the entire distribution
- Ability to see variations in D_3 with aggregate size

Approach: Calculate the fractal dimension based on dual measurements of the particle size

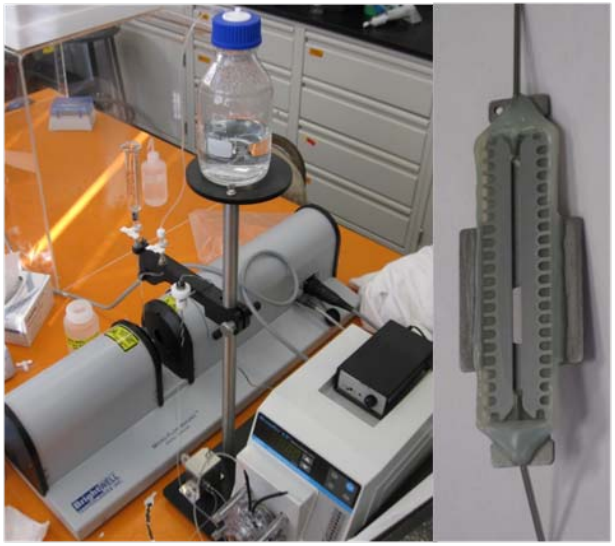
- Solid volume (Coulter Counter)
- Characteristic length (Image Analysis)

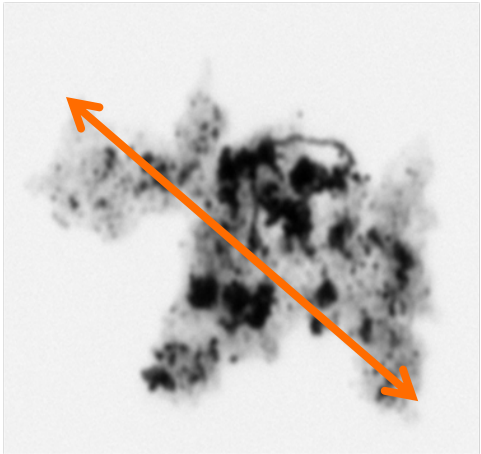
Coulter Counter

- PSD measurements based on **solid volume**
- Sample suspended in an electrolyte
- Use of multiple aperture tubes allows capture of the entire PSD
  - $4.19 – 2.14 \times 10^6$ μm^3
  - (2 – 160 μm spherical equivalent diameter)

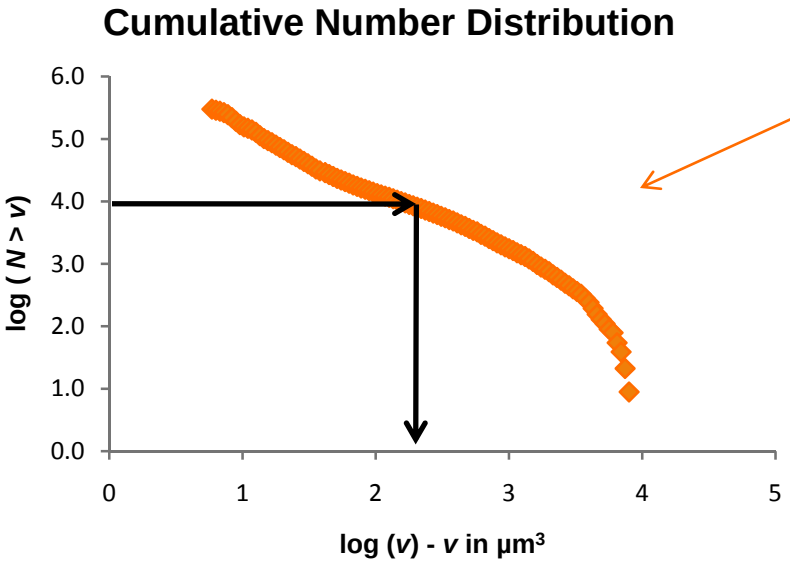
DPA-4100-D Particle Analyzer

- PSD measurements based on **Maximum Feret's diameter**
  - Maximum chord length
- Images are captured as sample travels through flow cell
- Minimal sample manipulation
- Large size range
  - High-magnification: 0.75 – 100 μm
  - Low-magnification: 2 – 400 μm

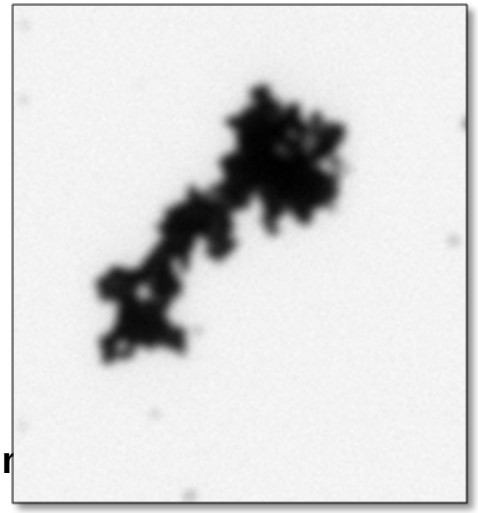


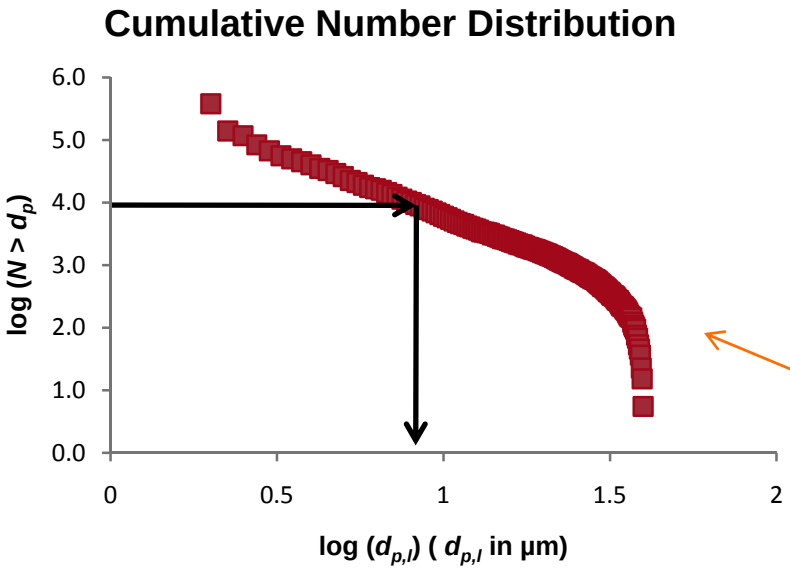


Demonstration of Method

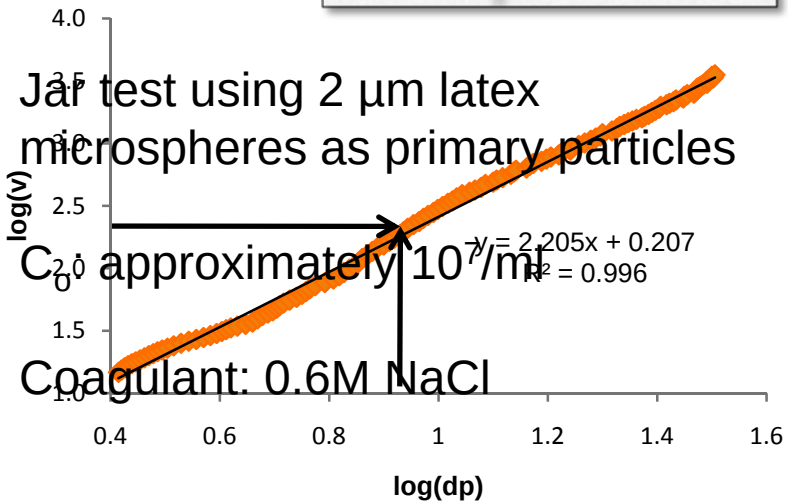


Based on volume





Solid volu



Jar test using 2 µm latex microspheres as primary particles

C_0: approximately 10^7/ml

Coagulant: 0.6M NaCl

Slope of log(v) vs. log(d_p) is D_3.

$D_3 = 2.2$

Based on maximum Feret's diameter.

Experiments

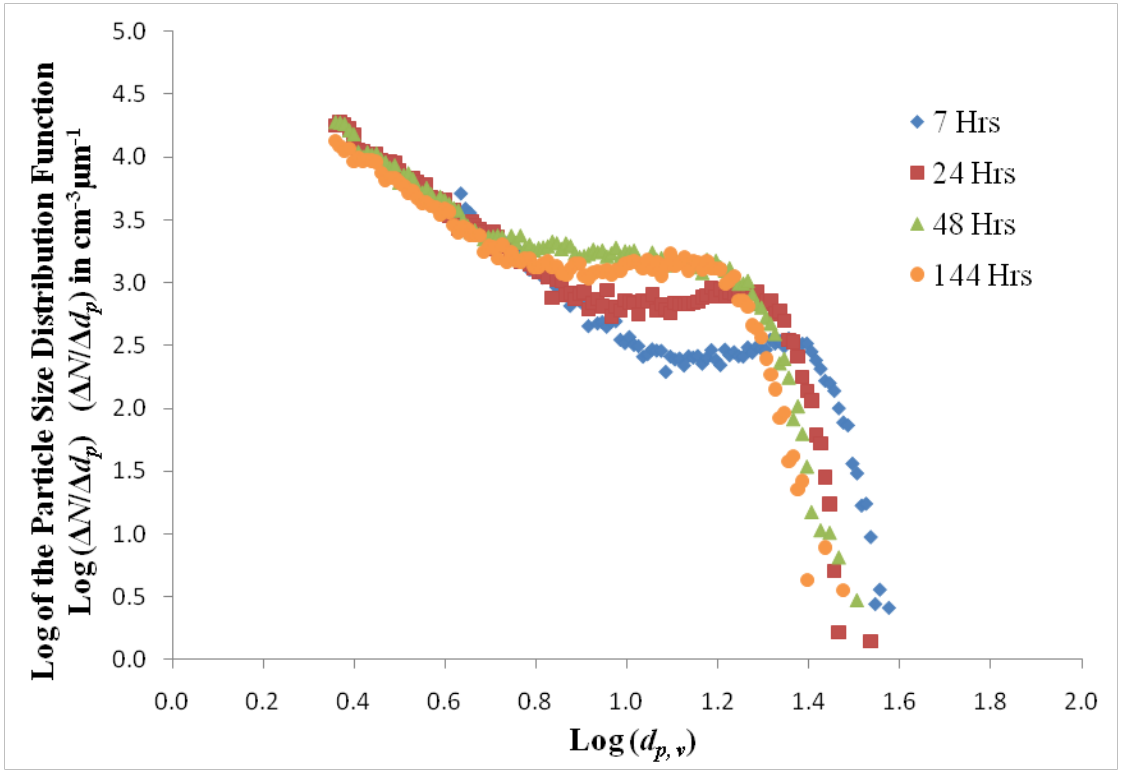
- Latex Microspheres
  - Well characterized, ideal model colloid system.
  - Test and validate that the methodology worked.
- Synthetic Water
  - Increase complexity while maintaining control of the water quality.
  - Able to add or remove constituents.
- Natural river water
  - Real system
  - Influent to a membrane WTP.

Microsphere Experiments

- Well characterized model colloids
  - Primary particle diameter: 2 µm
  - Dispersed and destabilized in 0.6 M NaCl electrolyte.

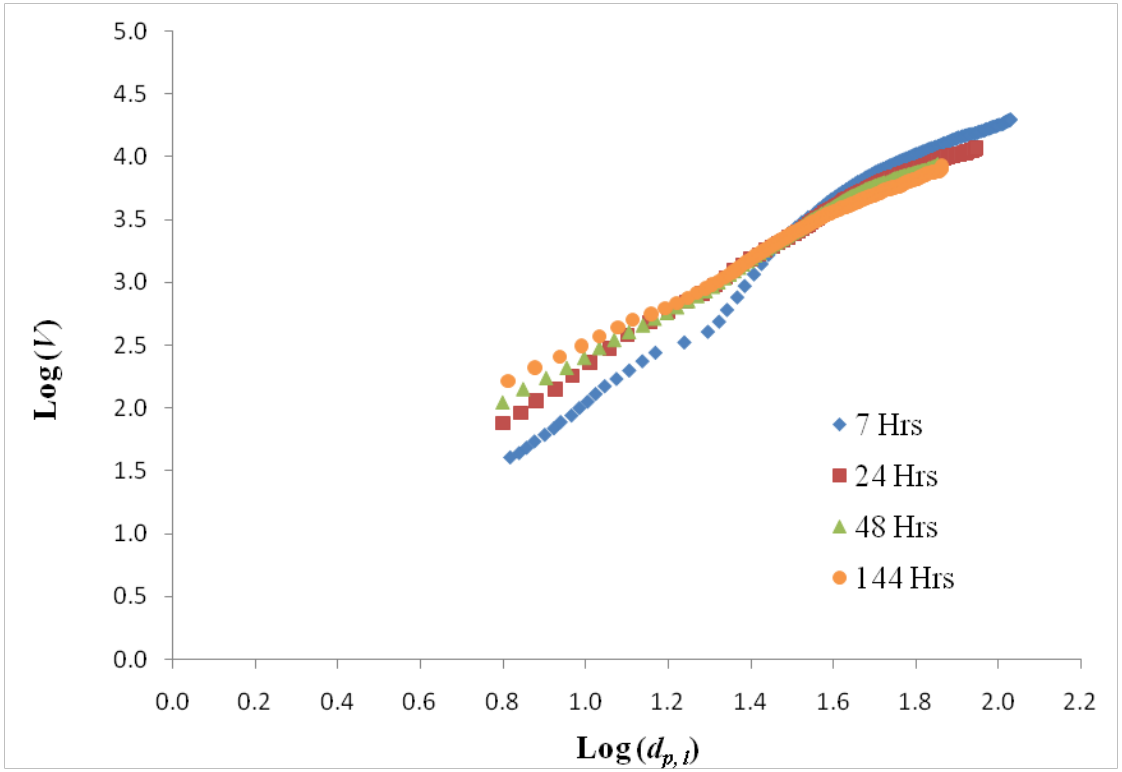
- Experiments
  - Extended flocculation.
  - 3 phase mixing (*flocculation, breakup, regrowth*).

Extended Flocculation



- Continued restructuring occurred during the first 48 hrs.

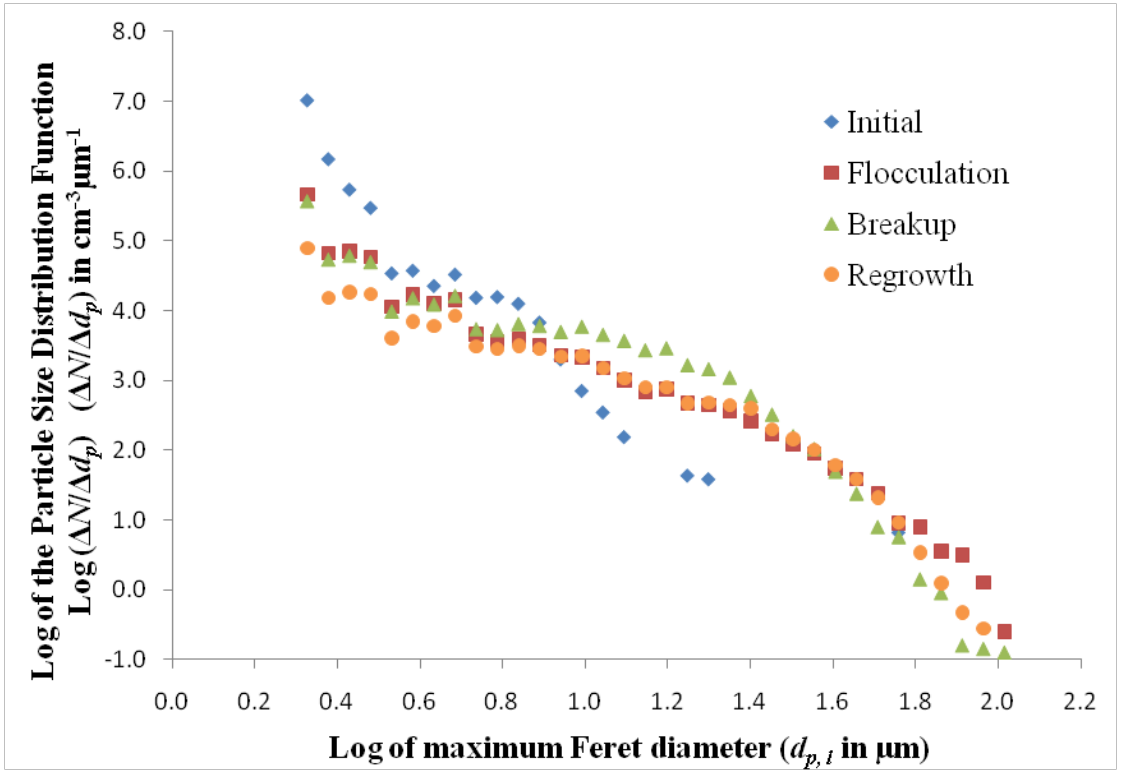
Extended Flocculation



Size Range	*7 Hrs*	*24 Hrs*	*48 Hrs*	*144 Hrs*
$0.8 < \log(d_{p,i}) < 1.5$	2.52	2.13	1.93	1.73
$1.5 < \log(d_{p,i}) < 1.7$	2.27	1.98	1.86	1.53
$\log(d_{p,i}) > 1.7$	1.21	1.17	1.04	1.28

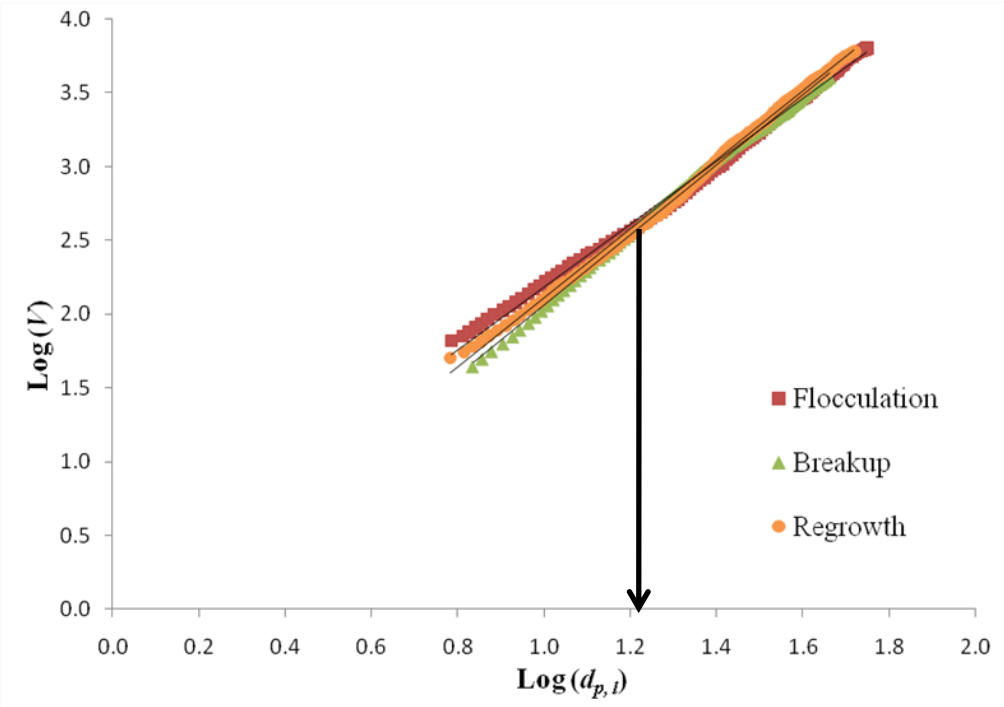
- D_3 decreased with increasing size.
- Largest size particles had fairly consistent D_3.
- Distribution better described by a single D_3 after 144 hours of mixing.
- Novel ability to detect changes in D_3 with d_p.

3 Phase Mixing



- Trends
  - Significant decrease in the concentration of small particles.
  - Formation of aggregates larger than 10 µm.
  - Restructuring due to *breakup*.
  - Recovery of the size distribution during *regrowth*.

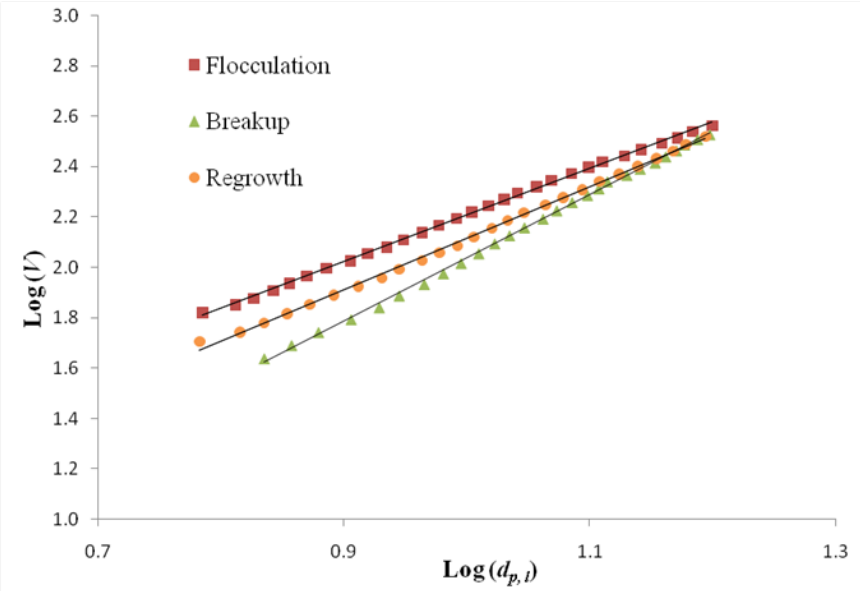
3 Phase Mixing – Fractal Analysis

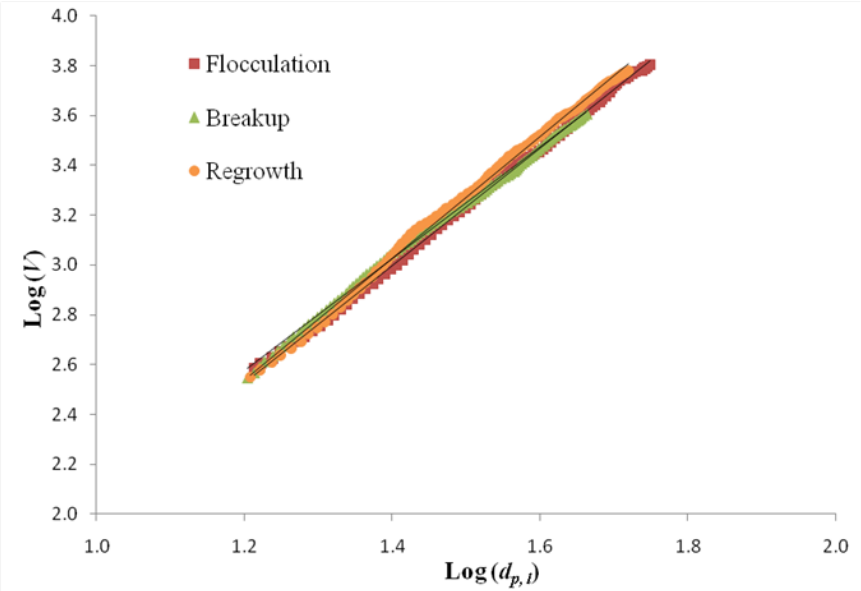


Size Range	*Flocculation*	*Breakup*	*Regrowth*
$0.8 < \log(d_{p,i}) < 1.7$	2.12	2.38	2.34

- Linear distribution typical of microsphere aggregates.
- Fractal Dimensions
  - *Flocculation* produced loose floc.
  - Compaction occurred due to *breakup* restructuring.
  - D_3 decreased during *regrowth*.
- Two regions in the distributions.

3 Phase Mixing – Fractal Analysis





Size Range	*Flocculation*	*Breakup*	*Regrowth*
$0.8 < \log(d_{p,l}) < 1.2$	1.85	2.51	2.05

Size Range	*Flocculation*	*Breakup*	*Regrowth*
$1.2 < \log(d_{p,l}) < 1.7$	2.35	2.24	2.45

- Breakup results in smaller, more compact floc.

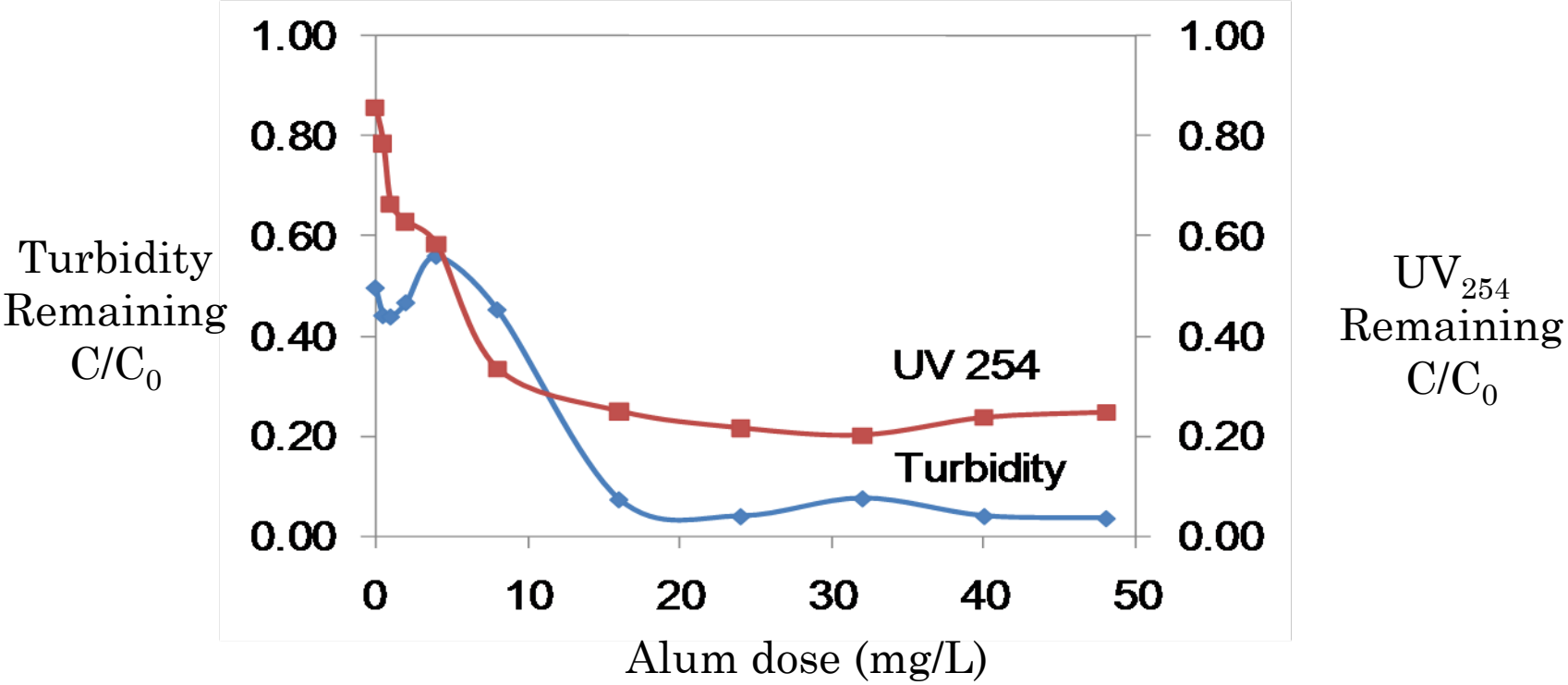
River Water Experiments

- Source water:
  - Santiam River: Source water for Albany, OR membrane water treatment plant

Parameter	Value
pH	6.2
Turbidity	10.2 NTU
DOC	1.16 mg/L
Alkalinity	12.4 mg/L as $CaCO_3$

- Jar tests conducted to examine NOM and turbidity removal as a function of alum dose

Jar Testing Results



- Chose three alum doses for further investigation
  - 1, 8, and 25 mg/L

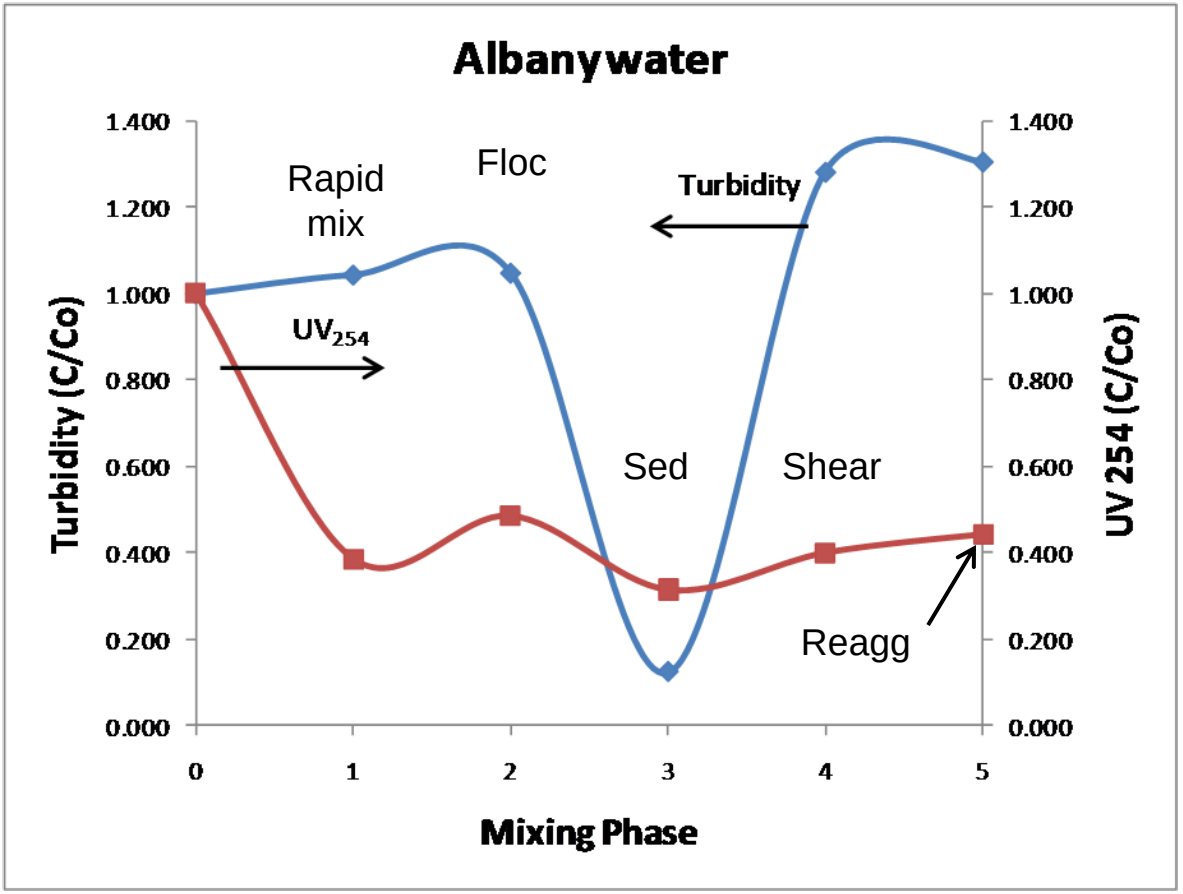
Particle Size Distribution/Floc Morphology Experiments

- Individual jar tests to investigate the effect of mixing conditions at chosen alum doses

Mixing Phase	Condition
Rapid Mix	100 rpm for 30 seconds
Flocculation	30 rpm for 30 min
Sedimentation	1 hour
Increased Shear	30 seconds on a magnetic stirrer
Reaggregation	30 rpm for 30 minutes

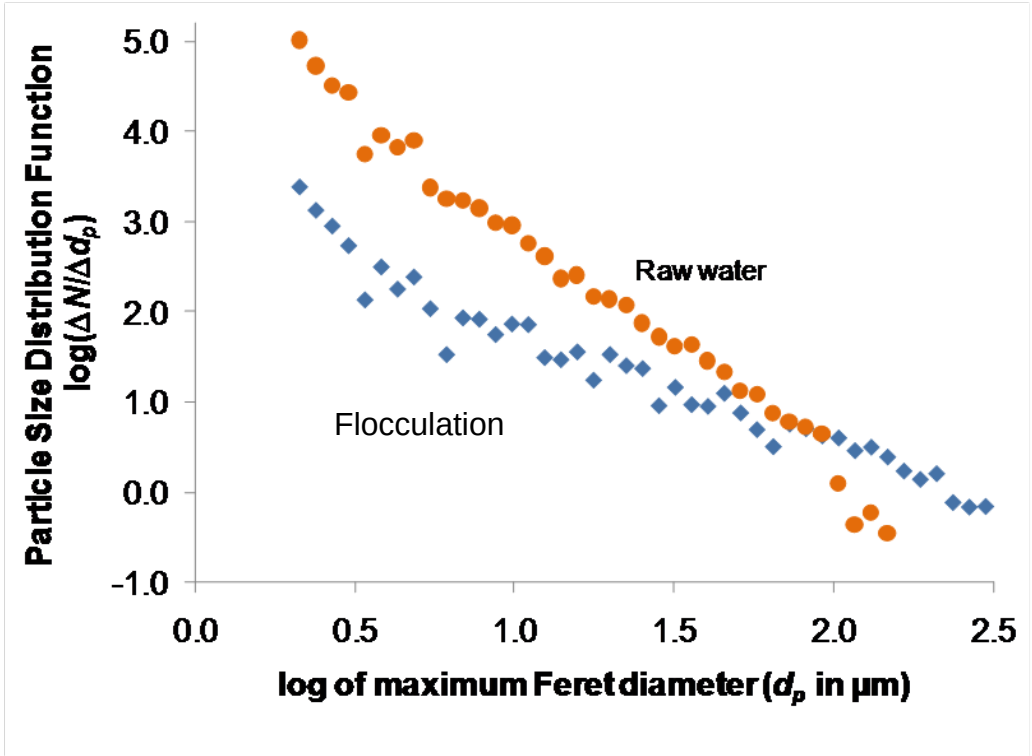
- Samples collected at the end of each phase for turbidity, UV_{254}, Coulter Counter, and DPA

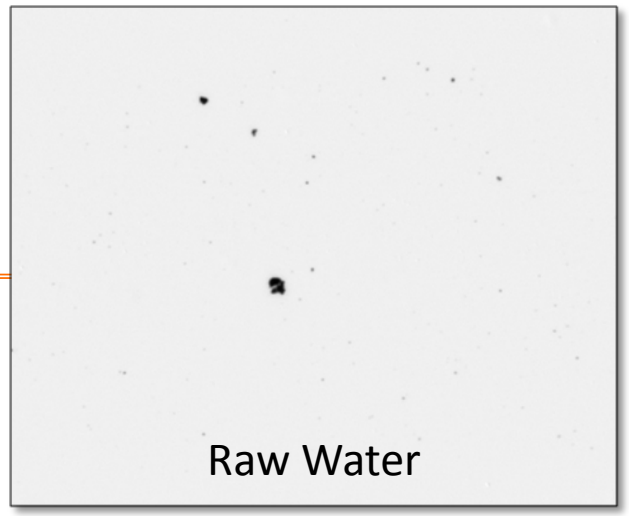
Effect of Mixing Condition

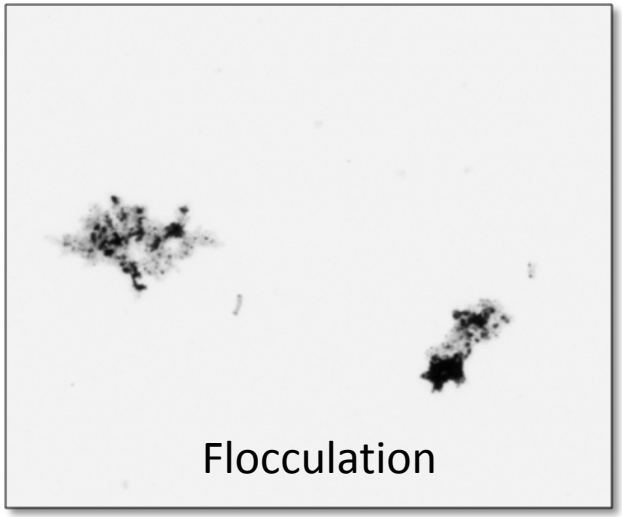


Alum Dose: 8 mg/L as $Al_2(SO_4)_3 \cdot 16\ H_2O$
pH: 6.2

FLOCCULATION

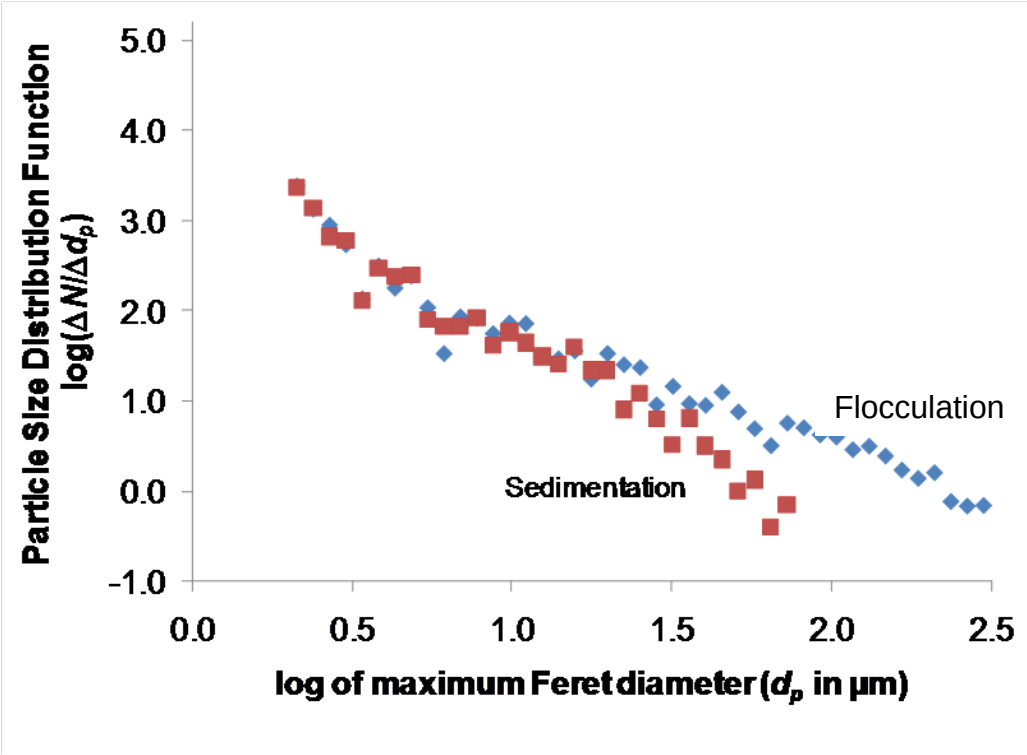


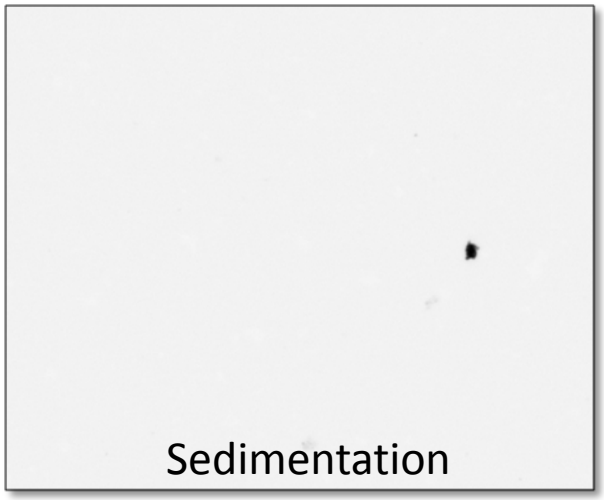




- Dramatic reduction in the concentration of small particles and formation of large floc

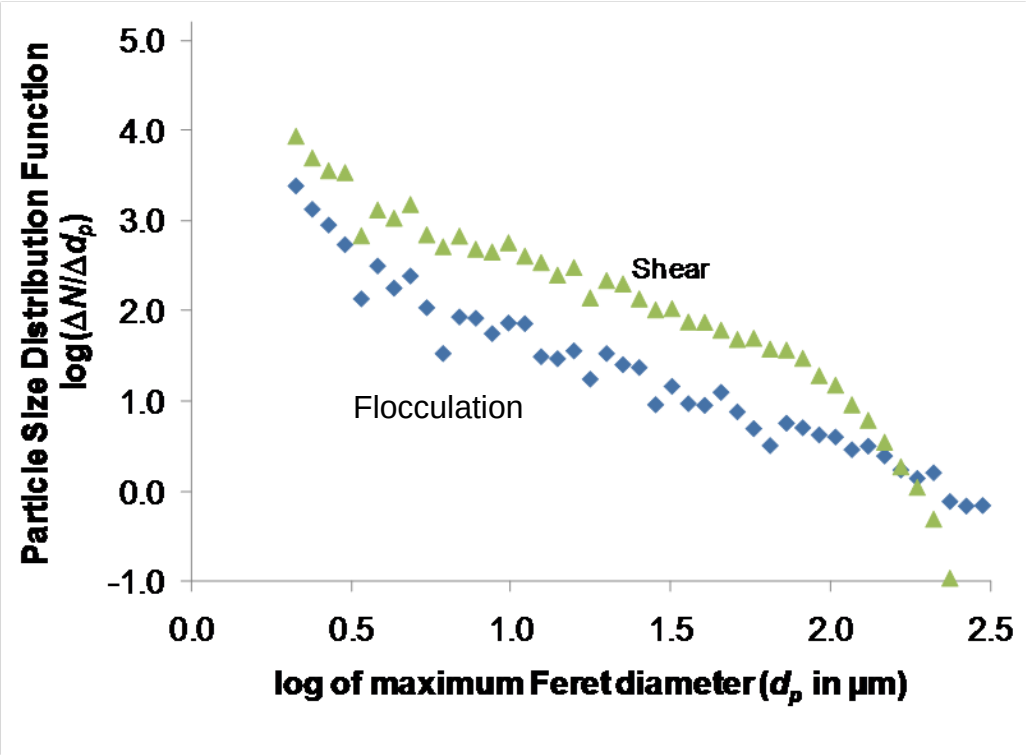
SEDIMENTATION

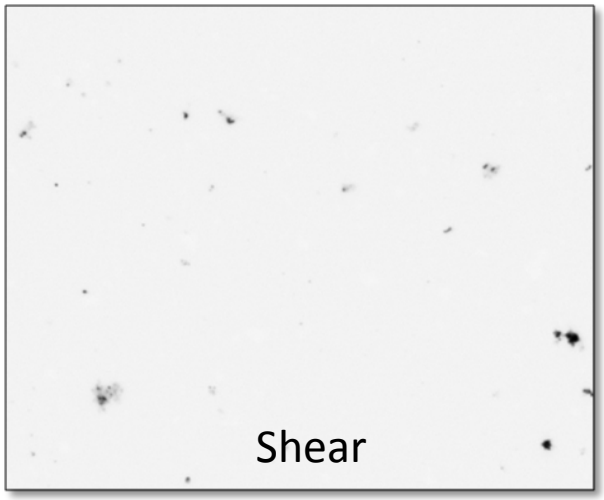




- Removal of largest particles from suspension

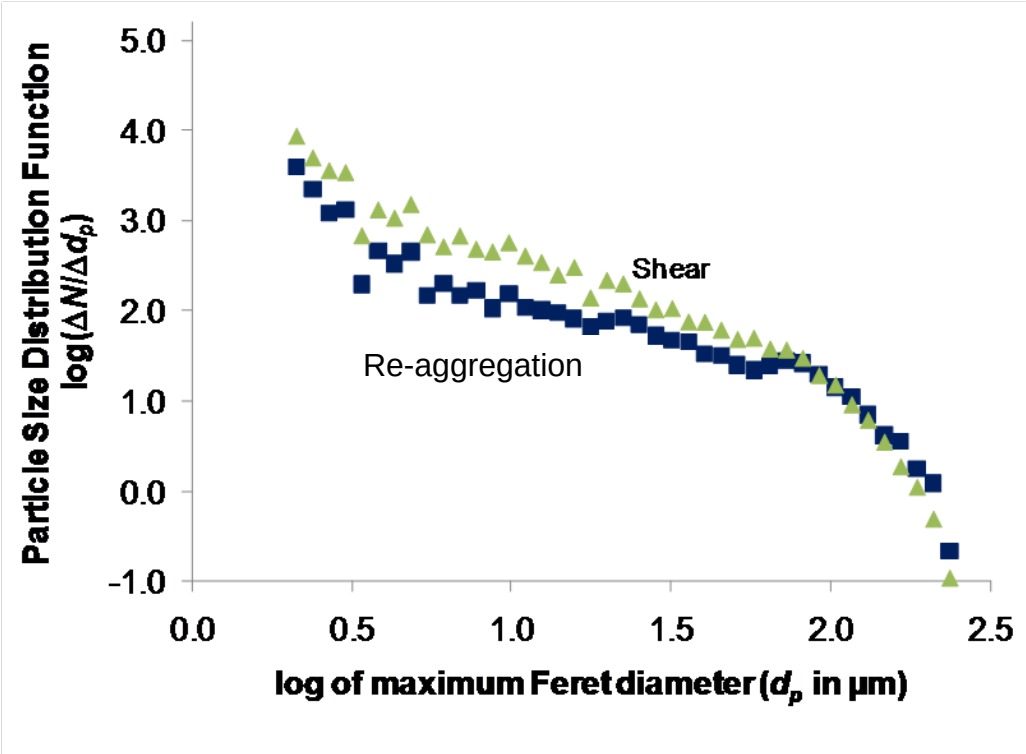
Increased Shear

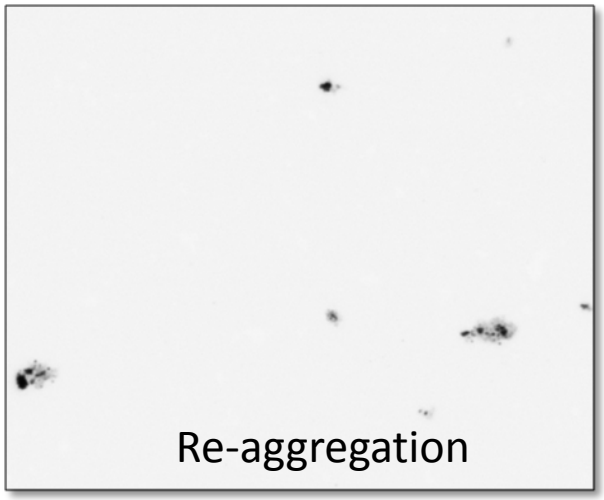




- Break-up of largest particles with a corresponding increase in smaller particles

Re-aggregation

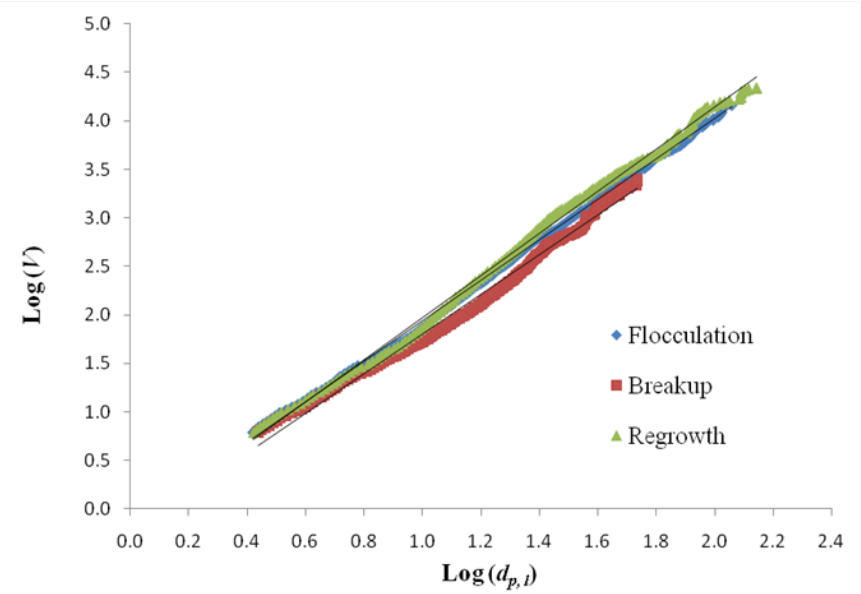




- Limited re-aggregation

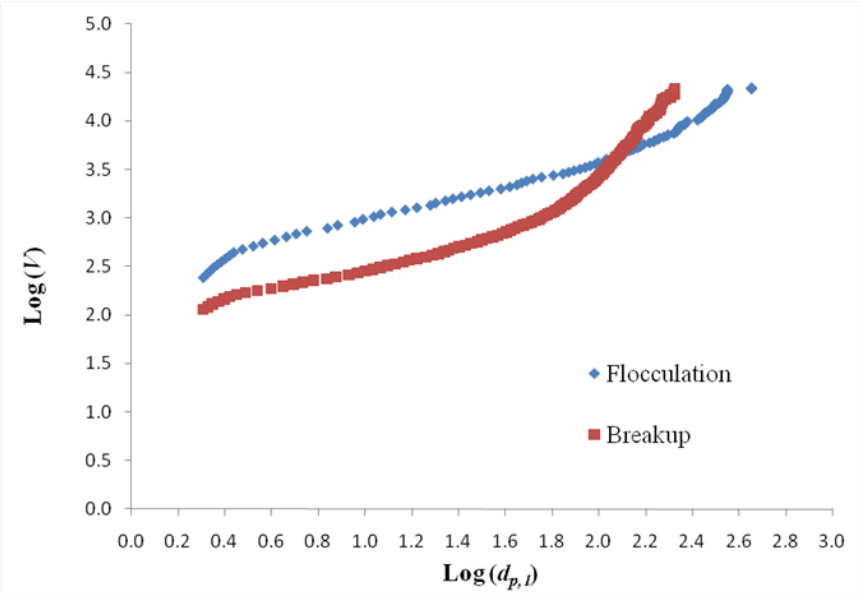
River Water Fractal Analysis

- 1 mg/L alum:



Mixing Phase	D_3	R^2
Flocculation	2.09	0.999
Breakup	2.05	0.991
Regrowth	2.17	0.997

- 8 mg/L alum:



Flocculation:

Size Range	D_3	R^2
$0.6 < \log(d_{p,i}) < 2.0$	0.56	0.999

Preliminary Findings

- Methodology for measuring the fractal dimension, D_3, is promising
  - Some difficulty in characterizing hydroxide floc
- Process configuration strongly influences the particle size distribution and morphology
  - Flocculation leads to larger aggregates with lower fractal dimensions
  - Increased shear results in breakup of formed floc
  - Once broken, flocs re-aggregate slowly
- NOM removal occurs early in the pre-treatment process

Ongoing Work

- Jar tests of synthetic water to examine the effects of:
  - Particle Concentration
  - Mixing condition
  - NOM concentration
  - Coagulants (e.g. iron, PACl)
- Low pressure membrane fouling tests.
  - Simulate process configurations in a bench-scale membrane filtration system
  - Relate particulate fouling to characteristics of the floc
  - Collect data on DBP formation potential
- Continue development of methodology for calculating fractal dimensions for real waters
- Develop guidelines for process selection and optimization

Acknowledgments

- Ian Maguire
- Oregon State University Research Office
- John Adams, City of Albany, OR
- Paul Mueller, CH_2M Hill

Questions?

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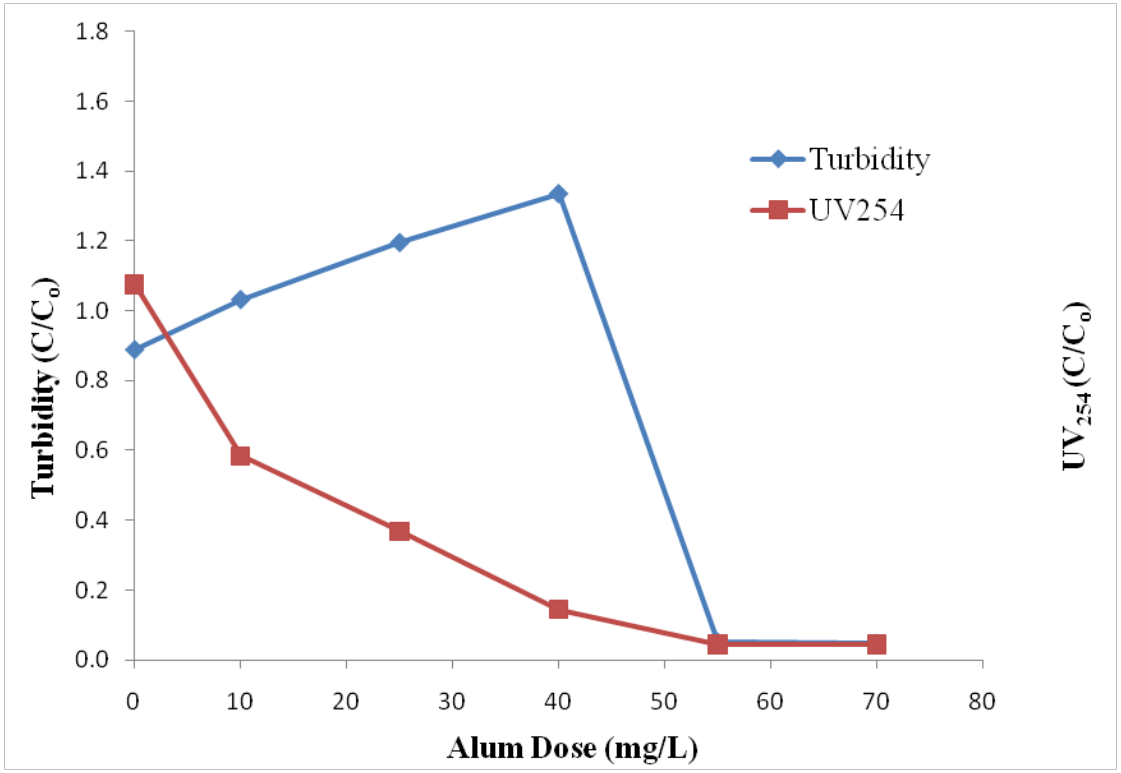
Synthetic Water Experiments

Synthetic Water Experiments

- Conducted to examine the influence of DOC.
- Two synthetic waters were investigated:
  - High DOC water
  - Low DOC water
- Jar testing was performed to determine the optimal removal for DOC (UV_{254}) and turbidity.

Synthetic Water Experiments

- High DOC synthetic water:



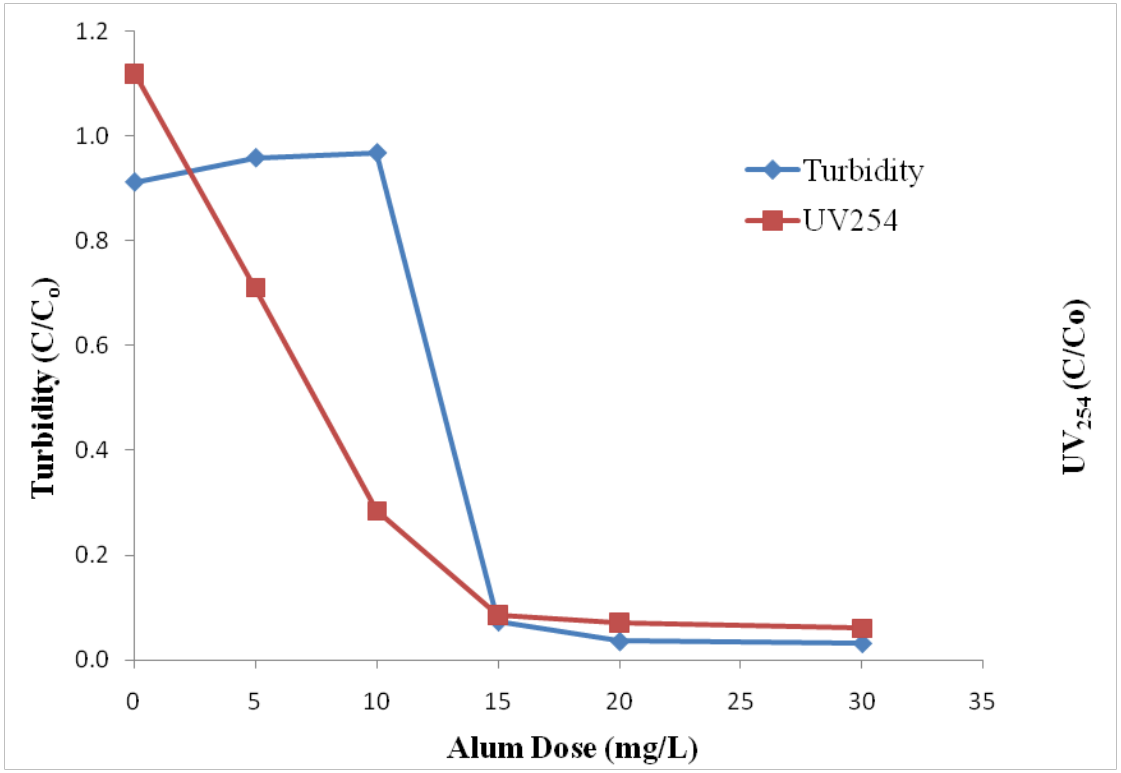
High DOC synthetic water recipe		
Kaolin	10.1	mg/L
DOC	5	mg/L
$CaCl_2$	0.5	mM
$NaHCO_3$	0.8	mM

*DOC added as Aldrich Humic Acid.

- 2 alum doses chosen for further analysis:
  - 55 mg/L
  - 40 mg/L

Synthetic Water Experiments

- Low DOC synthetic water:

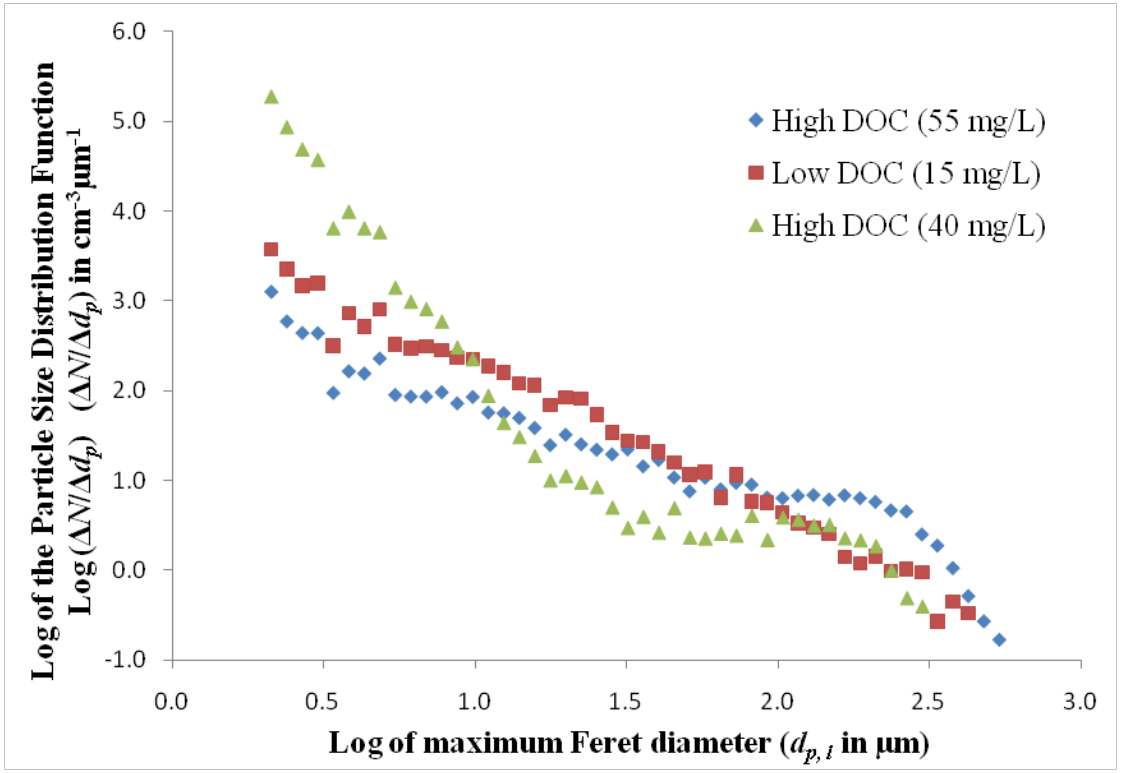


Low DOC synthetic water recipe		
Kaolin	10.1	mg/L
DOC	1	mg/L
$CaCl_2$	0.5	mM
$NaHCO_3$	0.8	mM

- 1 alum dose chosen for further analysis:
  - 15 mg/L

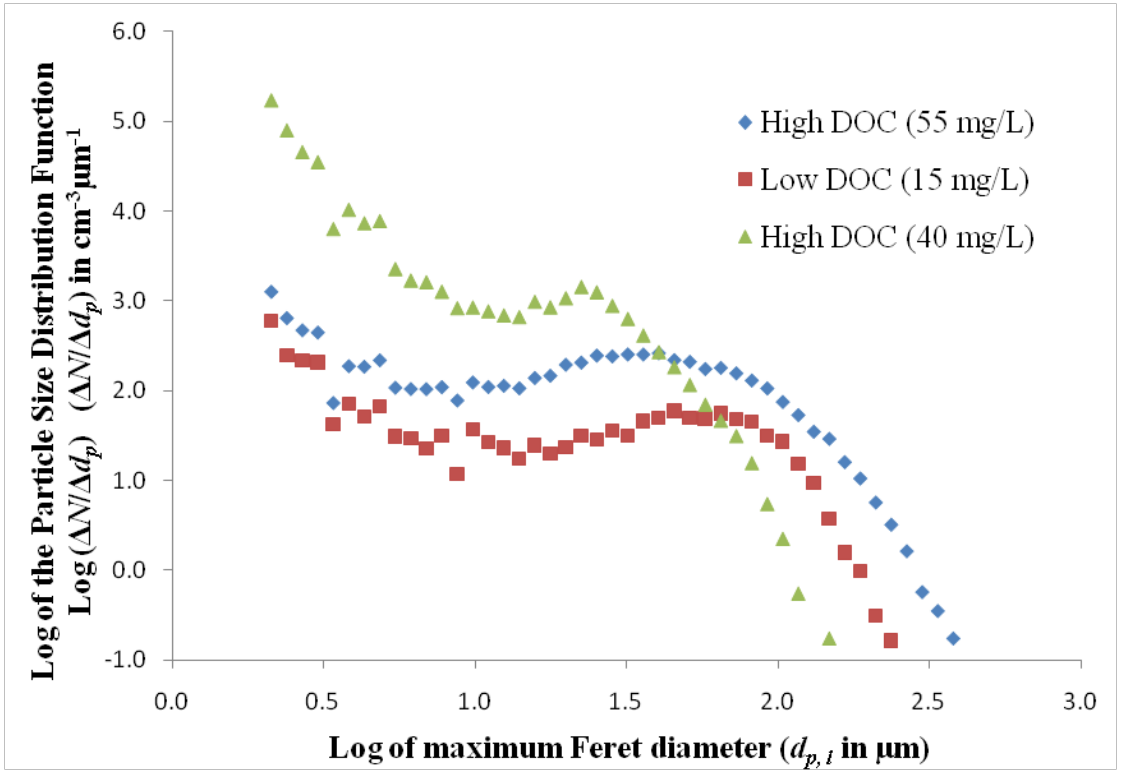
Synthetic Water Experiments

- *Flocculation mixing*



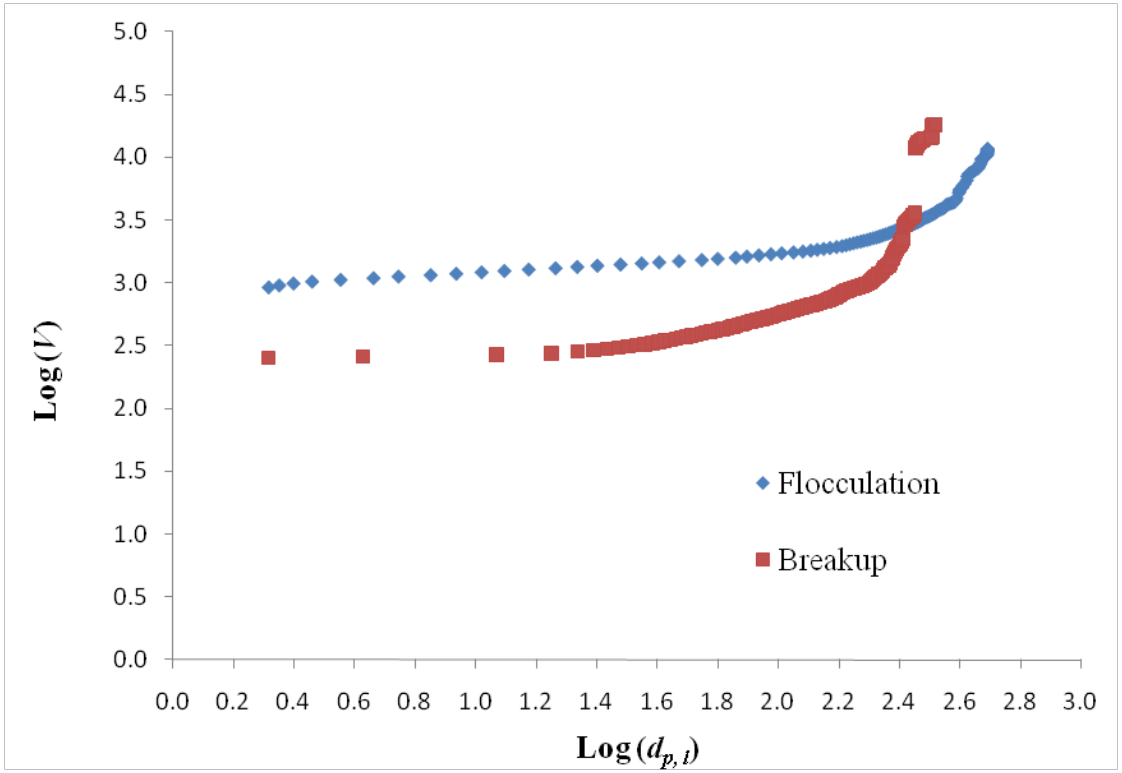
Synthetic Water Experiments

- *Breakup mixing*



Synthetic Water Experiments

- High DOC – optimum alum dose (55 mg/L)



- Breakage of large floc altered the size distribution.