The Metropolitan

Water Reclamation District

of Greater Chicago

WELCOME

TO THE NOVEMBER EDITION

OF THE 2012

M&R SEMINAR SERIES

BEFORE WE BEGIN

- SILENCE CELL PHONES & SMART PHONES
- QUESTION AND ANSWER SESSION WILL FOLLOW PRESENTATION
- PLEASE FILL EVALUATION FORM
- SEMINAR SLIDES WILL BE POSTED ON MWRD WEBSITE (www. MWRD.org: Home Page ⇒ Reports ⇒ M&D Data and Reports ⇒ M&R Seminar Series ⇒ 2012 Seminar Series)
- STREAM VEDIO WILL BE AVAILABLE ON MWRD WEBSITE (www.MWRD.org: Home Page ⇒ MWRDGC RSS Feeds)

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Office of Naval Research Fellow (DOD-NDSEG) , California Institute of Technology
Visiting Professor/Scientist in Chile, New Zealand, and Sweden

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B.S. Mechanical Engineering, Washington University, St. Louis, Missouri

Professional: A.S. of Civil Engineers; A.S. for Microbiology ; A.S. of Limnology and Oceanography
International Association for Sediment Water Science / of Hydraulic Eng. & Res.
Editorships: Limnology and Oceanography - Fluids and Environments; Water Resources Research; International Journal of Sediment Research, etc.
Published 68 papers (two book chapters); served as numerous panelists and keynote speakers and technical committee members and chair

Honors & Awards: Fulbright Distinguished Chair , 2012
Huber Research Prize, American Society of Civil Engineers , 2008
Career Award, National Institutes of Health (NIAID K25), 2006
McCormick Excellence Award, Northwestern University, 2006
Career Award, National Science Foundation, 1999

Implications of Pathogen-Biofilm Interactions for Surface Water Quality

Aaron Packman

Civil and Environmental Engineering

Northwestern University

Acknowledgements

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Dr. Kristin Searcy (now at Environ)
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USDA
NSF
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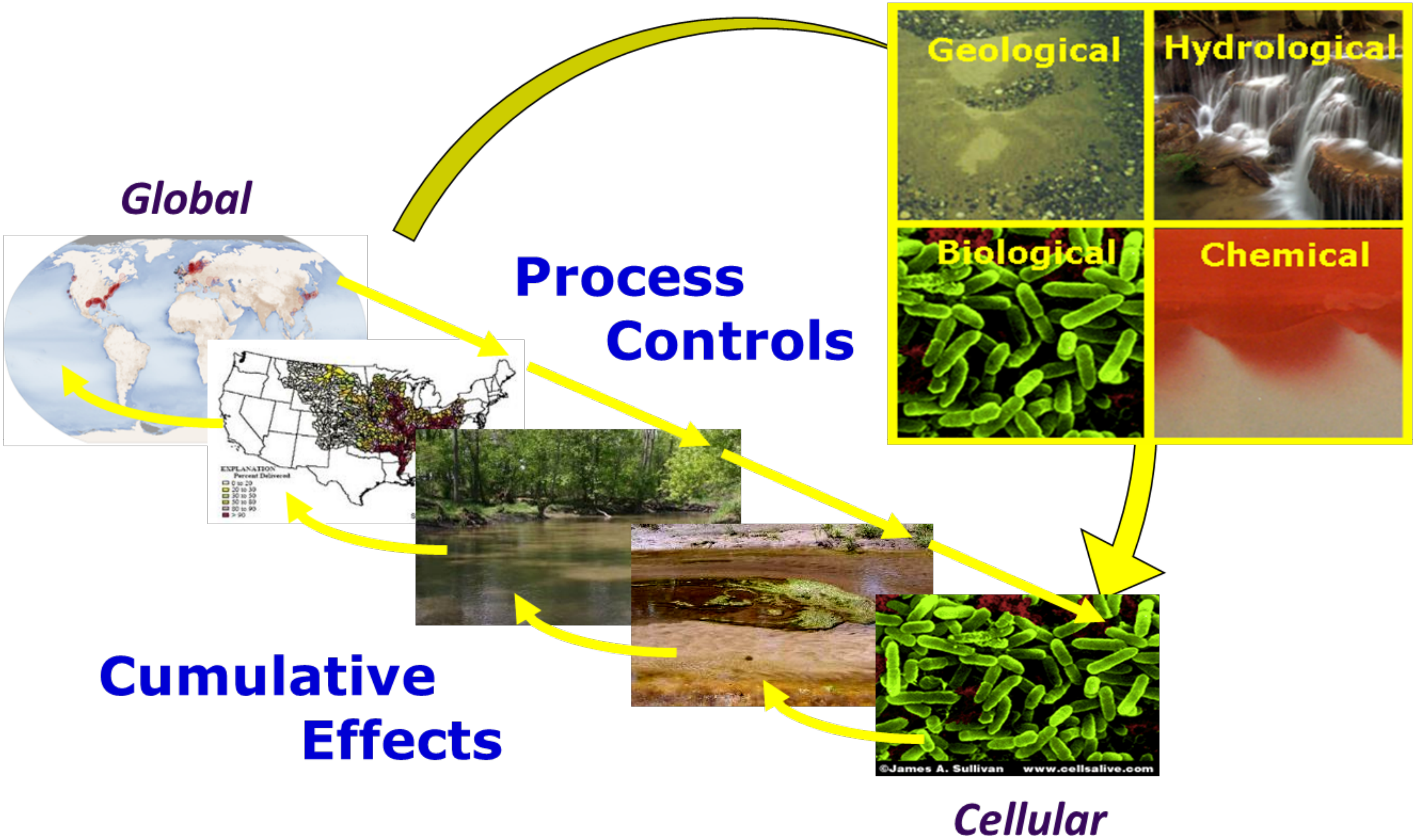
NATIONAL INSTITUTES OF HEALTH
Water Research Foundation

Microbial interactions across scales



Biofilm heterogeneity

Complex morphology

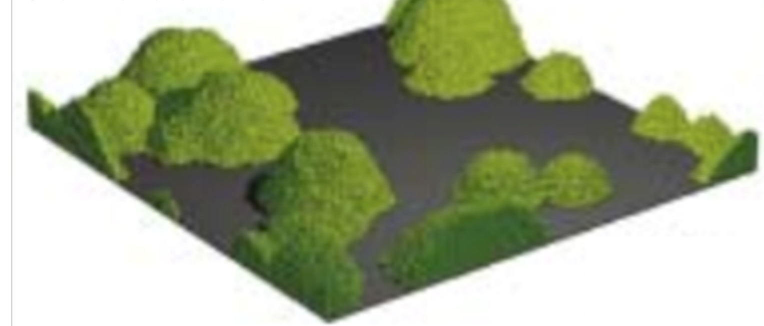
– Results from integrated adherence, motility, and growth
– Morphology varies with cell physiology and nutritional conditions
– Clusters and channels common (macroporous)

Complex composition

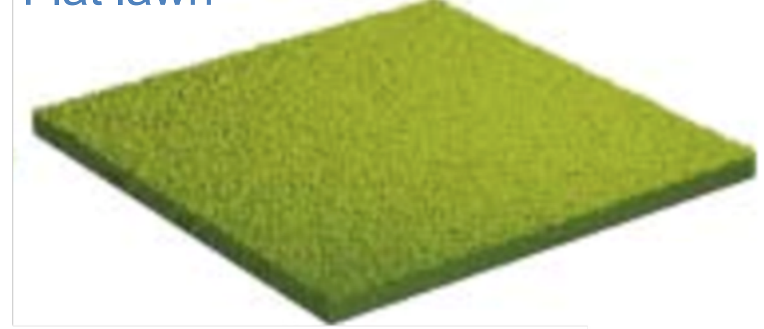
– Cells, polymer matrix (EPS), cellular products (lysed cells, eDNA, etc.)
– Complex microstructure (microporous)

Mushroom structures

Cell clusters



Flat lawn



Hall-Stoodley and Stoodley, 2005, Chambless and Stewart, 2007

Biofilm heterogeneity

Complex morphology

- Results from **integrated adherence, motility, and growth**
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Complex composition

- Cells, polymer matrix (EPS), cellular products (lysed cells, eDNA, etc.)
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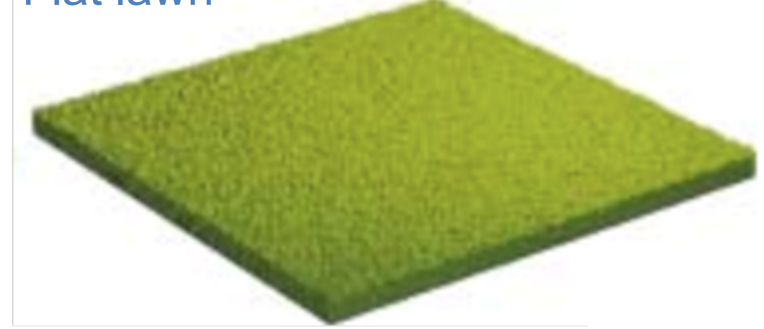
Multi-scale interactions

- Internal heterogeneity develops over time
- Internal heterogeneity (habitat) is coupled with external nutritional environment
- Coordinated activity builds biofilm
- Structure is an *emergent* property

Mushroom structures

Cell clusters

Flat lawn



Hall-Stoodley and Stoodley, 2005, Chambless and Stewart, 2007

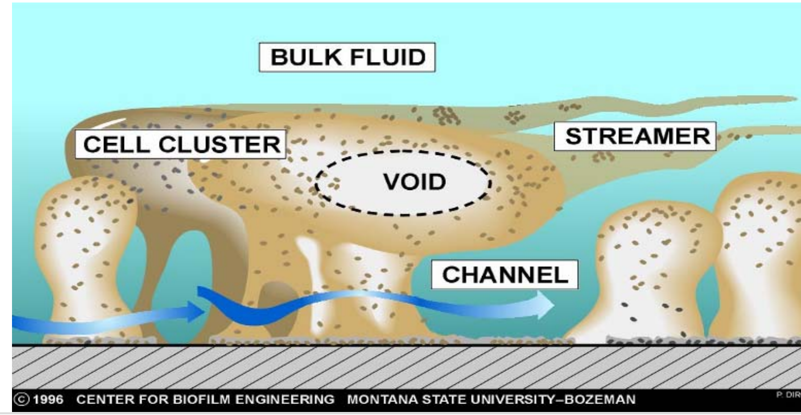
Biofilm heterogeneity

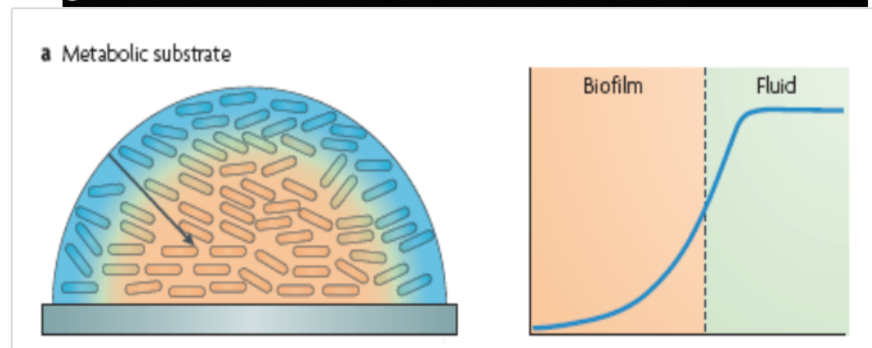
Transport-limited environment

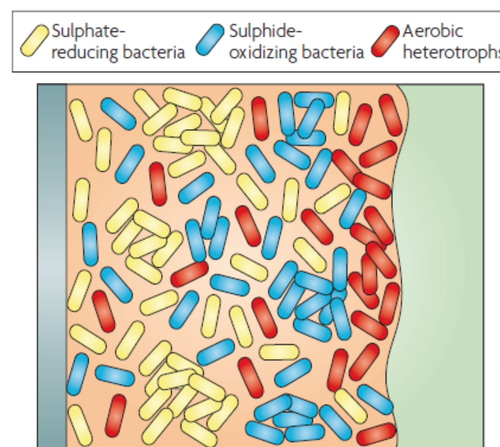
- Hindered transport environment around and within cell clusters
- Complex advective flowfield transitioning to diffusion at small (unknown) scales

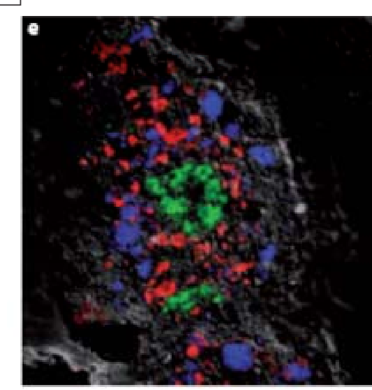
Patterns of community activity

- High community metabolism plus limited transport → internal depletion
- Strong selective pressures (variable oxygen, carbon, nutrients)
- Diverse ecological micro-niches supports diverse community







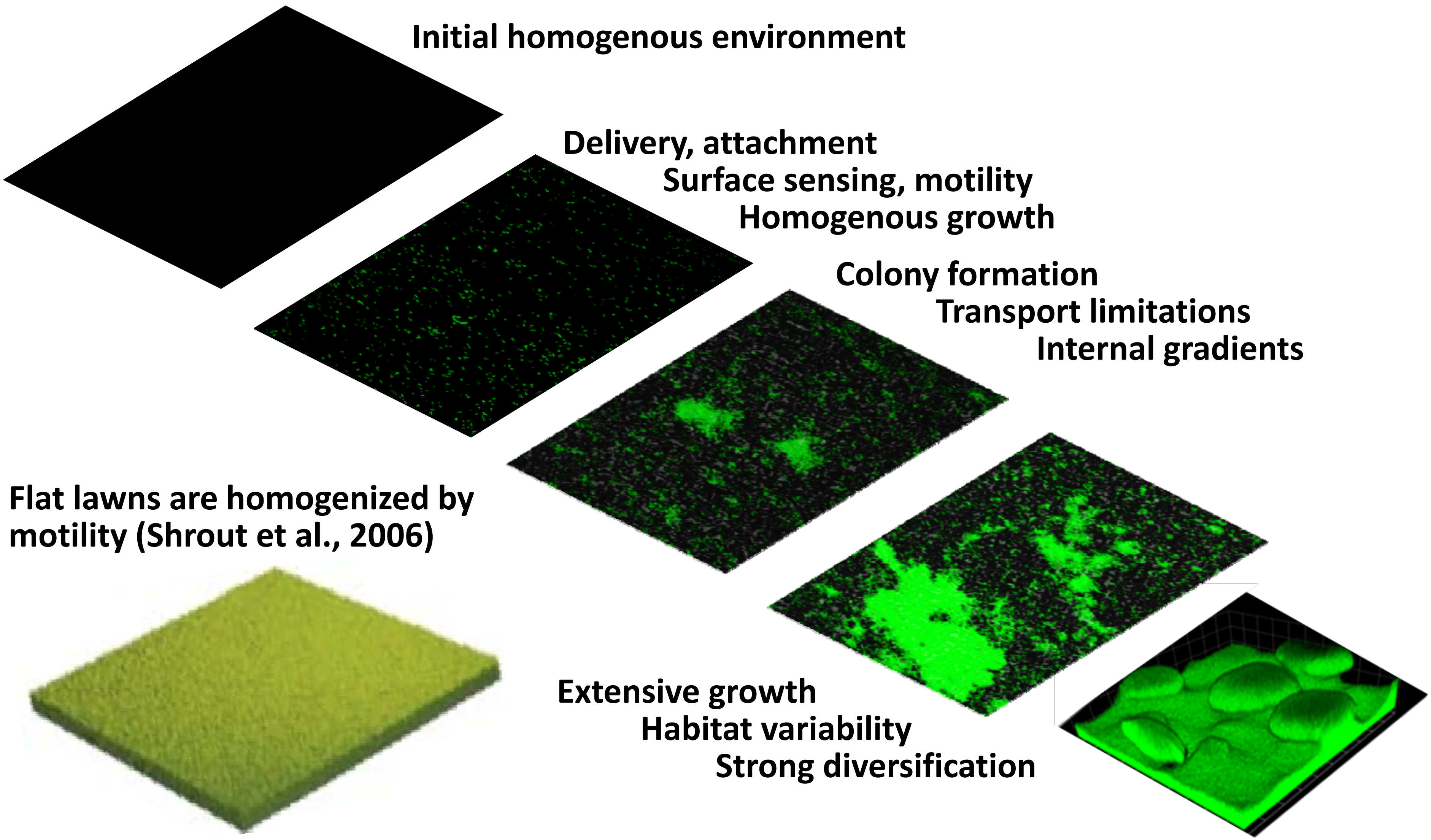


Stewart and Franklin, 2008; Battin et al,. 2007; Maixner et al., 2006

Objective is to address fundamental, multi-scale challenges in biofilms

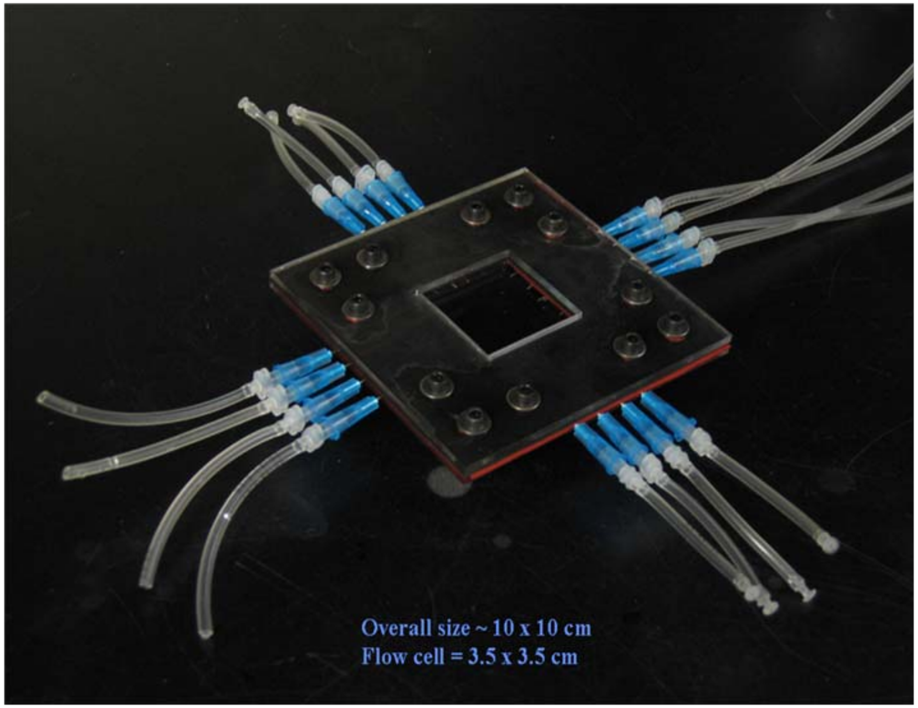
1. Develop capability to observe and quantify spatial patterns and transport dynamics within biofilms
2. Predict longer-term, larger-scale temporal dynamics of biofilm growth and diversification (i.e., development of heterogeneity)
3. Assess important outcomes in pathogen transmission in natural and engineered water systems

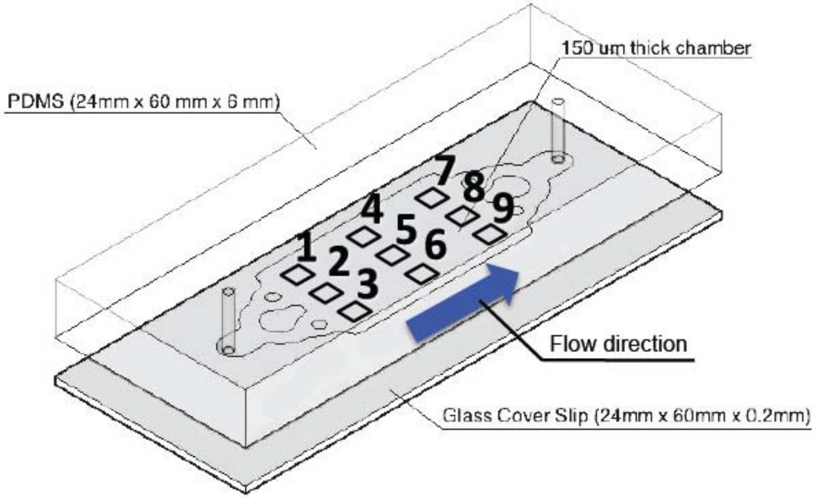
Development of biofilm heterogeneity

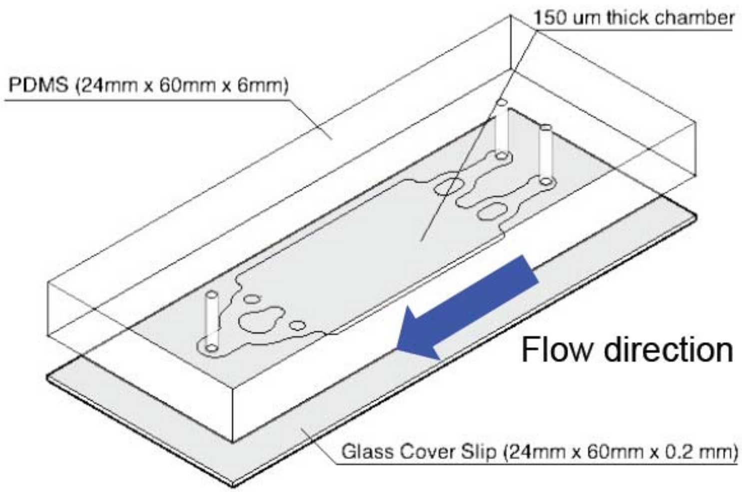


Flat lawns are homogenized by motility (Shrout et al., 2006)

New flow cell designs for biofilm-environment interactions

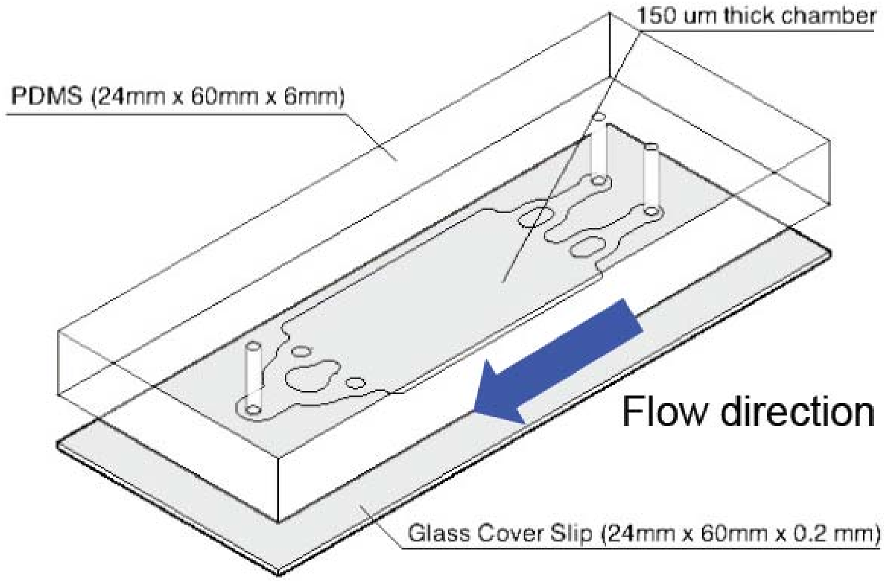


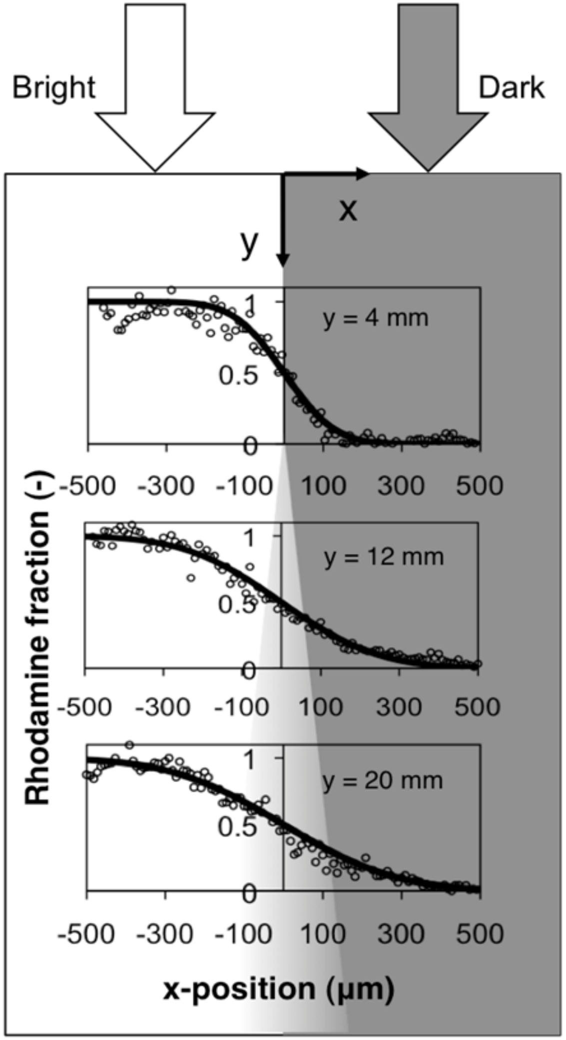




Zhang et al., 2011; Lee et al. unpublished

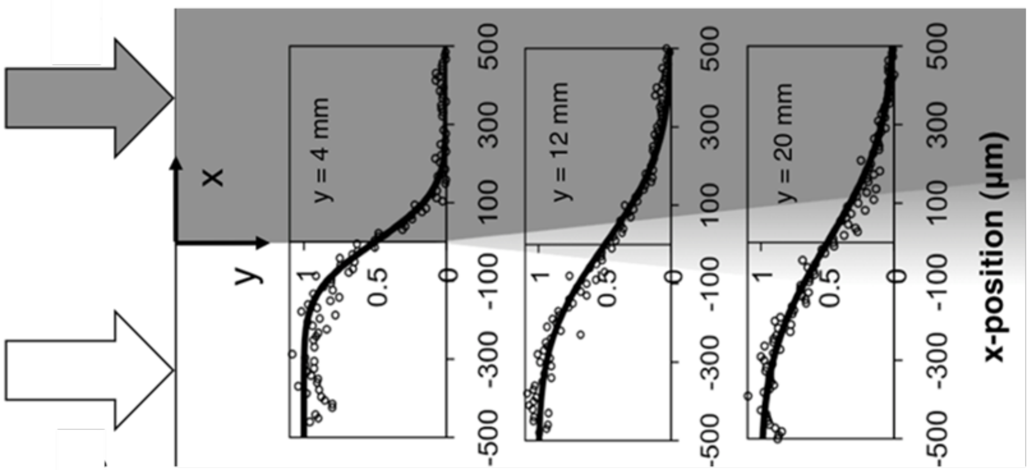
Flow cell with imposed chemical gradient

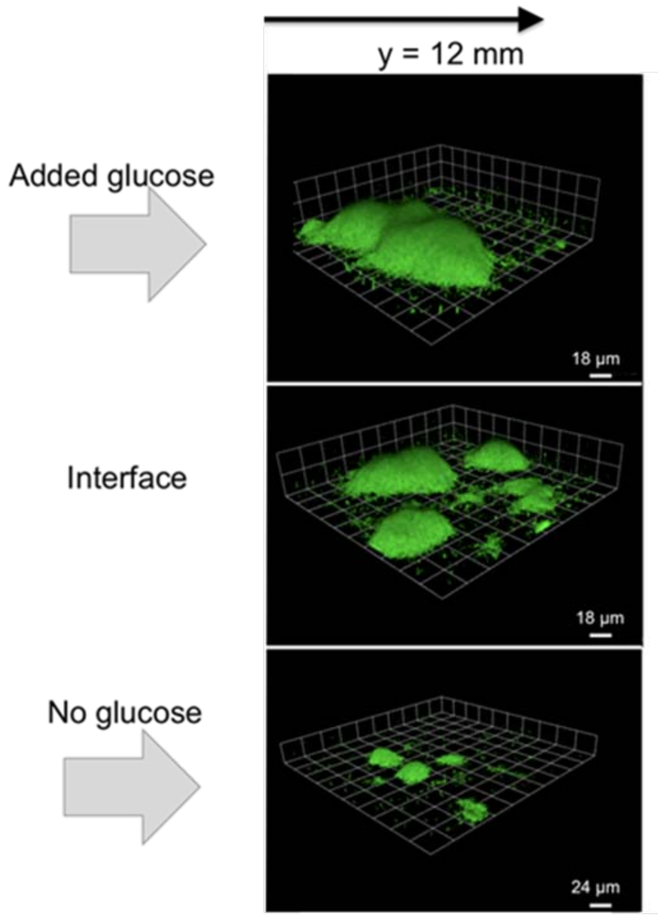




Lee et al. unpublished

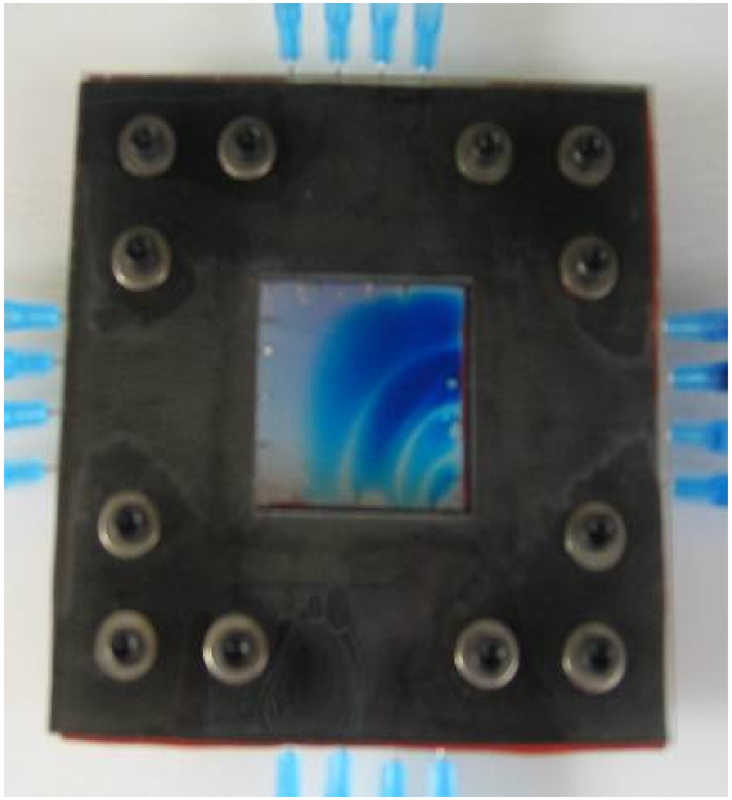
Differential growth under nutritional gradient

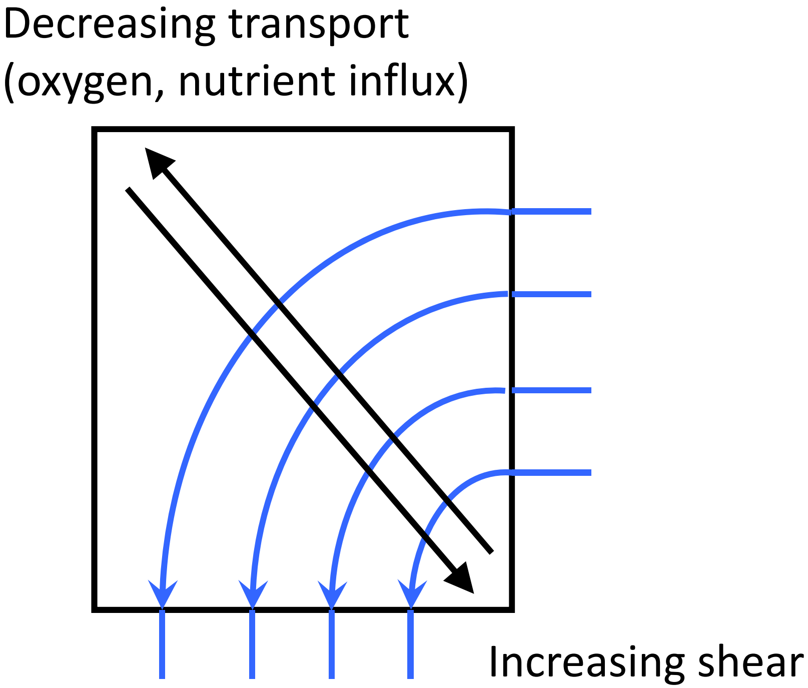




Lee et al. unpublished

Flow cell with imposed turning flow: Simultaneous flow and influx gradient





Zhang et al., 2011

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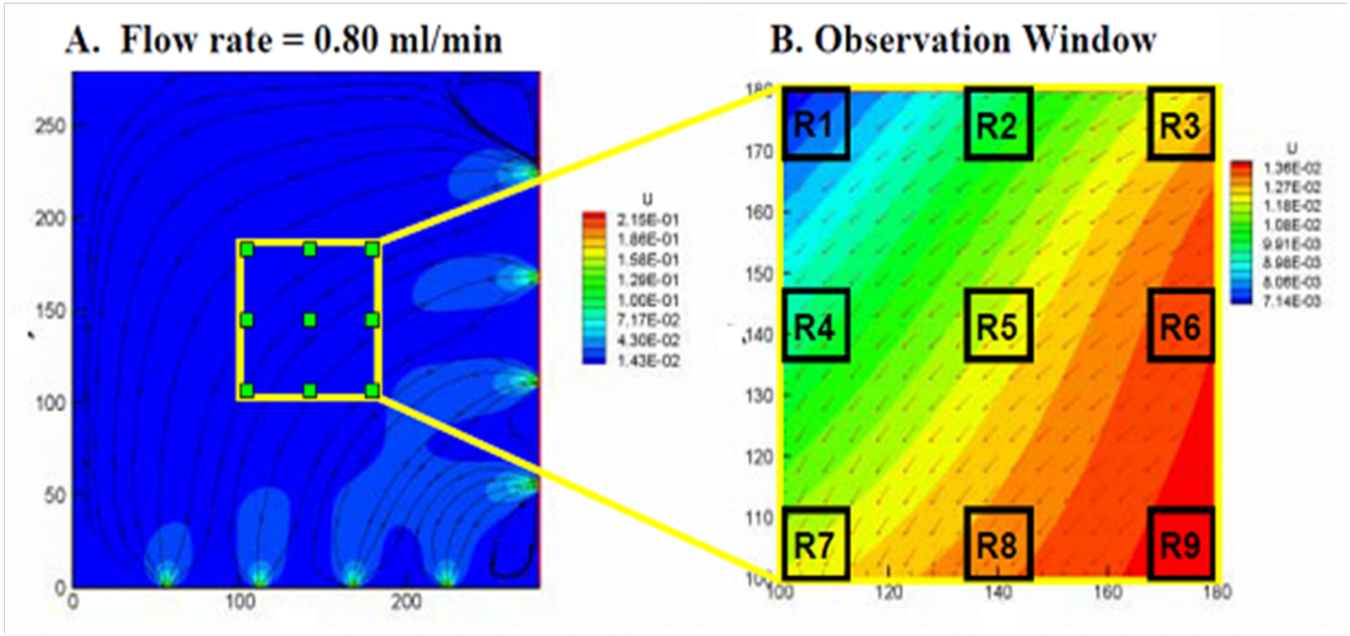
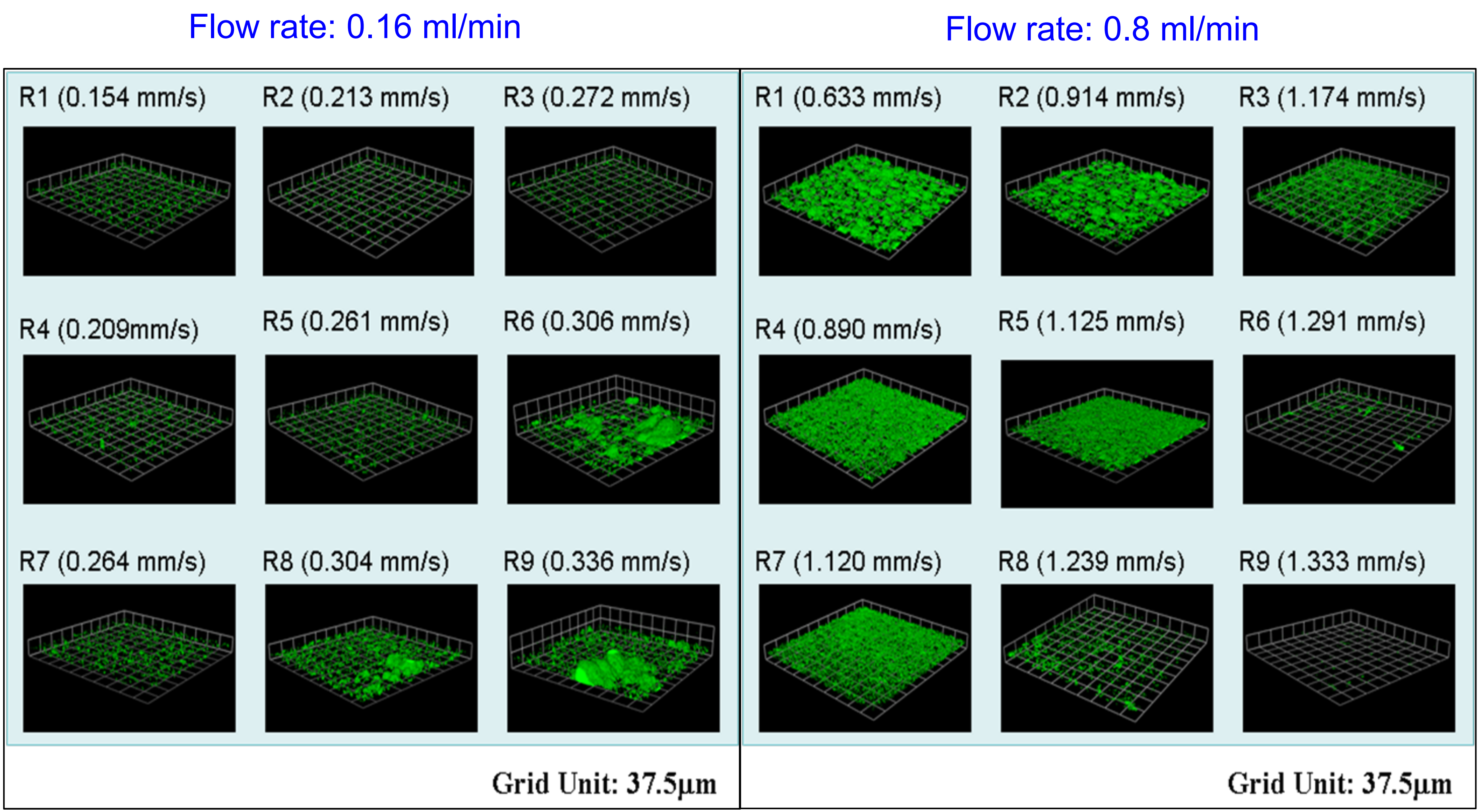


Zhang et al., 2011

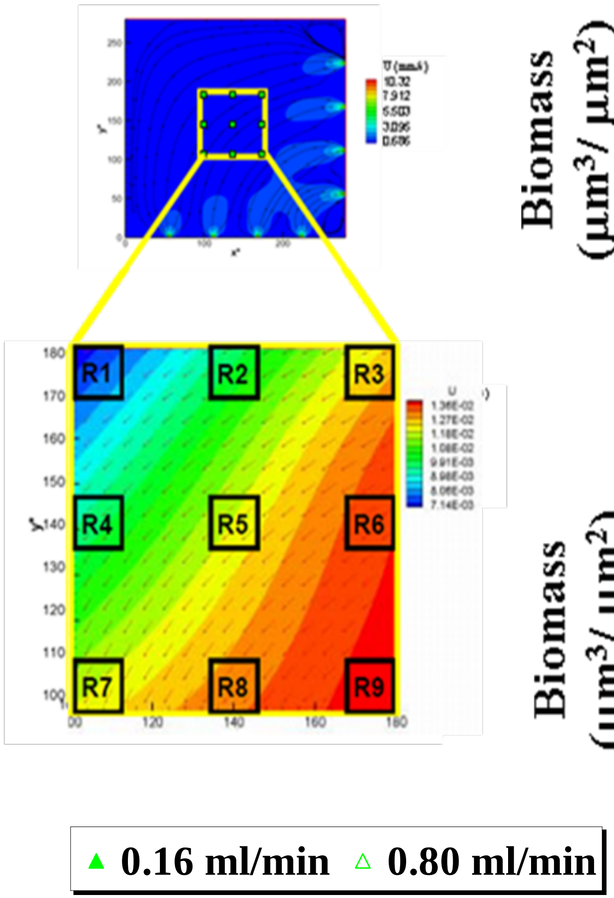
Dramatic spatial patterns under flow gradient

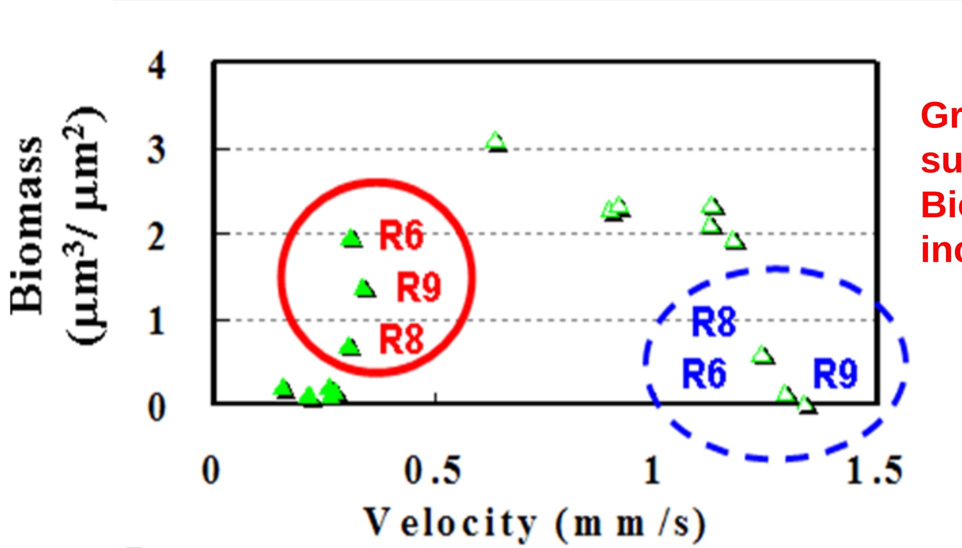


P. aeruginosa PAO1-*gfp*, Medium: 1% LB, T = 7 days

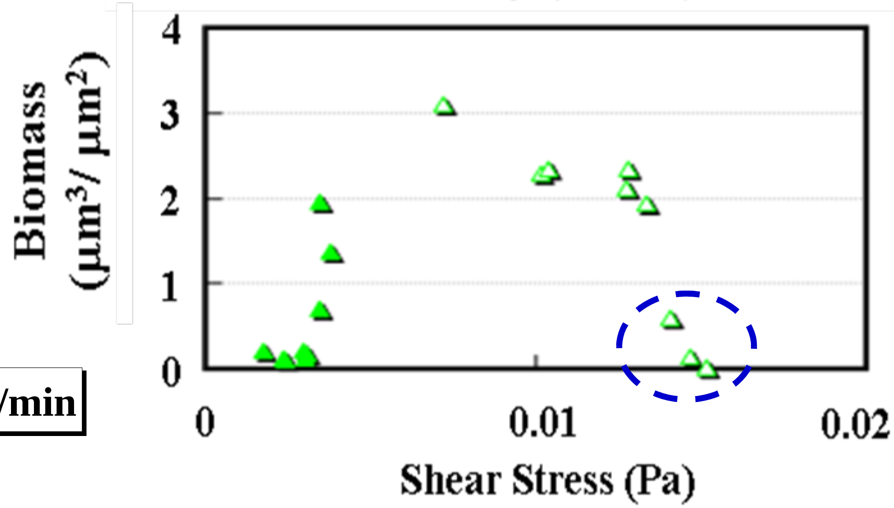
Zhang et al., 2011

Dual transport limitation on growth: Influx and Shear





Growth limitation from substrate availability. Biofilm growth initially increases with influx.

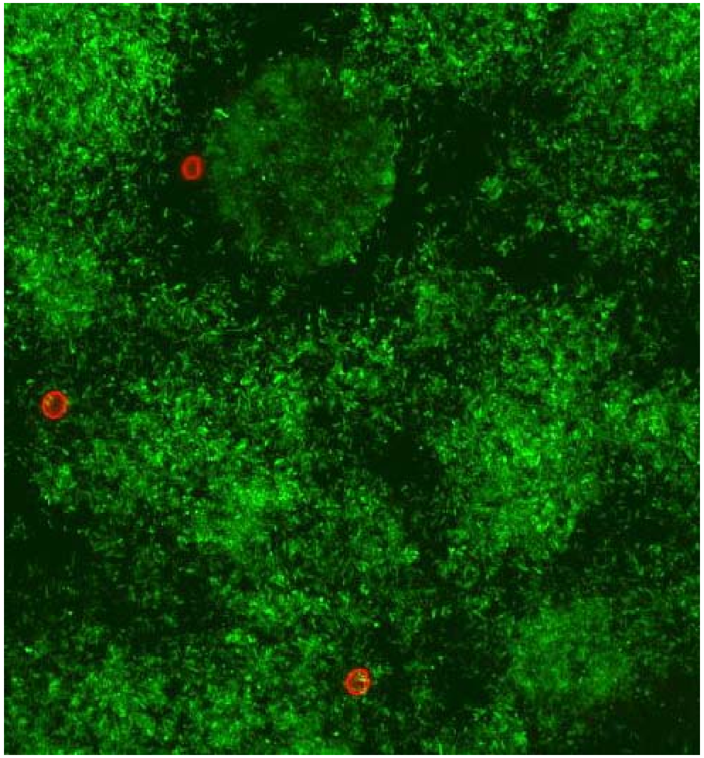


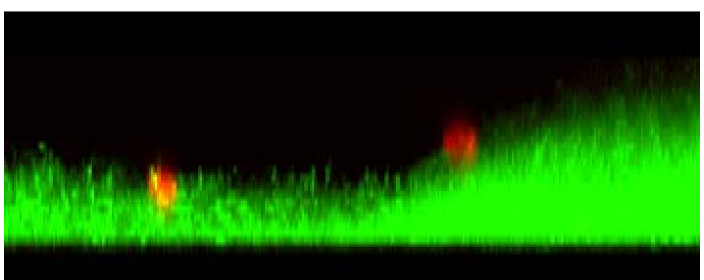
Strong detachment starting at boundary shear of ~0.013 Pa. Almost no biofilm persists at >0.015 Pa.

P. aeruginosa PAO1-*gfp*, Medium: 1% LB, T = 7 days

Zhang et al., 2011

Biofilms capture pathogens





C. parvum oocysts (red) captured by a *Pseudomonas aeruginosa* biofilm (green)

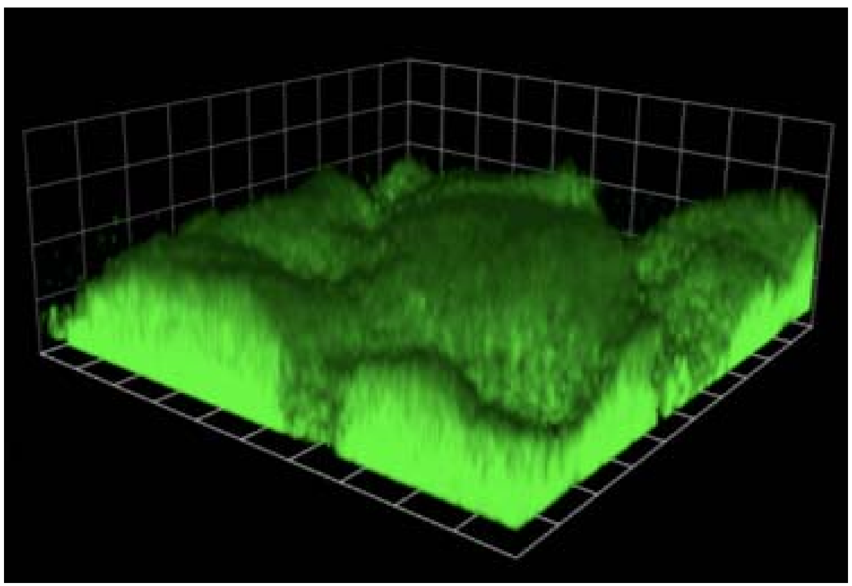
Confocal microscopy resolves 3D spatial structure

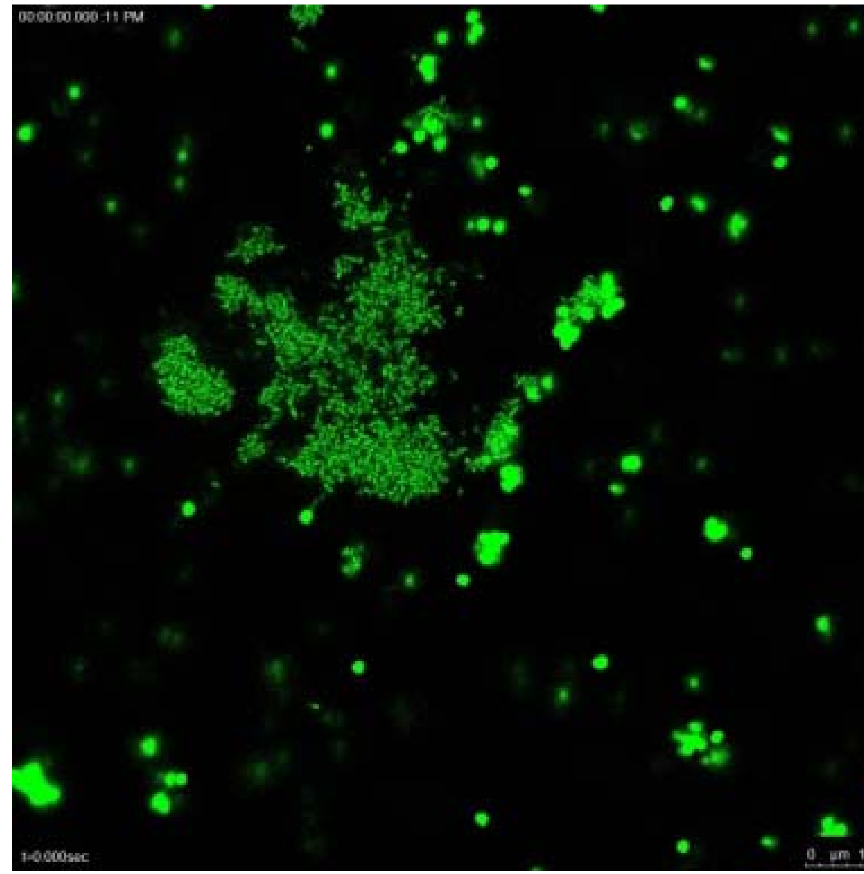
Oocyst capture increases with biofilm roughness

Searcy et al., AEM, 2006b

Dynamic colloid interactions with biofilms

P. aeruginosa biofilm
Cultured in flow cell under 1% TSB medium
Flow rate = 0.01 ml/min, Re = $\mathcal{O}(1)$
3D image: 109 x 109 x 35 μm
Particle tracking with 1 μm fluorescent beads





Lee at el., in prep.

Dynamic colloid interactions with biofilms

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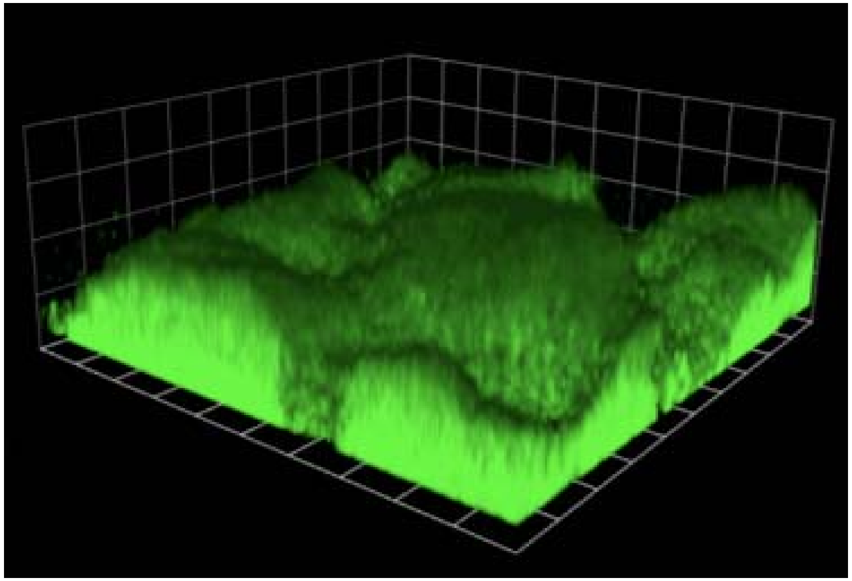

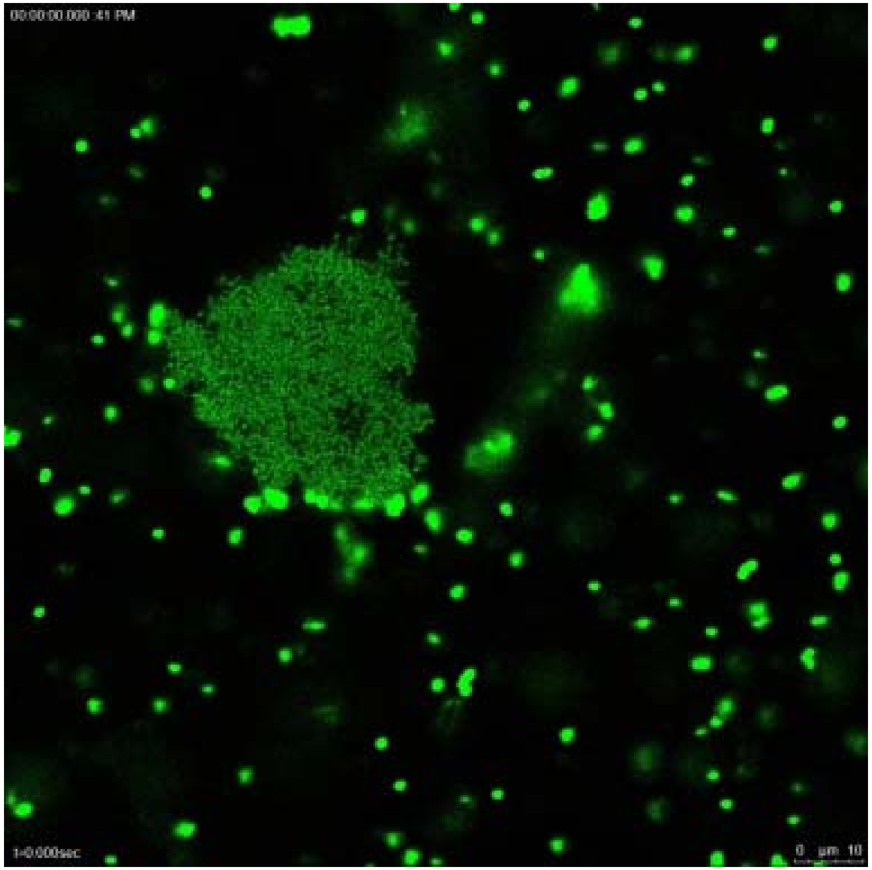

Lee at el., in prep.

Flow quantification by particle tracking velocimetry

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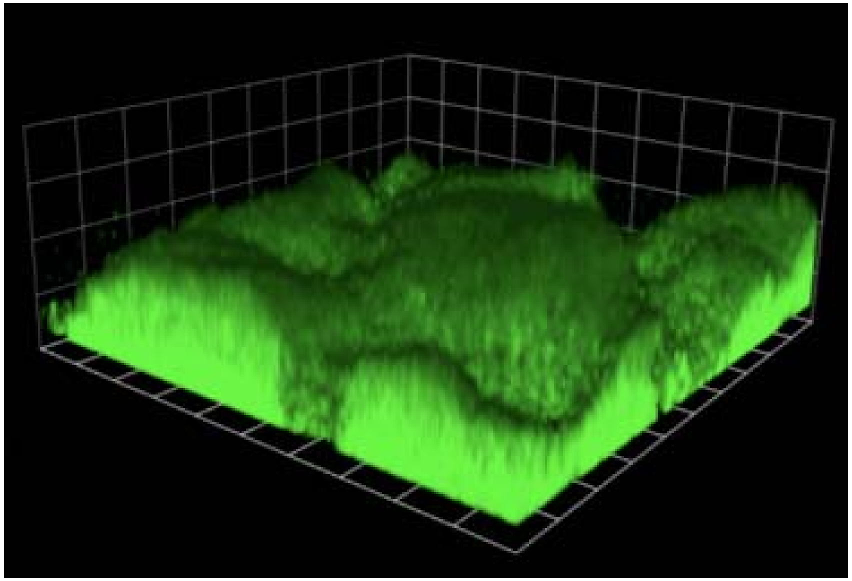
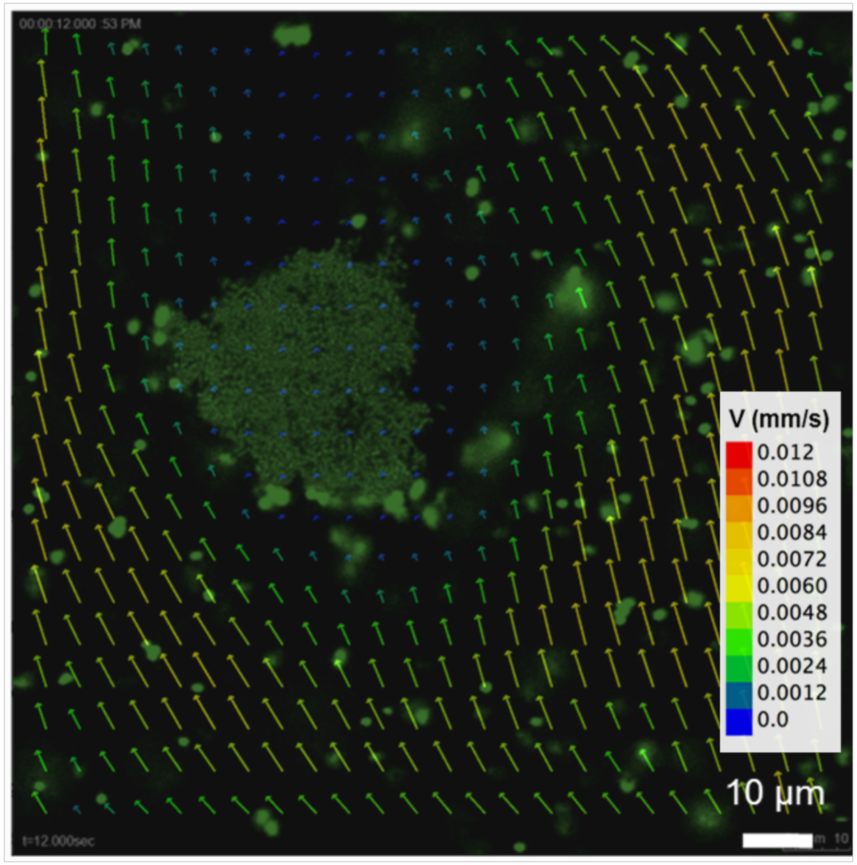
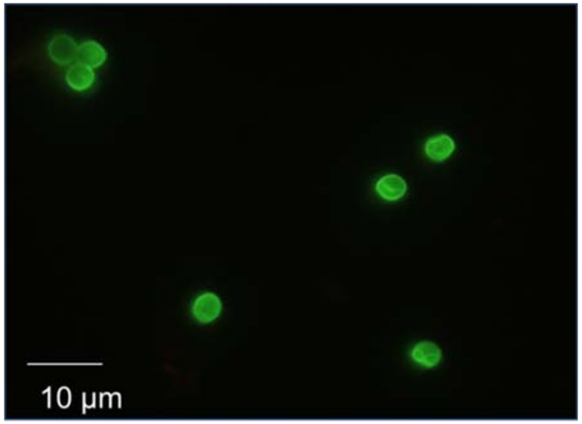


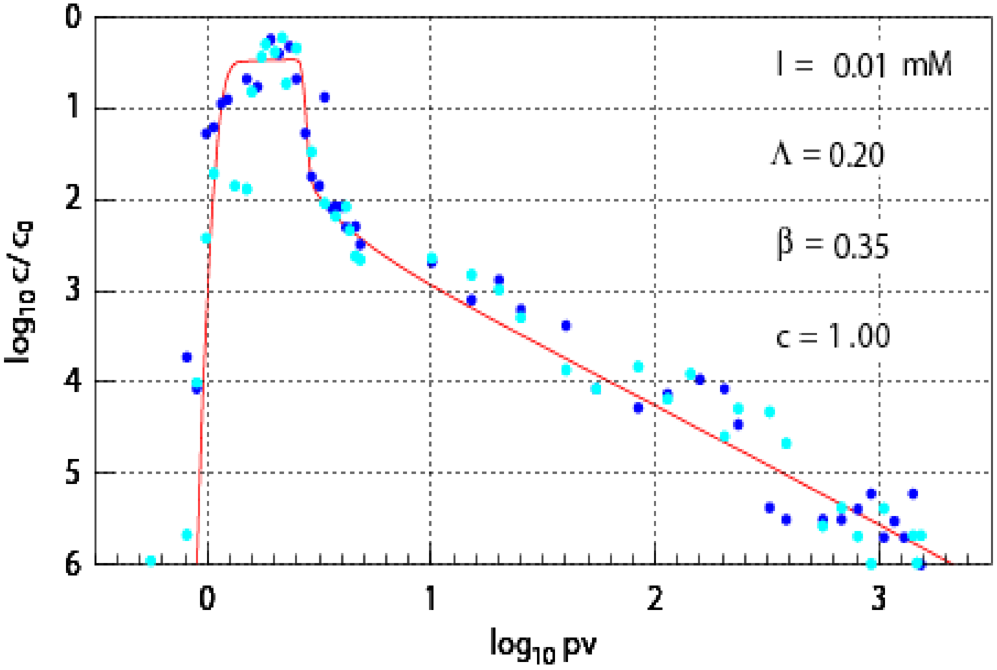


Lee at el., in prep.

Pathogen filtration is also often reversible

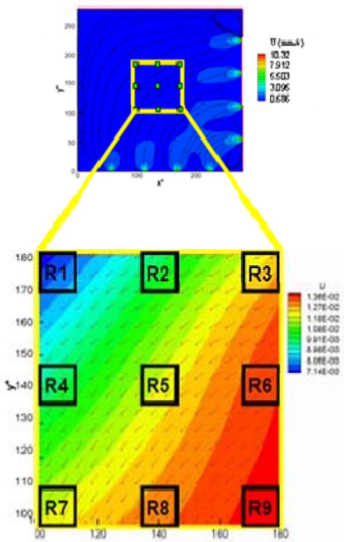


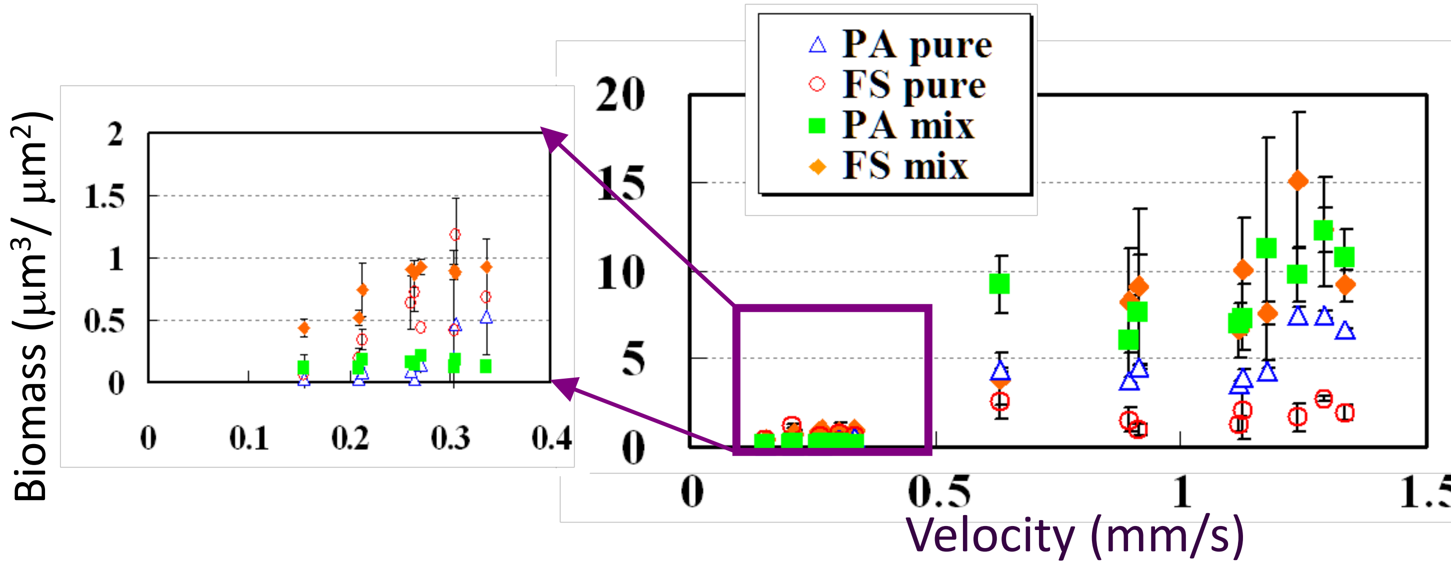
C. parvum transport in a sand column

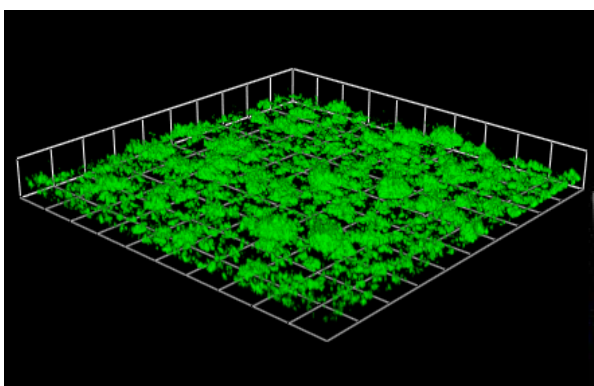


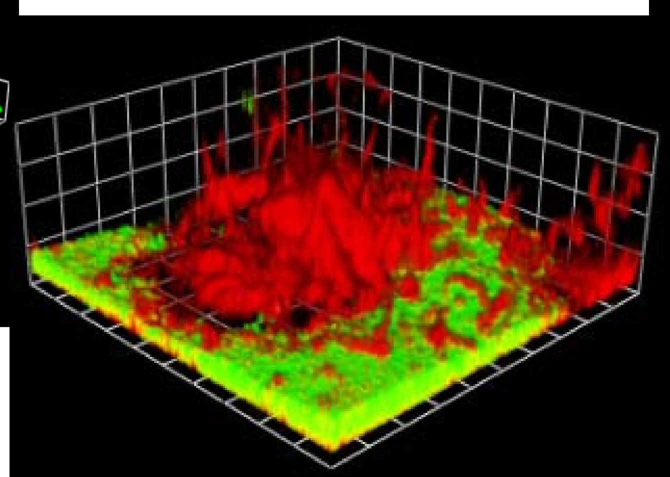
Cortis et al., 2006

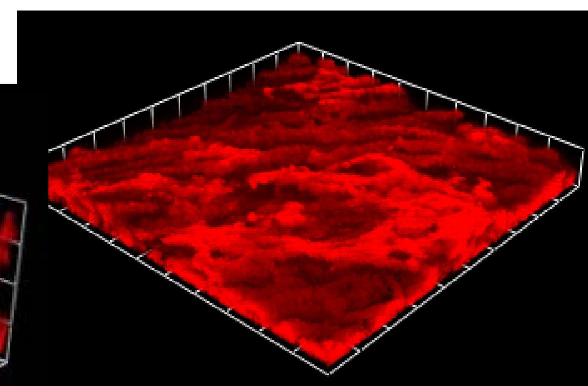
Multi-species biofilms show complex dynamics











P. aeruginosa

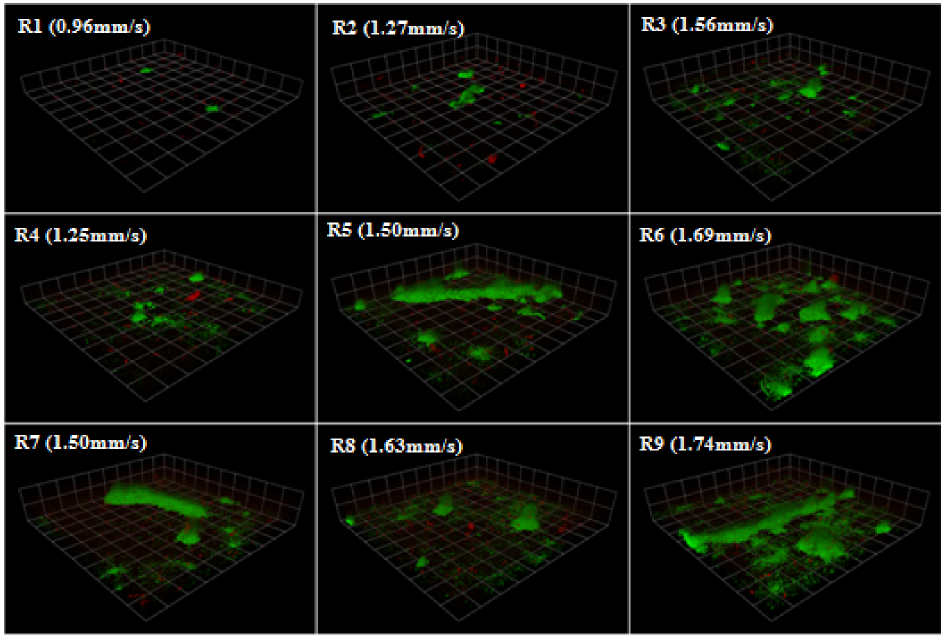
Flavobacterium CDC-65

Zhang et al., FEMS Micro. Ecol., in revision

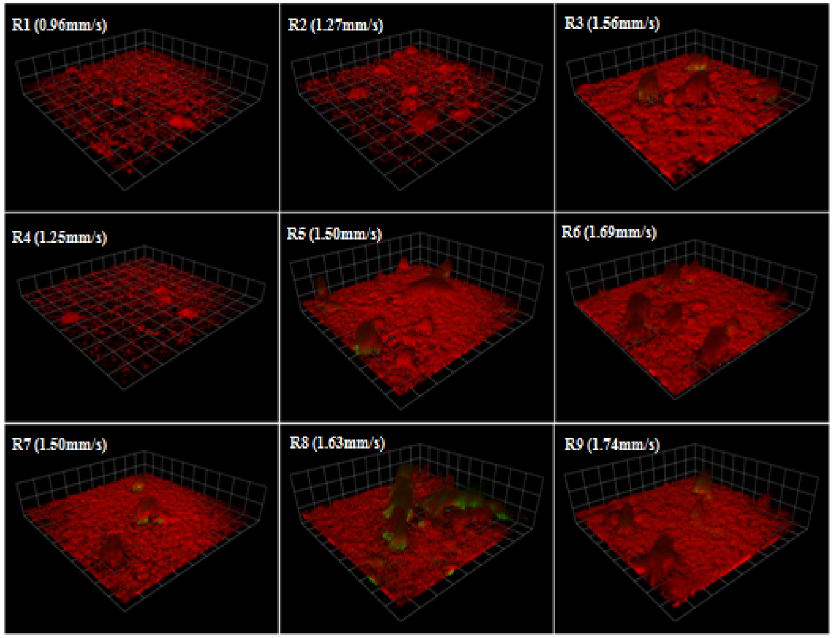
Colonization of biofilms by planktonic cells also depends on flow environment

Colonization of *P. aeruginosa* biofilms by *E. coli* in R2A medium

Deposition of *E. coli* on 3-day *P. aeruginosa* biofilm



Overgrowth by *E. coli* after add'l 3 days

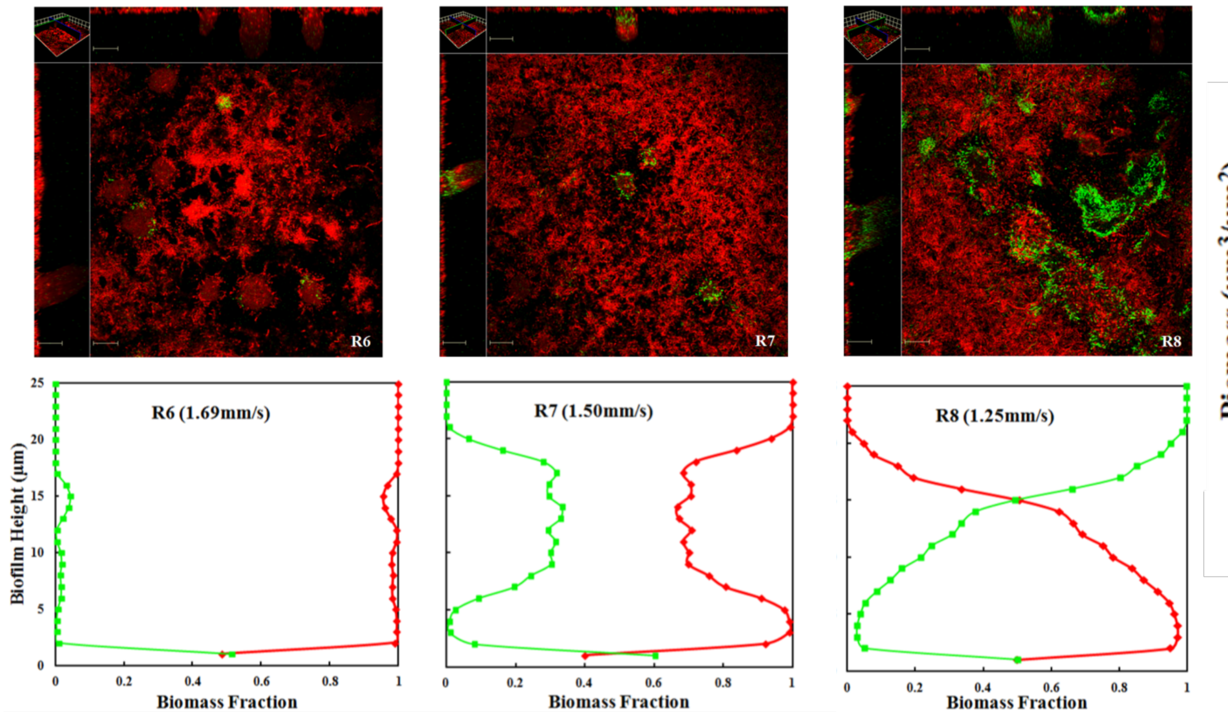


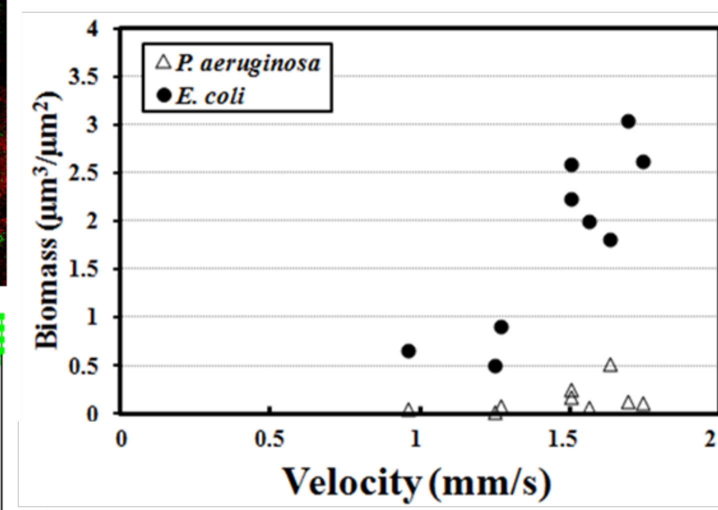
P. aeruginosa

E. coli

Culotti et al., in prep

Colonization of biofilms by planktonic cells also depends on flow environment





P. aeruginosa

E. coli

Culotti et al., in prep

Implications for colloid and pathogen dynamics in rivers

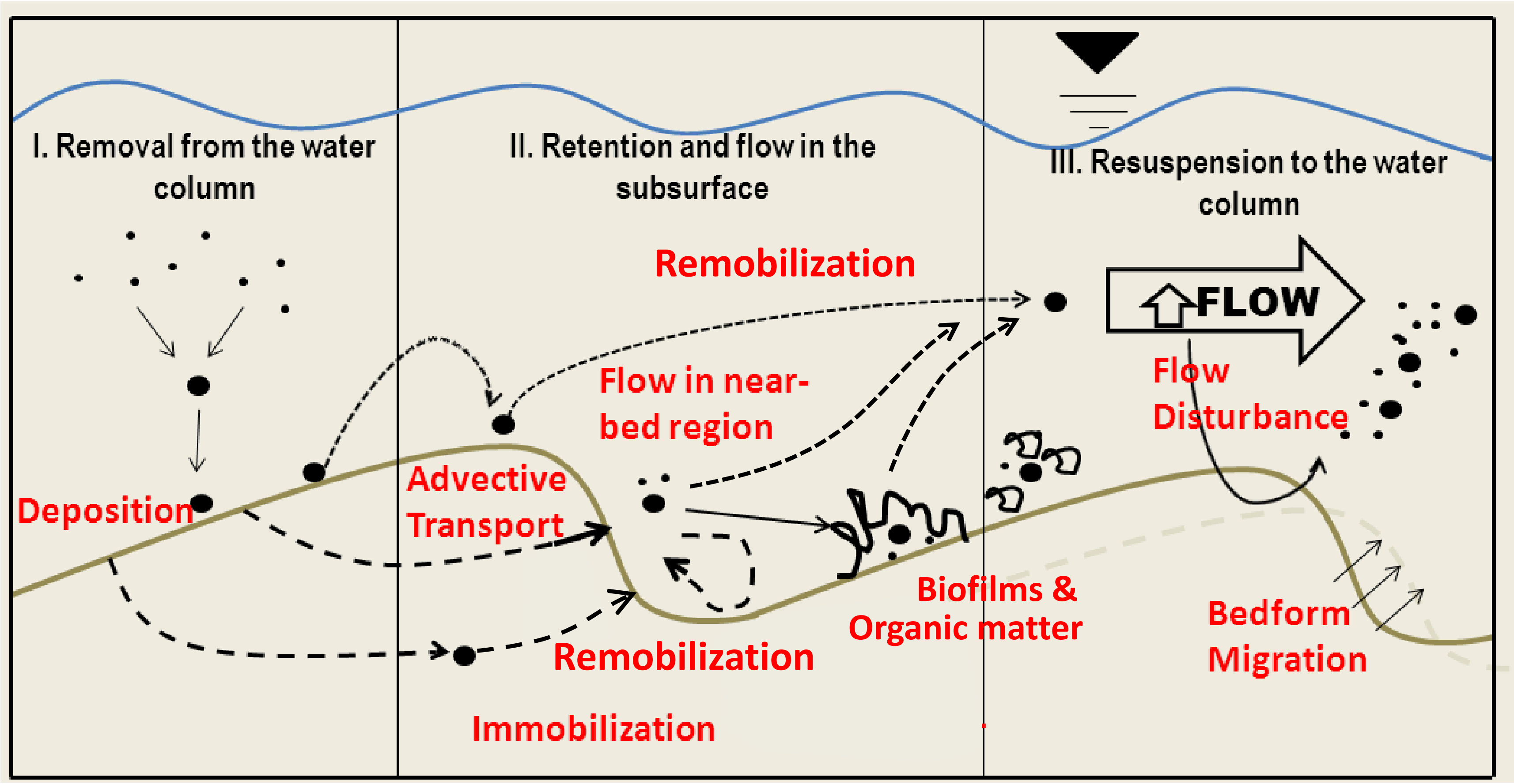

North Saskatchewan River


Difficult Run, VA, USA


Sugar Creek, Indiana, USA

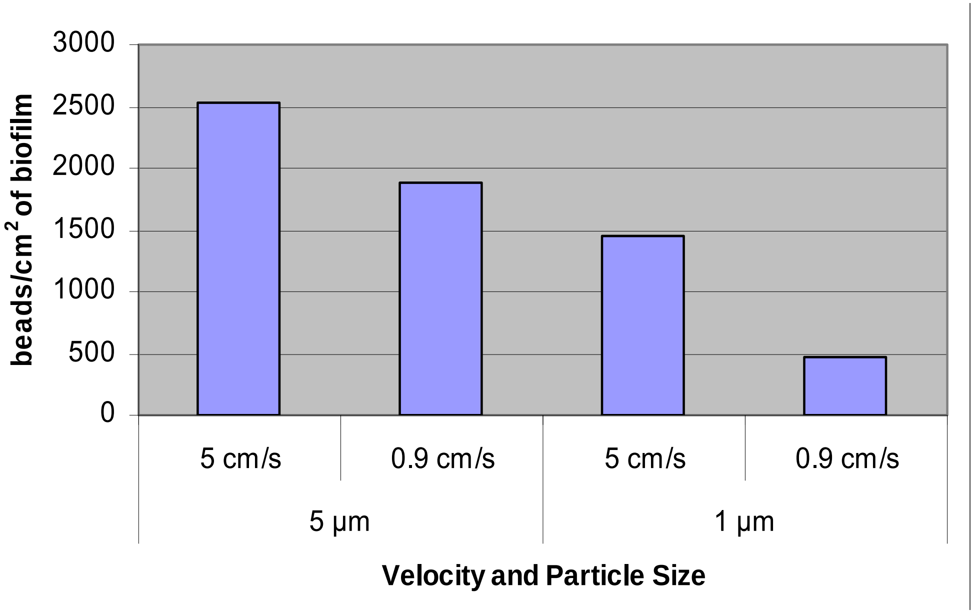

Clear Run, NC, USA

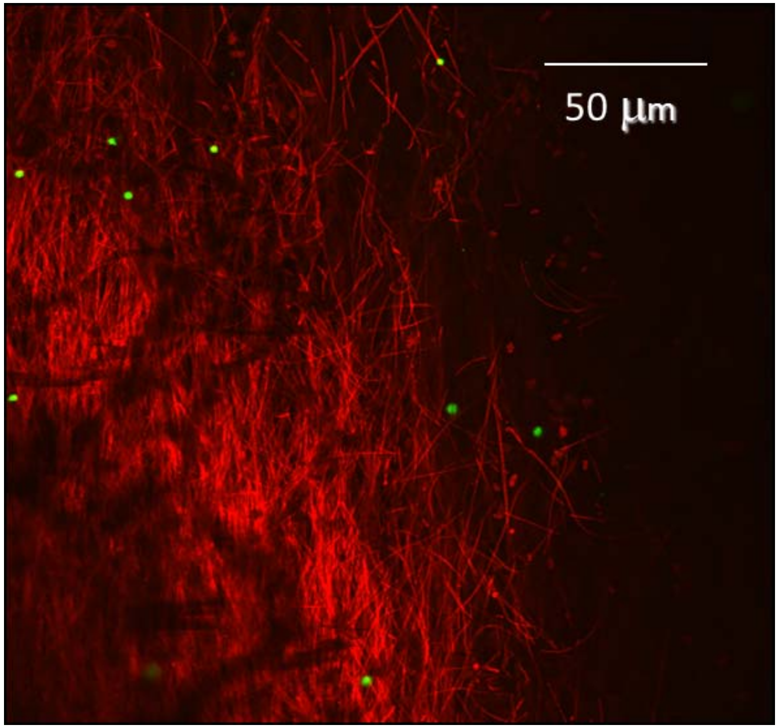
Processes hypothesized to control fine particle deposition, retention, and resuspension in streams



Drawing by Jennifer Drummond and Aaron Packman, Northwestern University

Streambed biofilms capture particles

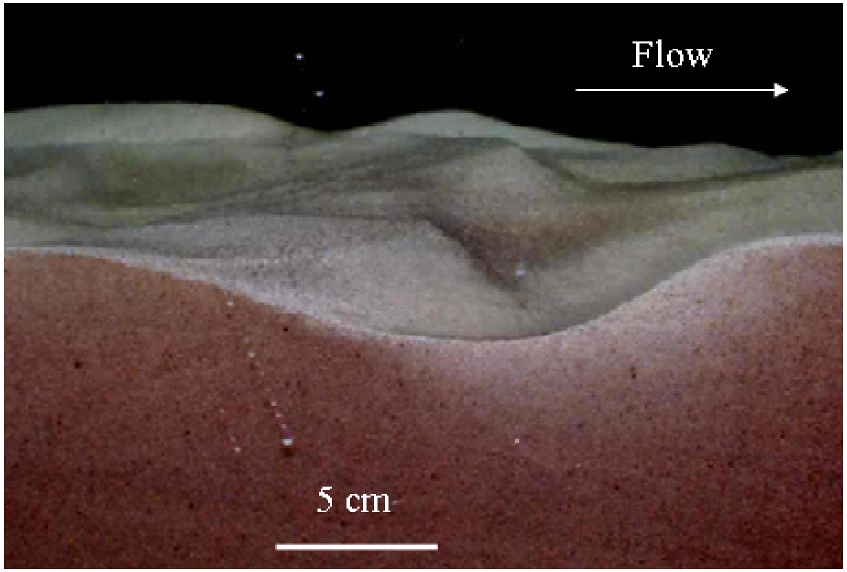


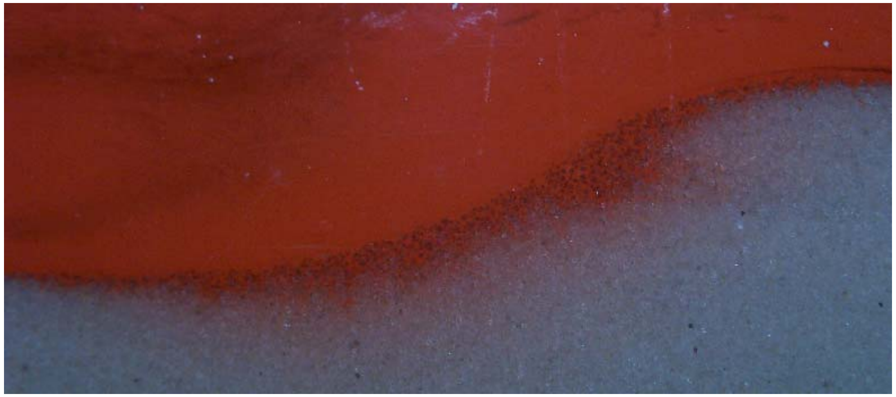


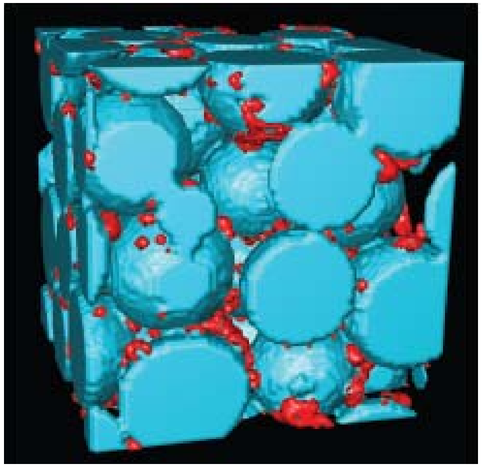
Greater capture of larger colloids particles (5 µm > 1 µm microbeads).
Deposition increased with overlying stream velocity (5 cm/s > 0.9 cm/s)

Arnon et al., 2010

Streambed sediments capture particles too



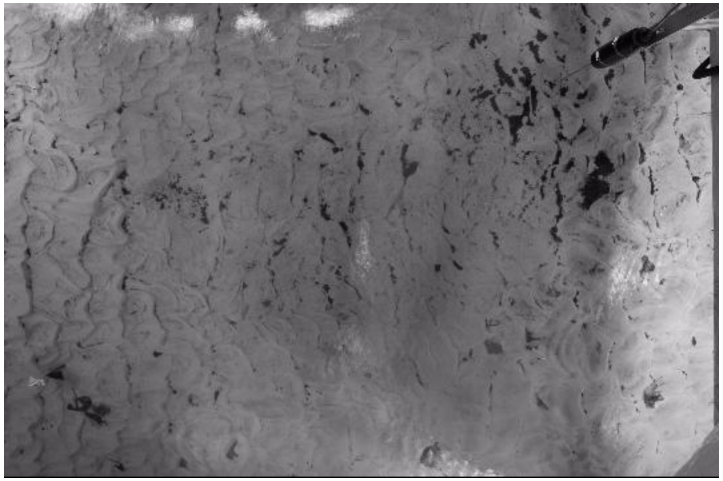




Packman & MacKay, 2003 (WRR); Ren and Packman, 2005 (ES&T); Chen et al., 2009 (WRR, GRL), 2010 (WRR)

Solute and particle injections in Clear Run, NC

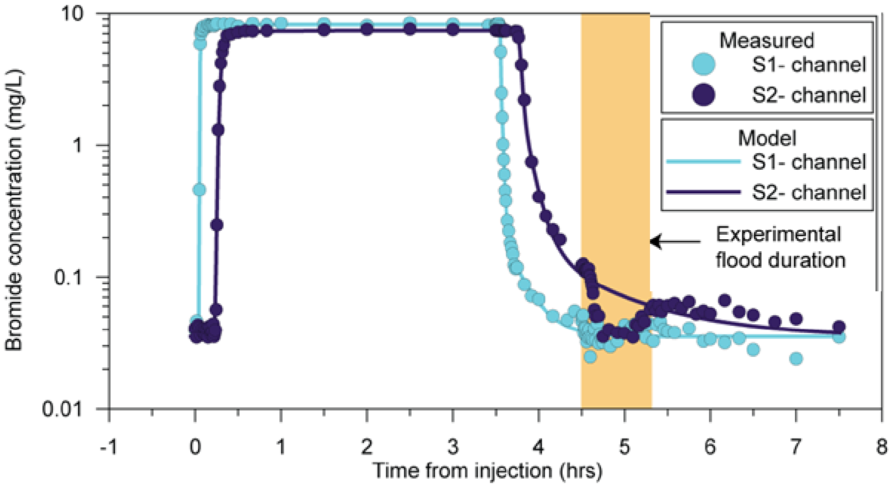
Q ≈ 60 L/s, Width ≈ 3 m, Depth ≈ 6 cm



Harvey et al., 2012, JGR-Biogeosci

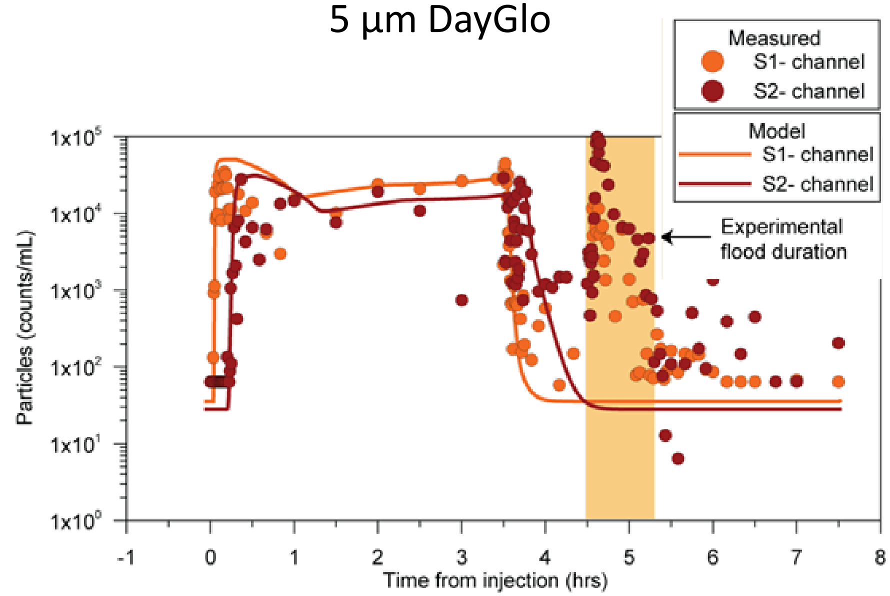
Solute and particle injections in Clear Run, NC under baseflow and artificial flood

Conservative tracer



Fluorescent fine particles

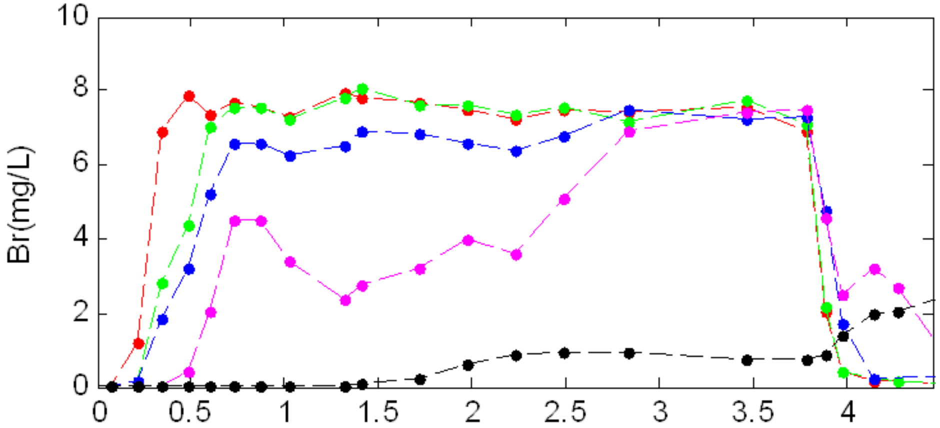
5 µm DayGlo



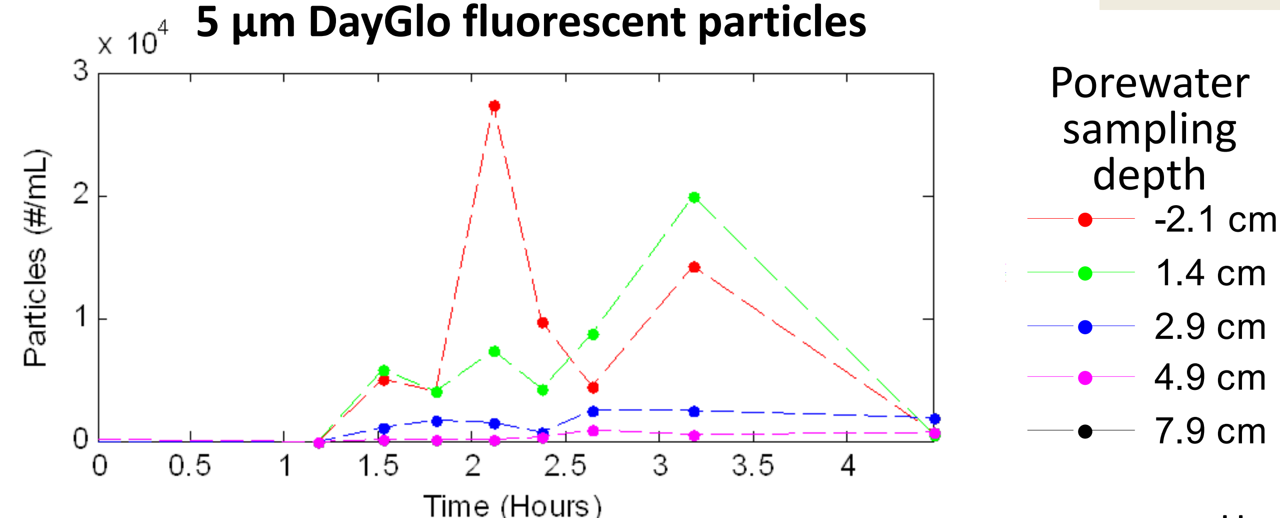
Harvey et al., 2012, JGR-Biogeosci

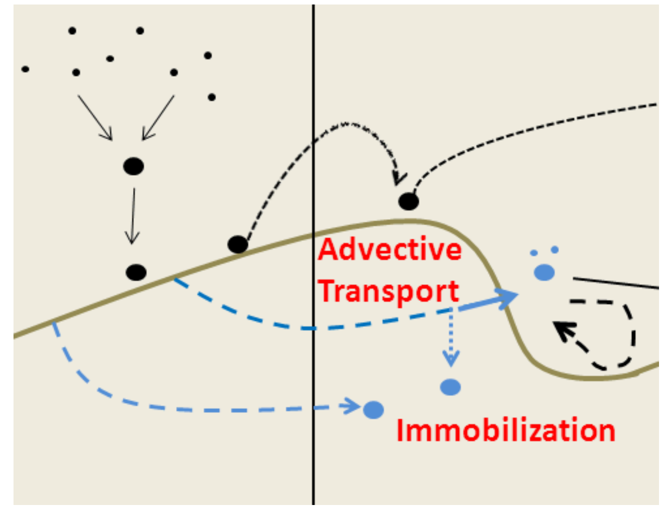
Direct evidence of subsurface transport of stream-borne colloids

Conservative Tracer: Bromide



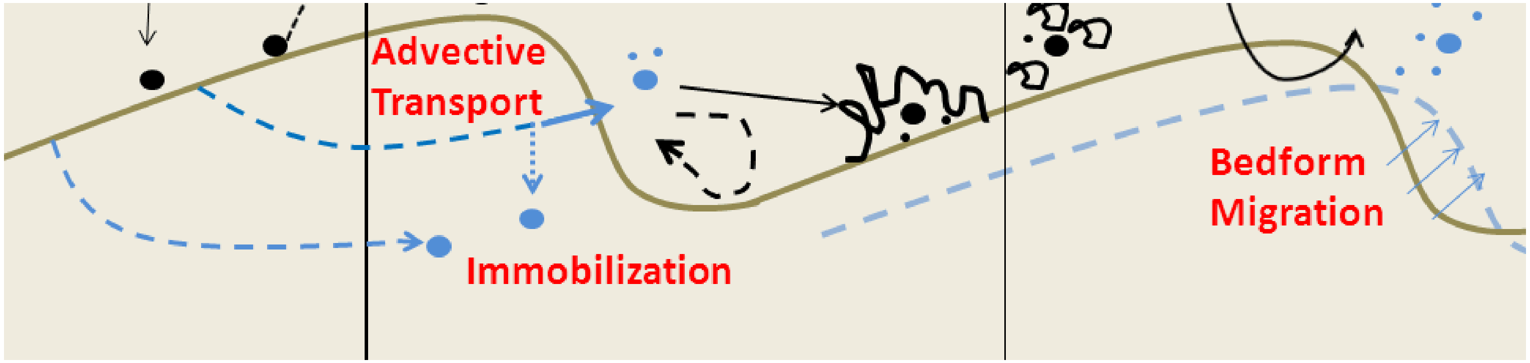
5 µm DayGlo fluorescent particles

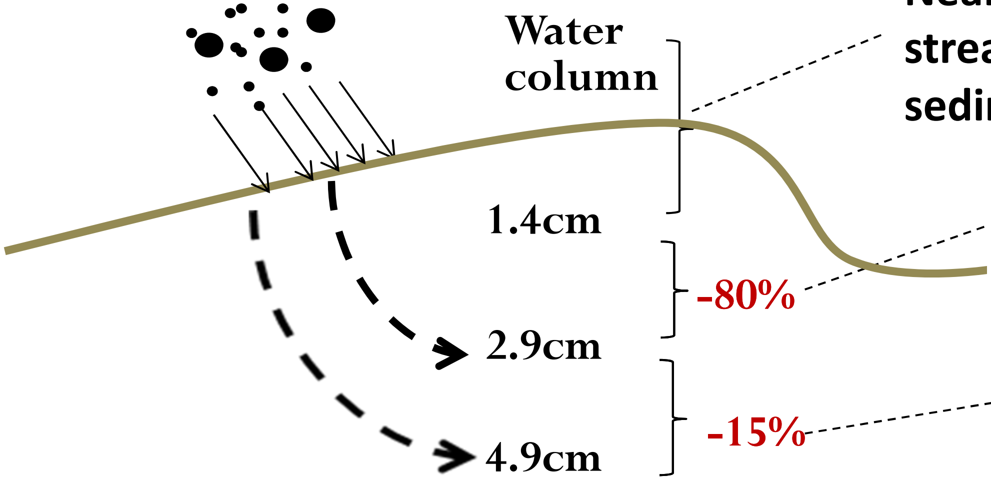




Harvey et al., 2012, JGR-Biogeosci

Direct evidence of colloid accumulation in sediments





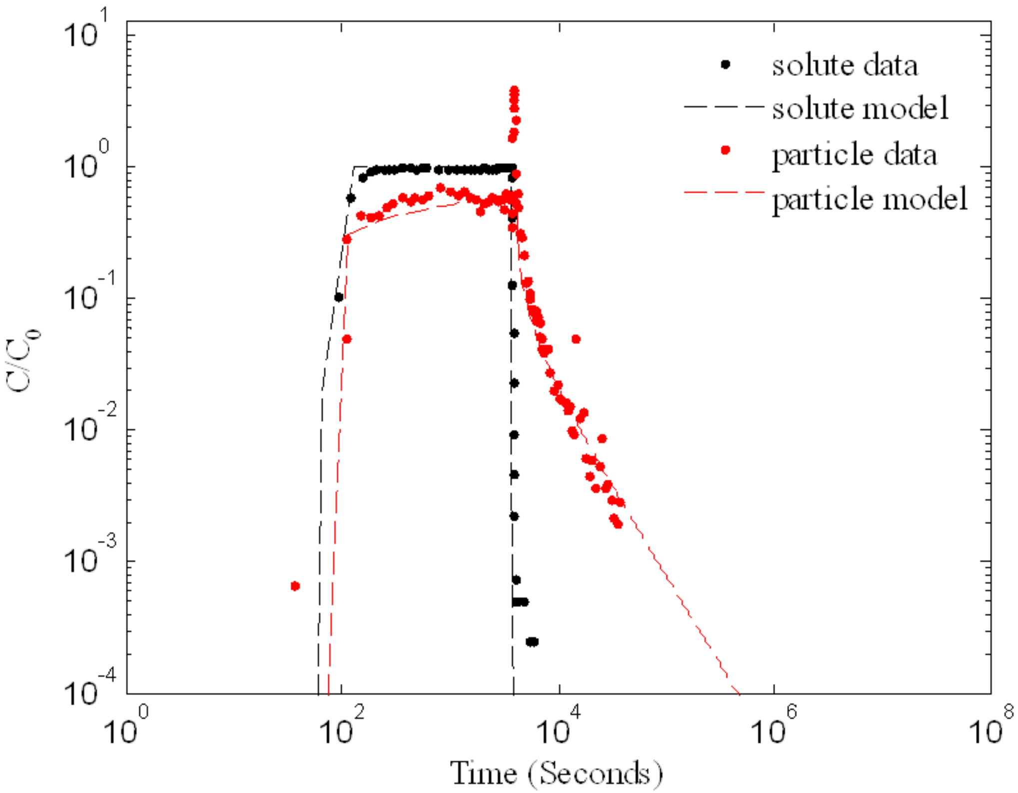
Near-surface concentrations followed in-stream concentrations because of bed sediment transport

80% at depths between 1.4 and 2.9 cm (deposited+mobile)

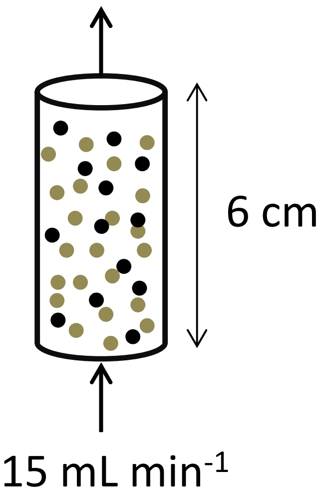
15% at depths between 2.9 and 4.9 cm (deposited+mobile)

Harvey et al., 2012, JGR-Biogeosci

Reversible filtration observed with natural streambed sediment in column experiment



Conservative Tracer: Lithium
Fine Particle Tracer: 5 µm DayGlo fluorescent particles

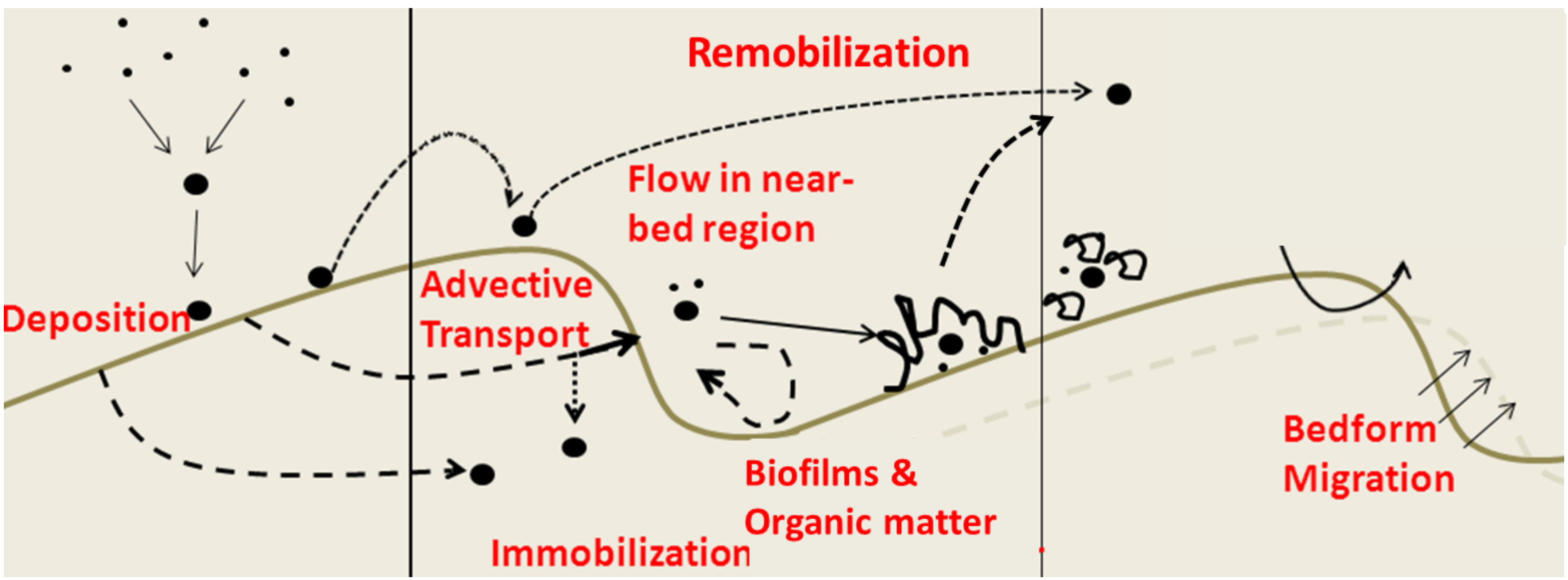


Mobile-Immobile Random Walk Model fit:
Lithium Advection-Dispersion + almost no storage
Colloid Advection-Dispersion + power law storage (heavy tail)

Drummond et al., in prep.

Colloid remobilization by hyporheic exchange, reversible filtration, and bed sediment transport

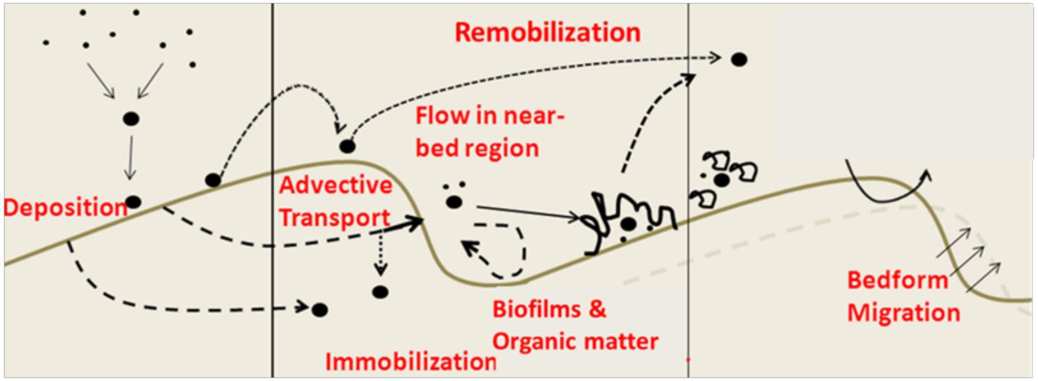
Direct evidence for ongoing efflux of suspended particles from bed during baseflow. Likely also ongoing turbulent resuspension.



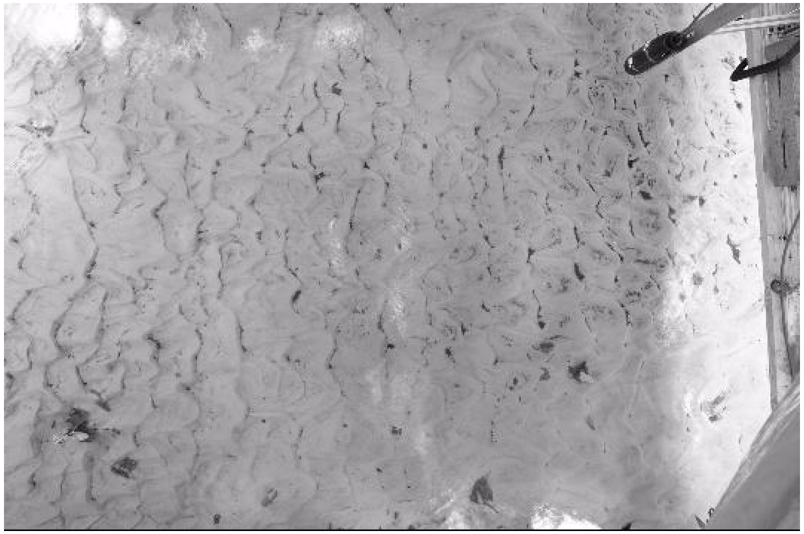
Drummond et al., in prep.

Strong colloid resuspension during floods associated with bed sediment transport

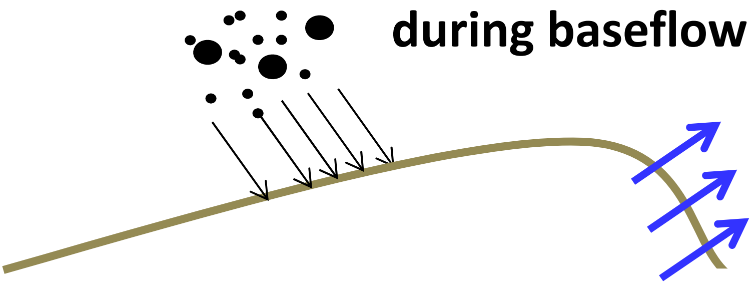
Baseflow



Floodflow

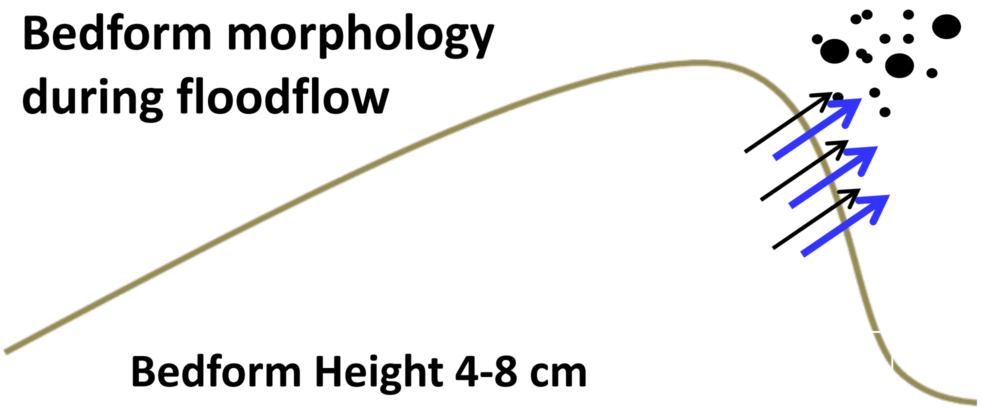


Bedform morphology during baseflow



Bedform Height 1-2 cm
Crest Migration Rate 0.4 ± 0.3 cm s^{-1}

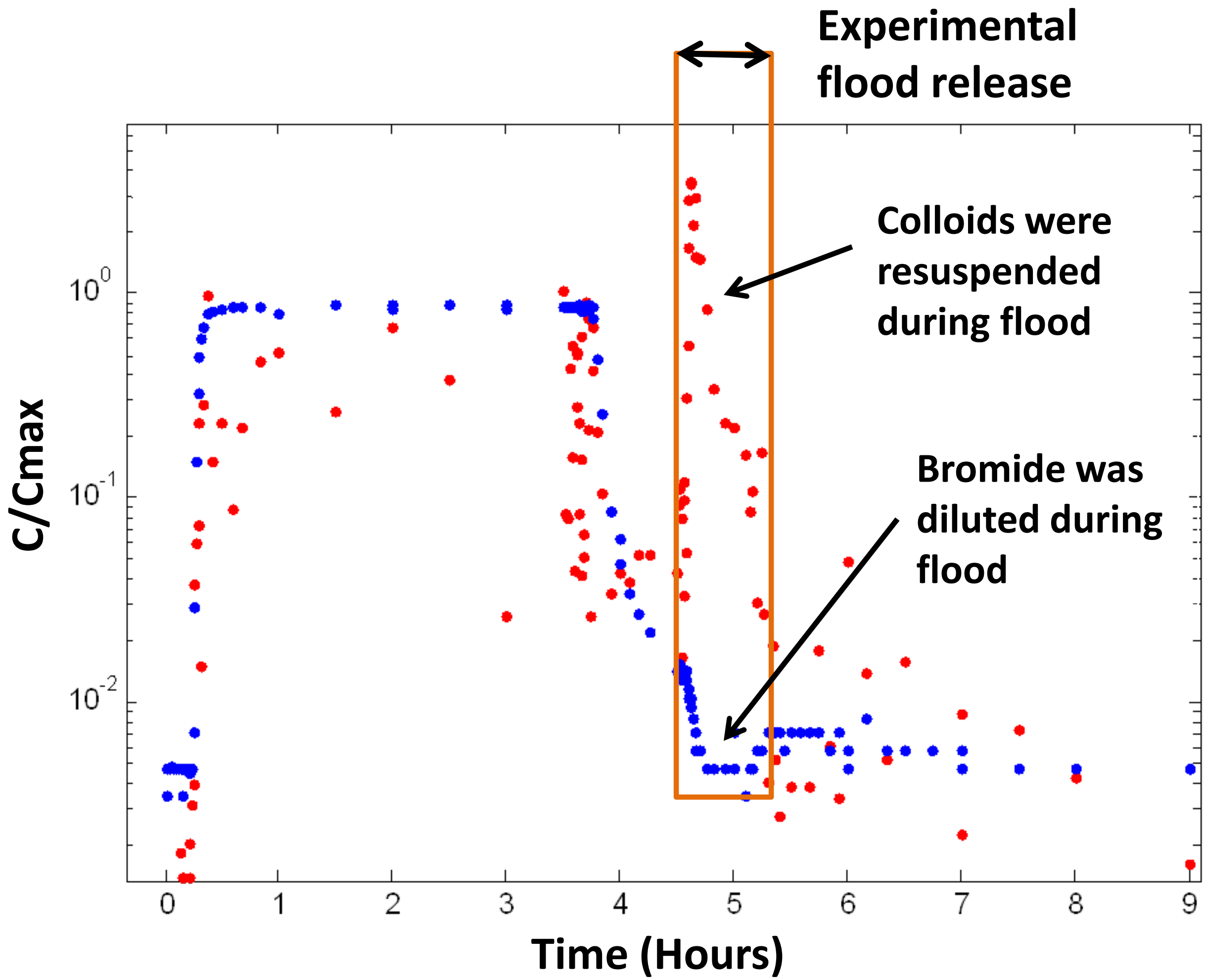
Bedform morphology during floodflow



Bedform Height 4-8 cm
Crest Migration Rate 3.4 ± 2.4 cm s^{-1}

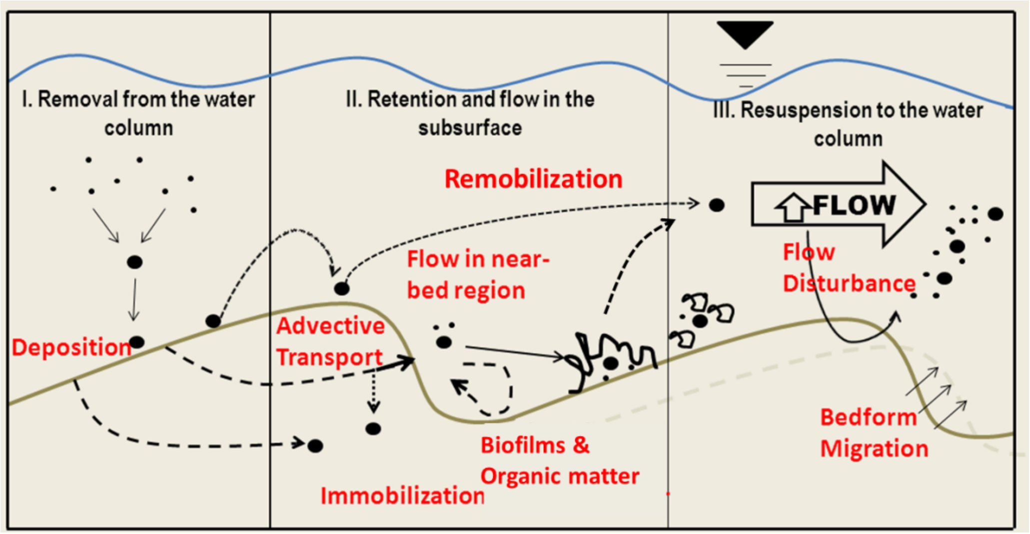
Drummond et al., in prep.

Direct evidence of strong colloid resuspension during floods: Colloid export in stream



Harvey et al., 2012, JGR-Biogeosci

Proposed mobile/immobile model for colloid and pathogen transport in rivers with multiple convolution of different processes



Convolution of the following processes:

- Advective exchange
- Settling/sedimentation
- Subsurface filtration
- Subsurface heterogeneity
- Turbulent deposition/resuspension
- Retention/release in biofilms
- Bedform turnover
- Streamflow variations

Mobile/immobile model for downstream transport

Assume motion can be represented by an uncoupled jump PDF:

$$\Psi(x,t) = \lambda(x)\,\psi(t)$$

In-stream Brownian motion

Subsurface retention

$$\frac{\partial C}{\partial t} = -U\frac{\partial C}{\partial x} + K\frac{\partial^2 C}{\partial x^2} - \int_0^t \frac{\partial C(t-\tau)}{\partial t} M(\tau)\,d\tau$$

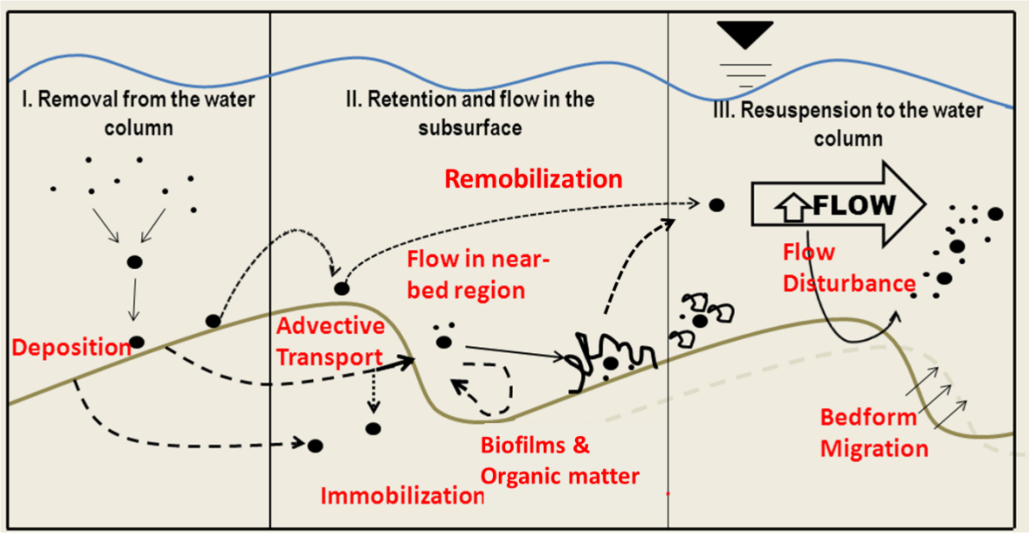
Mobile, in-stream transport

Immobile, subsurface

Can represent multiple processes in memory function by convolution

Haggerty et al., 2002; Wörman et al., 2002; Boano et al., 2007, Marion et al.,2008

Proposed model: Mobile/immobile random walk with multiple convolution of different processes



Convolution of the following processes:

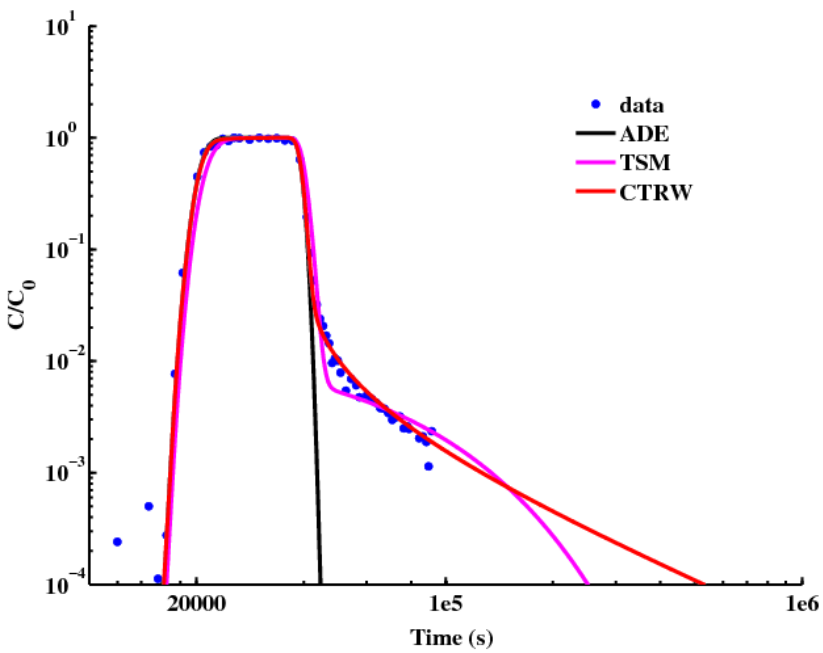
- Advective exchange
- Settling/sedimentation
- *Irreversible* filtration
- *Weak* subsurface heterogeneity
- Turbulent deposition/resuspension
- Retention/release in biofilms
- Bedform turnover
- Streamflow variations

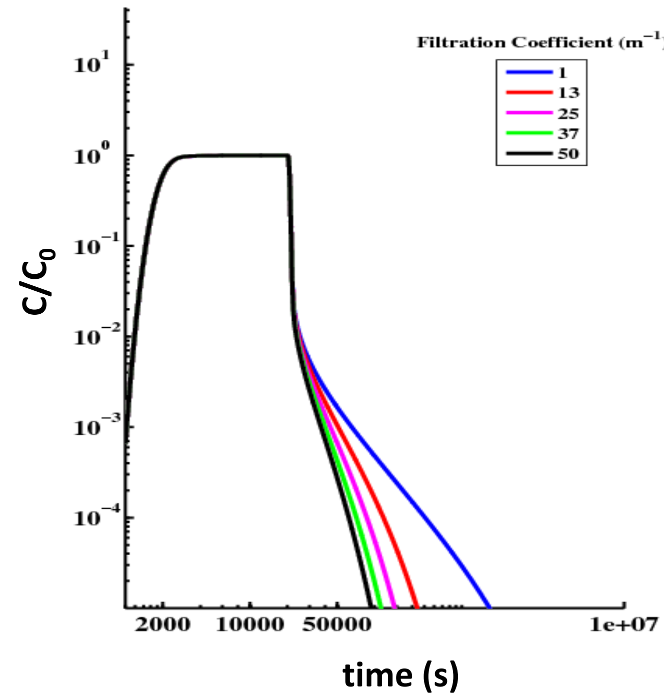
Packman et al., 2000ab; Boano et al., 2007; Aubeneau et al., in prep.

Solute and particle BTC’s

Simulation of conservative solute transport (data from Johansson et al., 2001)

Simulation of particle transport with irreversible filtration (1st order removal)





$$\tilde{\psi}(u) = \tilde{\psi}_0[u + \sum_{i=1}^{n} \Lambda(i) - \Lambda(i)\tilde{\varphi}_i(u)]$$

$$\tilde{\psi}(u) = \tilde{\psi}_0[u + \sum_{i=1}^{n} \Lambda(i) - \Lambda(i)\tilde{\varphi}_i(u) * (1u - k_i)]$$

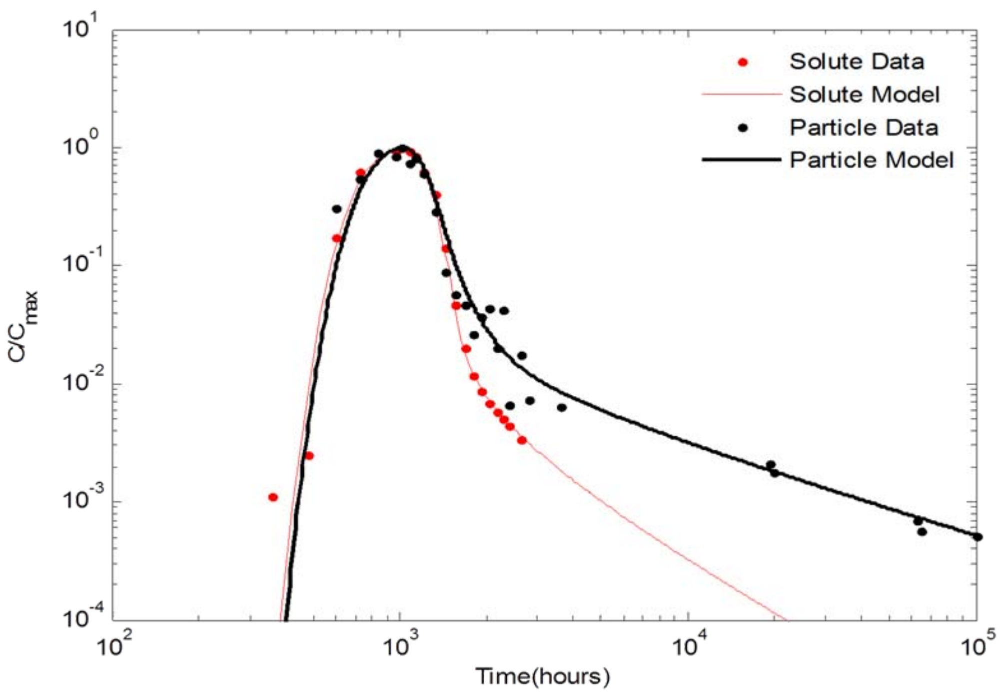
Aubeneau et al., in prep.

Inverse modeling of fine particle dynamics

Newbold et al., 2005

Bloomington Creek, Idaho

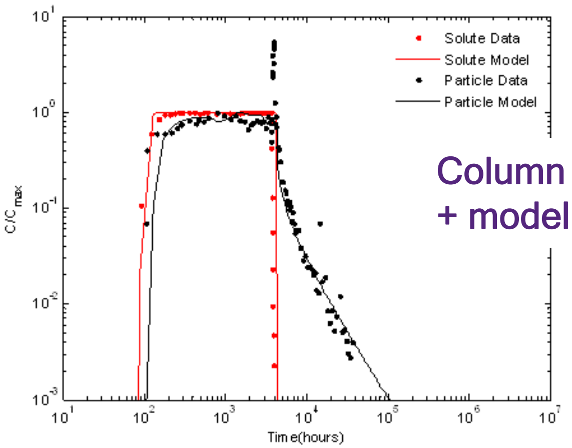
Tracers: Rhodamine + ^{14}C-labeled fine particulate organic matter



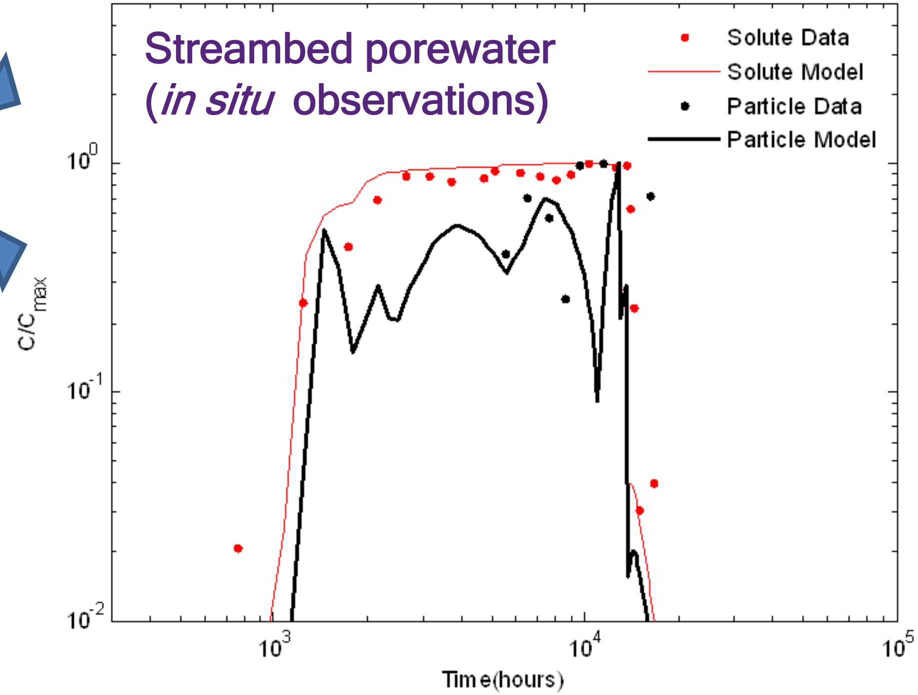
Predictive modeling

Clear Run, NC, *Harvey et al.*, 2012

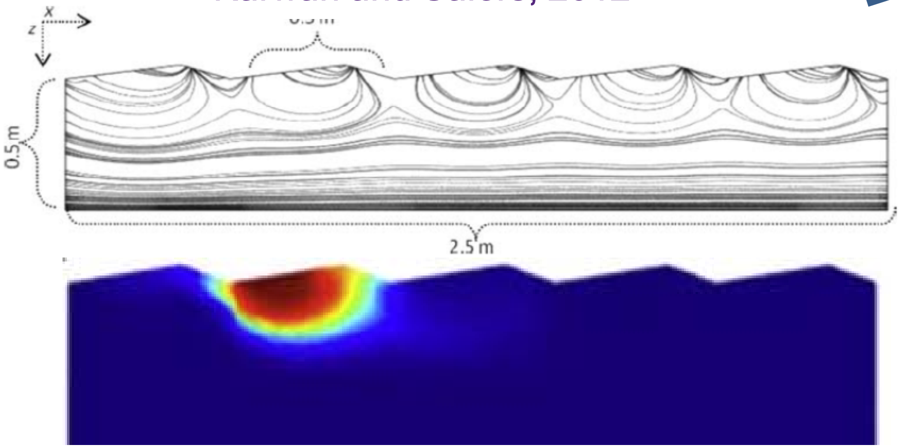
<u>Tracers</u>: Bromide; Dayglo fluorescent microspheres



Column experiment data + model (*ex situ*)

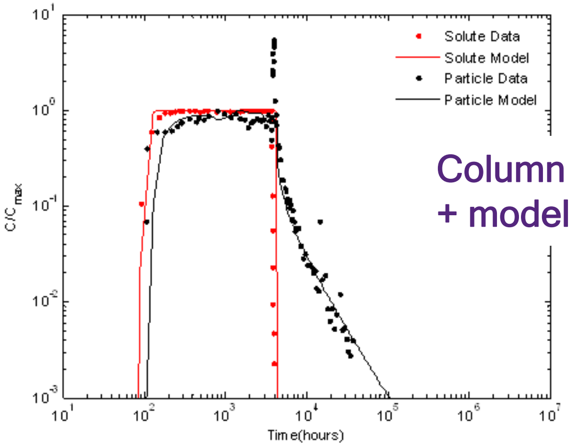


Porewater flow and filtration
Karwan and Saiers, 2012

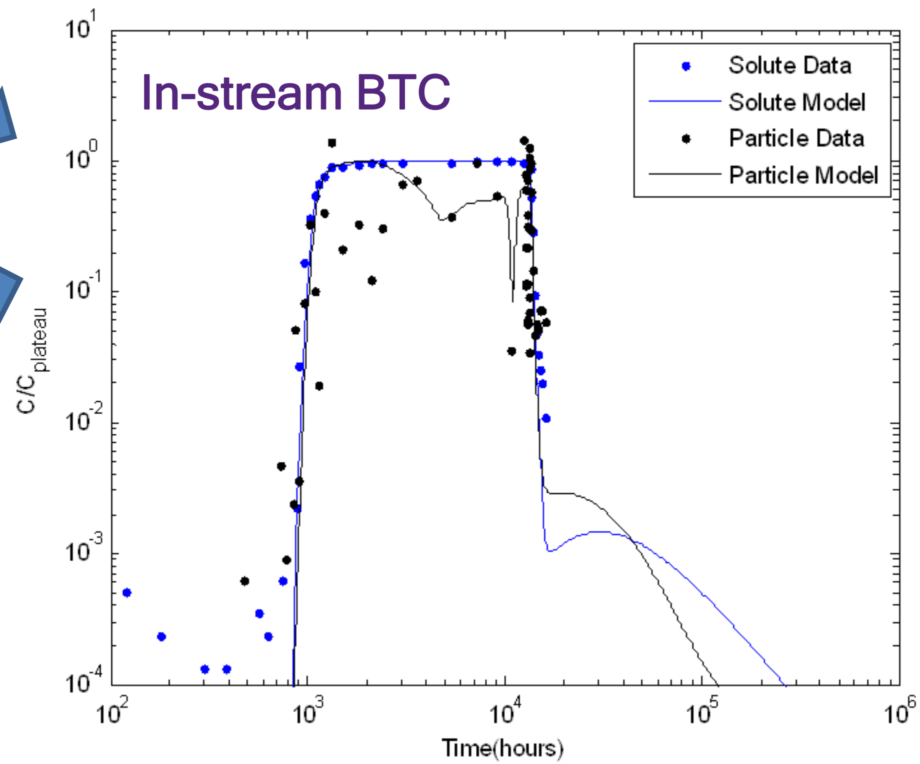


Predictive modeling

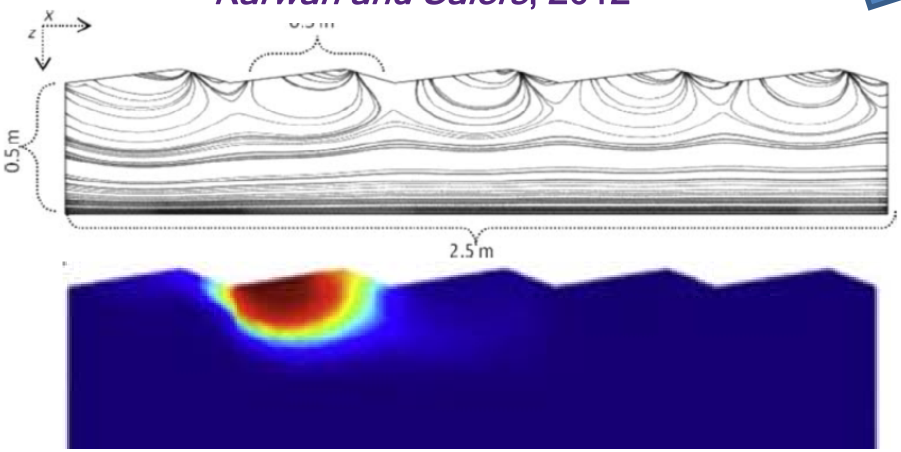
Clear Run, NC, *Harvey et al.*, 2012
<u>Tracers</u>: Bromide & Dayglo fluorescent fine particles



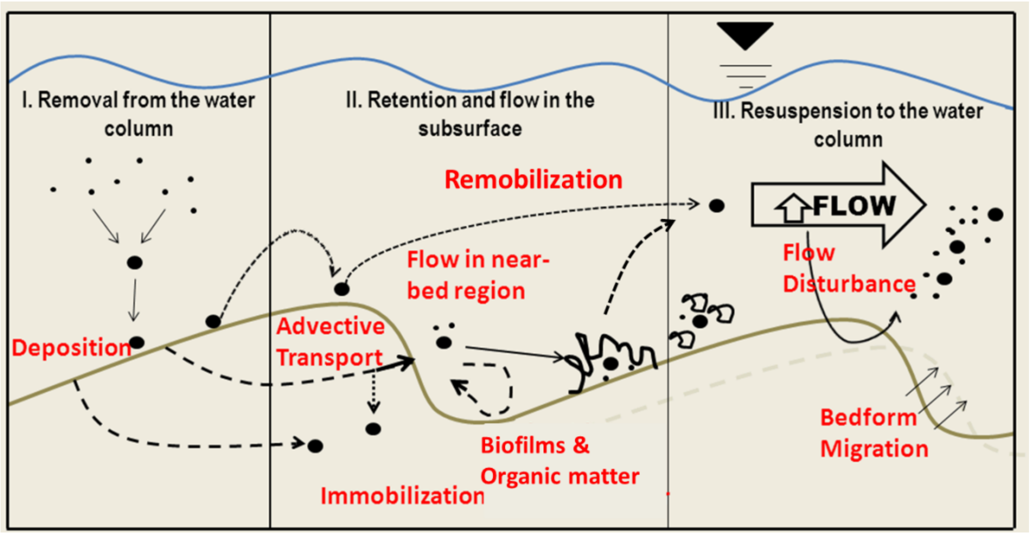
Column experiment data + model (*ex situ*)



Porewater flow and filtration
Karwan and Saiers, 2012



Proposed model: Mobile/immobile random walk with multiple convolution of different processes

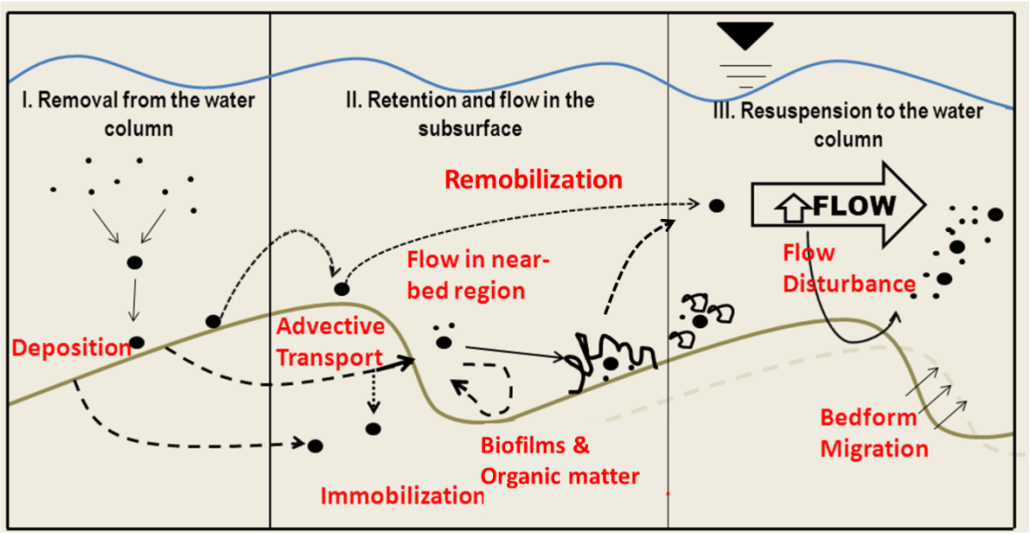


Convolution of the following processes:

- Advective exchange
- Settling/sedimentation
- *Reversible* filtration
- *Weak* subsurface heterogeneity
- Turbulent deposition/resuspension
- *Limited* retention/release in biofilms
- Bedform turnover
- *Limited* streamflow variations

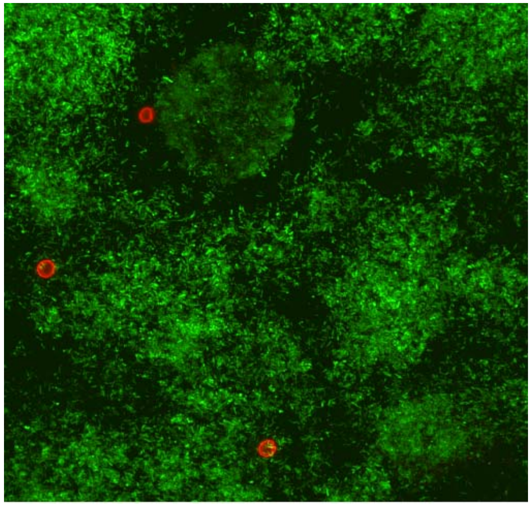
Can be extended to floodflow by considering changing morphodynamics during flood.

Proposed model: Mobile/immobile random walk with multiple convolution of different processes

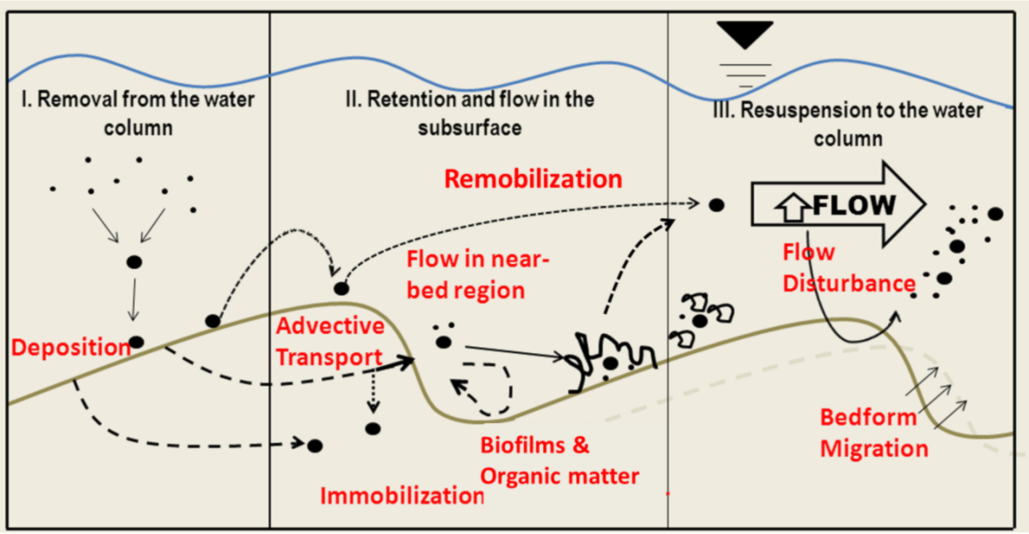


Biological processes affecting passively transmitted cysts & spores

- Deposition in biofilm EPS
- Shear-induced detachment
- Biofilm sloughing (biological)
- Predation/die-off



Proposed model: Mobile/immobile random walk with multiple convolution of different processes



Biological processes affecting passively transmitted cysts & spores
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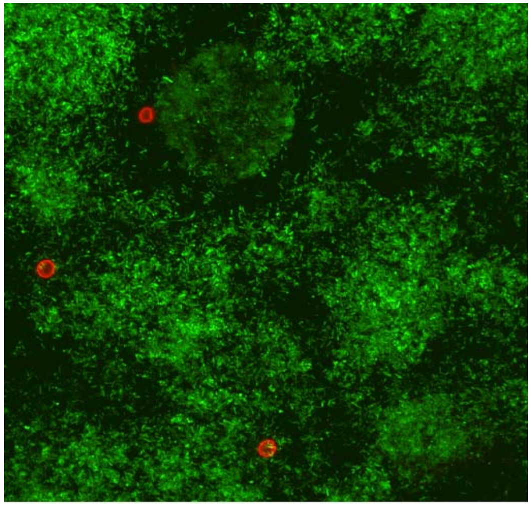
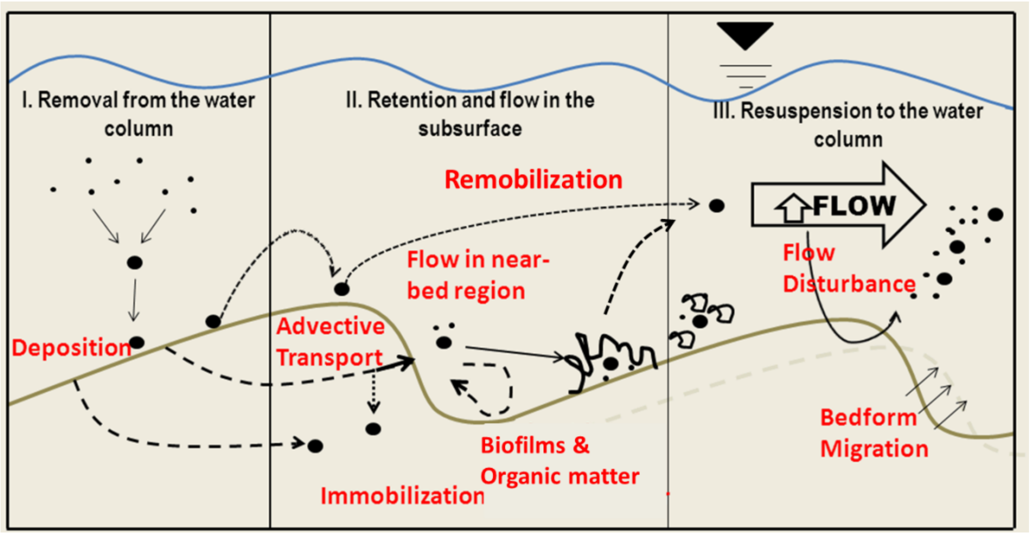


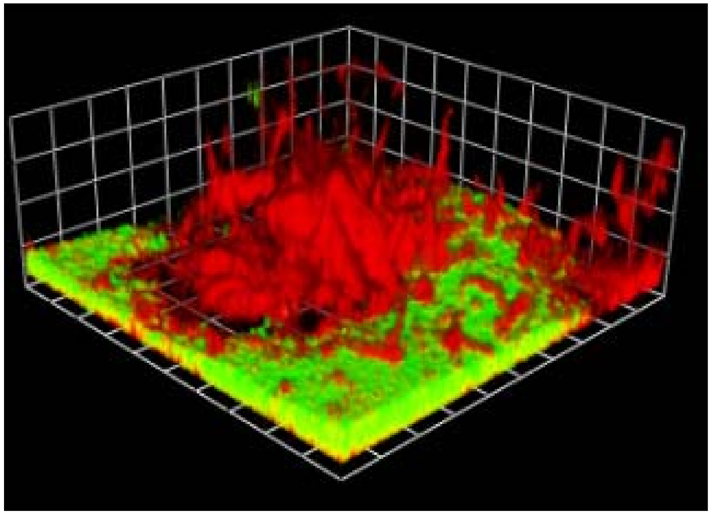
Incorporate information from 3D flow-biofilm interactions and associated shear-induced detachment and biologically-induced sloughing.

McCormick
Northwestern Engineering

Proposed model: Mobile/immobile random walk with multiple convolution of different processes



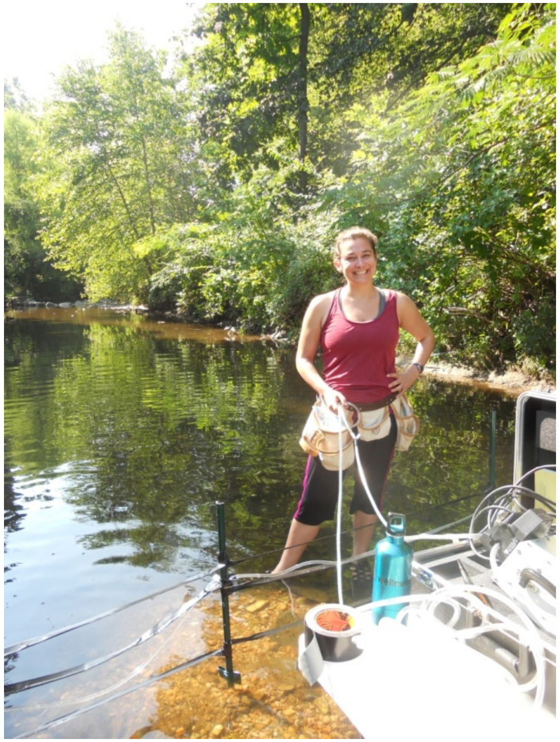
For opportunistic bacteria, potential colonization of biofilms and sediments must also be considered.



We are obtaining information on limited multispecies interactions of indicators, pathogens, and base biofilms (defined monospecies and natural base biofilms)

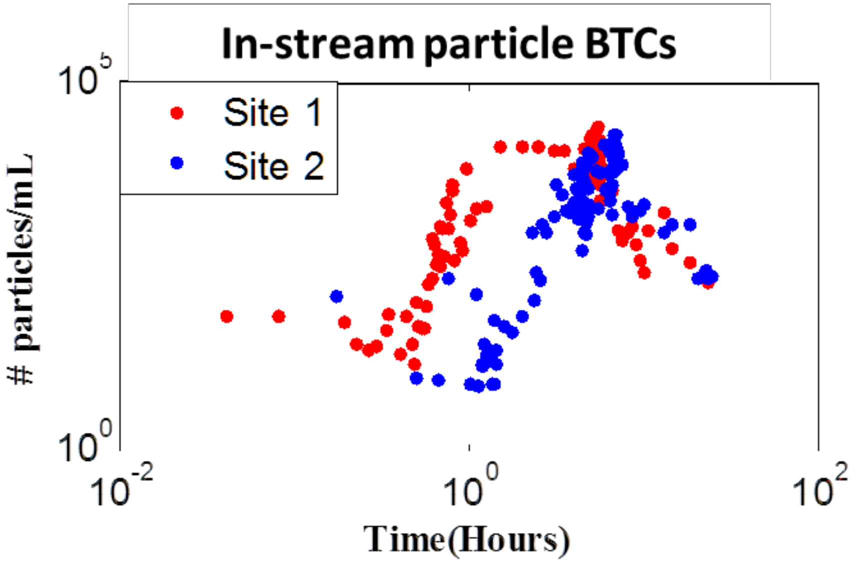
McCormick
Northwestern Engineering

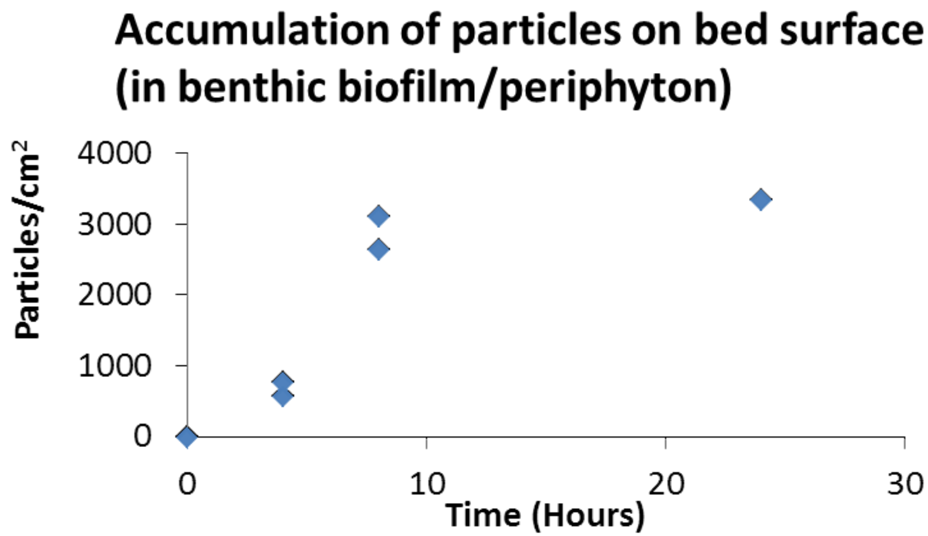
Solute and particle injections in Accotink Creek and Difficult Run, VA

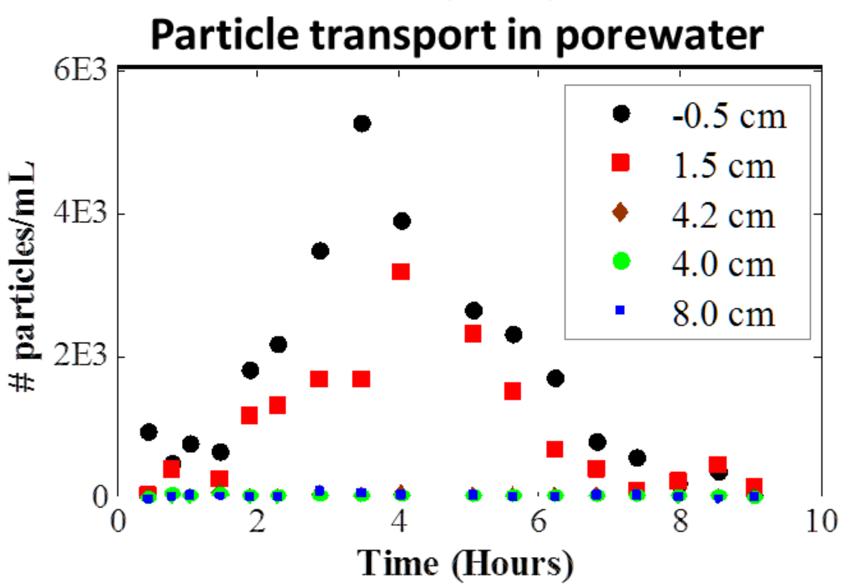


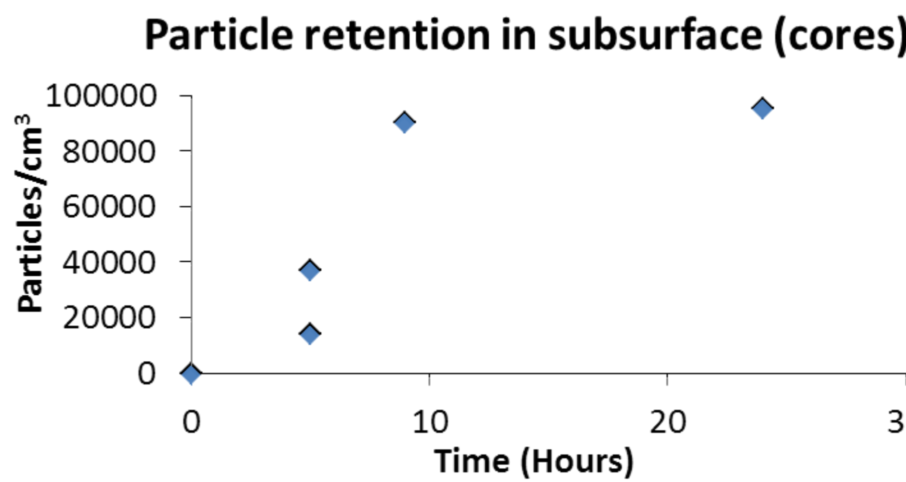
Drummond et al., in prep.

Accotink Creek: Direct evidence of deposition/resuspension from benthic biofilms and bed sediments









Drummond et al., in prep.

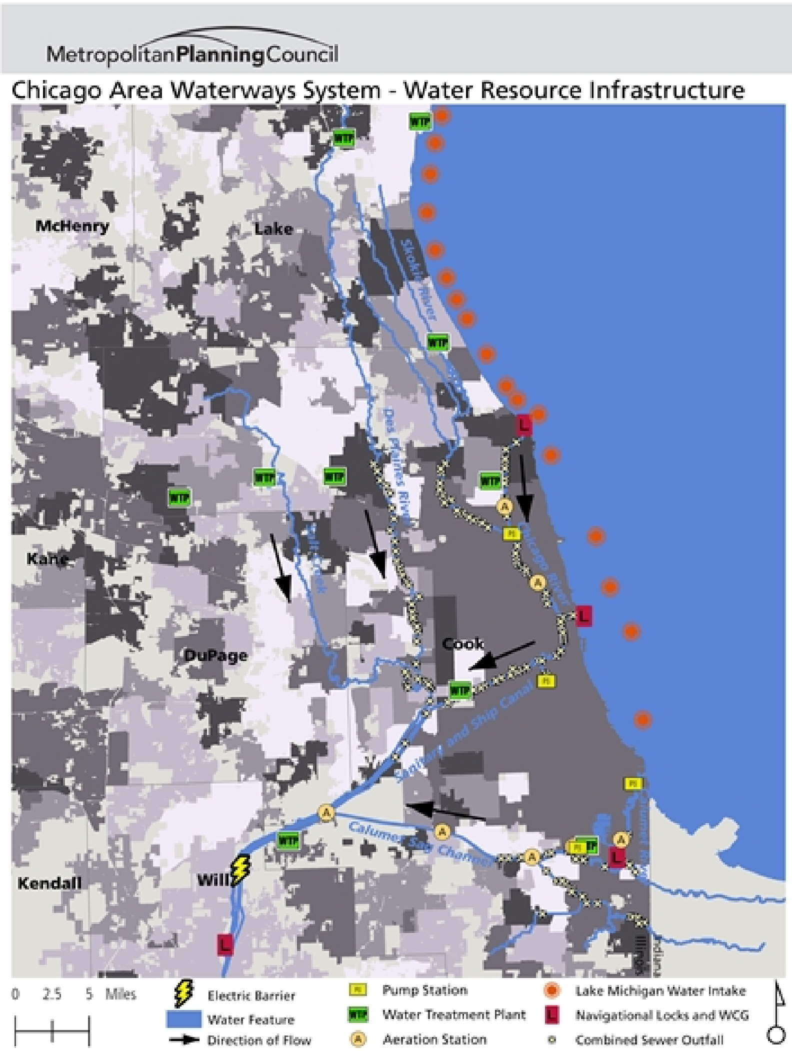
Seven Important Processes

1. Biofilms capture and release particles & pathogens
2. Pathogen filtration is often reversible
3. Multi-species biofilms show complex dynamics
4. Streambed biofilms and sediments capture and release particles
5. *Direct evidence* of particle capture in benthic biofilms and underlying hyporheic sediments
6. *Direct evidence* of slow, ongoing remobilization from biofilms and bed sediments during baseflow
7. *Direct evidence* of rapid, extensive remobilization from the streambed during flood flow

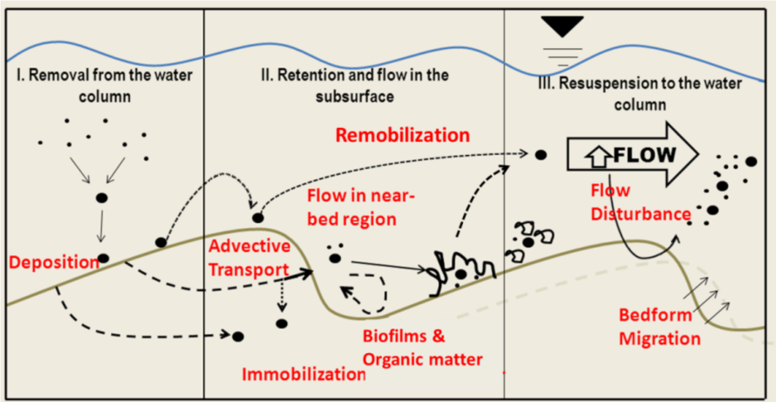
Conclusions and Implications

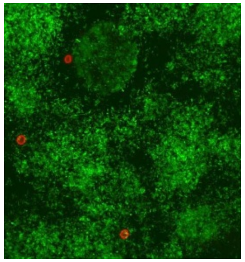
1. **Rivers are strong horizontal filters, but deposited particles and pathogens become resuspended over time. Deposited particles are slowly mobilized during baseflow and rapidly & extensively mobilized by high flows that scour the bed.**
2. **New theoretical frameworks provide the potential for quantitative assessment of transmission risks under varying loading scenarios and hydrological and climatological conditions.**
3. **Organisms having an active life-cycle in aquatic environments show complex interactions with pre-existing biofilms.**
4. **More information is needed on the dynamics of important pathogens in natural and engineered water systems (interactions with surfaces and biofilms, metabolism & motility, persistence & die-off in all relevant reservoirs)**

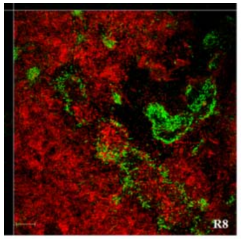
Proposed approach for Chicago-area waterways

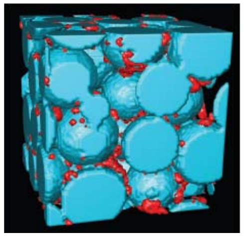


Coupling of anomalous transport, microbial ecology, and network dynamics is a major challenge!









examiner.com

Proposed solution:

- Collect extensive data on microbial community in all important reservoirs
- Build hydraulic model for water flow
- Measure solute and particle transport dynamics, and biofilm processes
- Incorporate anomalous transport submodels for passive (cysts, spores) and active (bacteria) pathogens