

# Interactions of *Cryptosporidium parvum* oocysts with sediments and biofilms: Implications for waterborne disease transmission in agricultural watersheds

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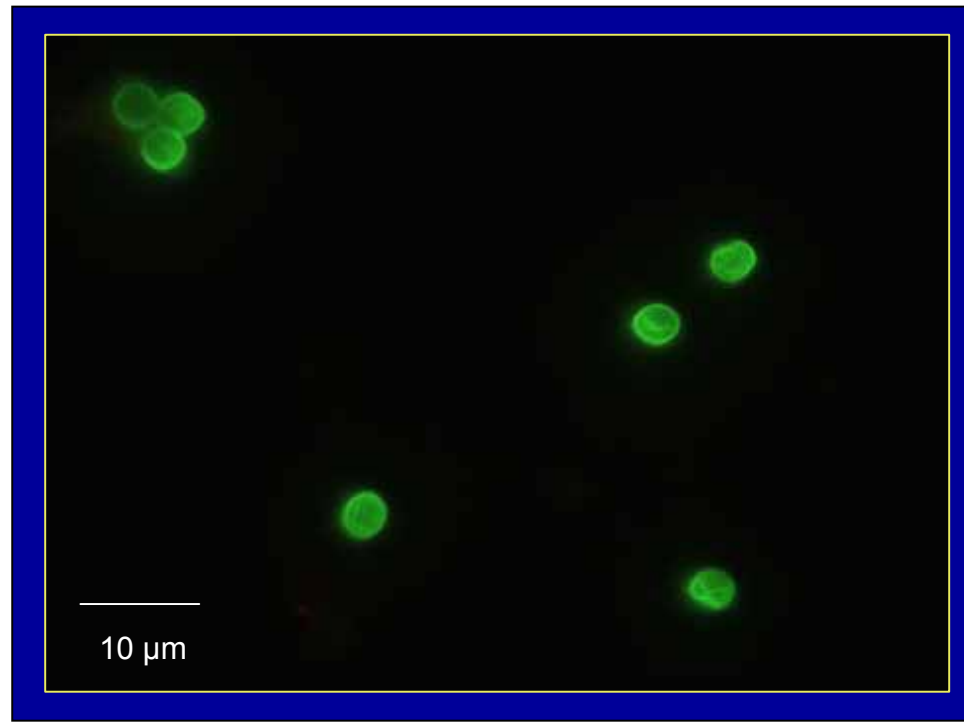


McCormick

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Department of Civil and Environmental Engineering

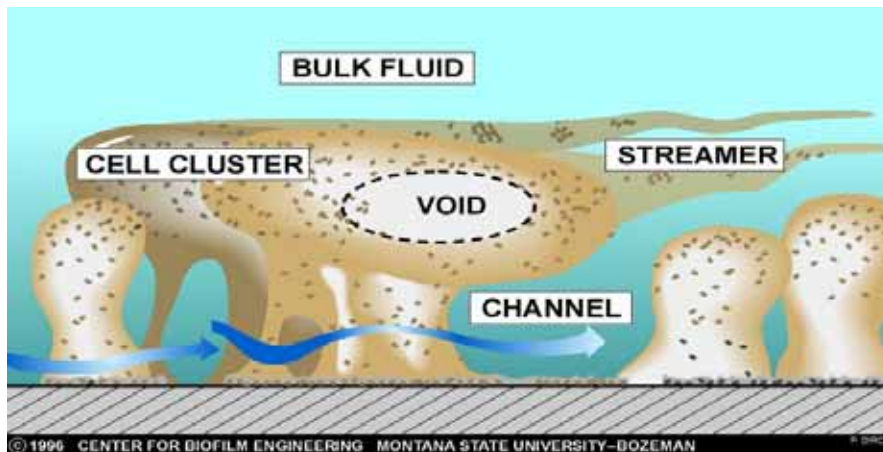
# Transmission of waterborne disease

Investigate transport of *Cryptosporidium* spp.  
over many scales

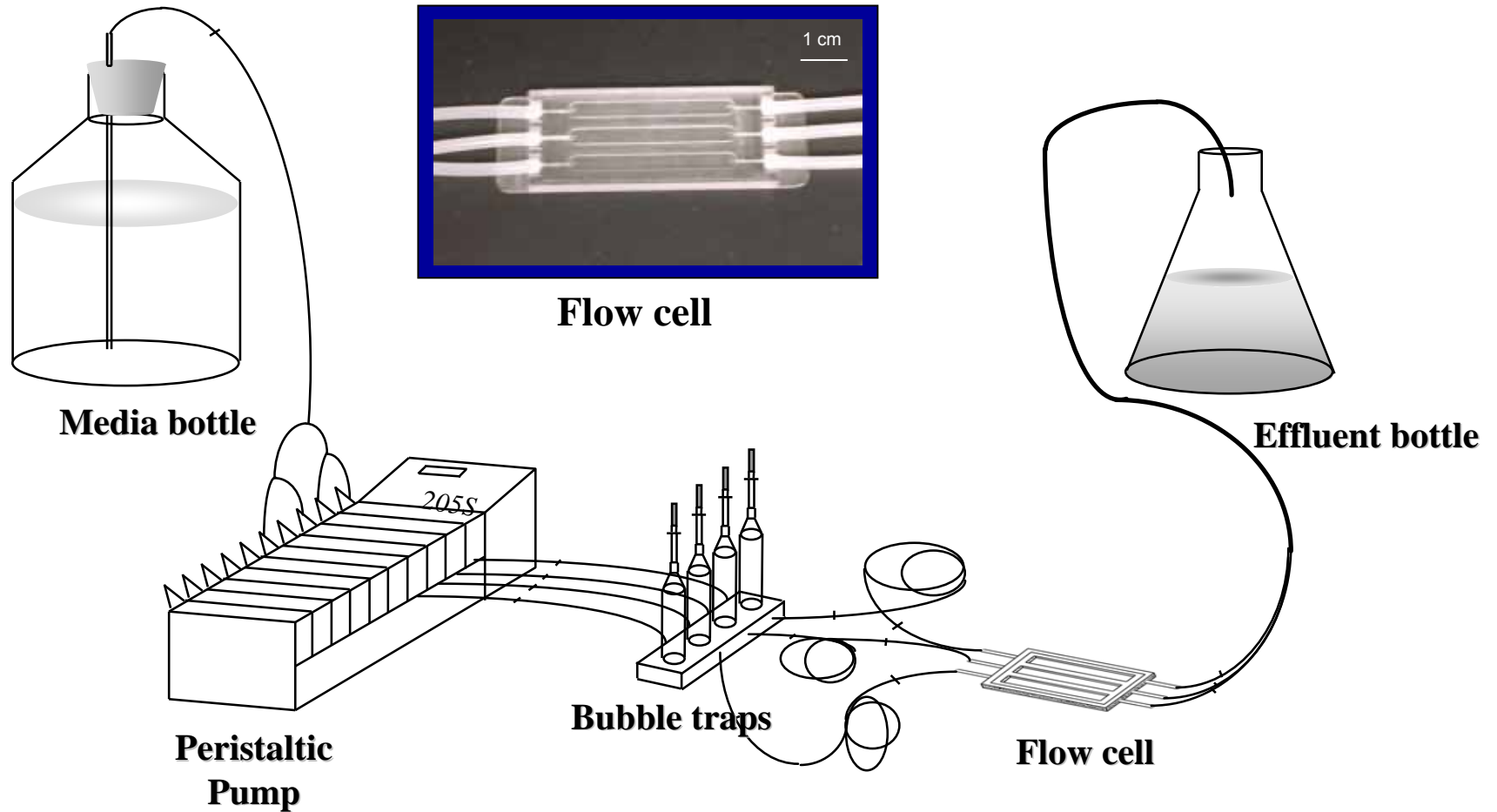


# Sedimentary Biofilms

- Surface-attached microbial community encased in a matrix of extra-cellular polymeric substances (EPS).
- Ubiquitous in aquatic systems. Contain most of the microbial biomass in shallow freshwater environments.
- Alter surface properties. Protect resident cells from physical and chemical stresses.

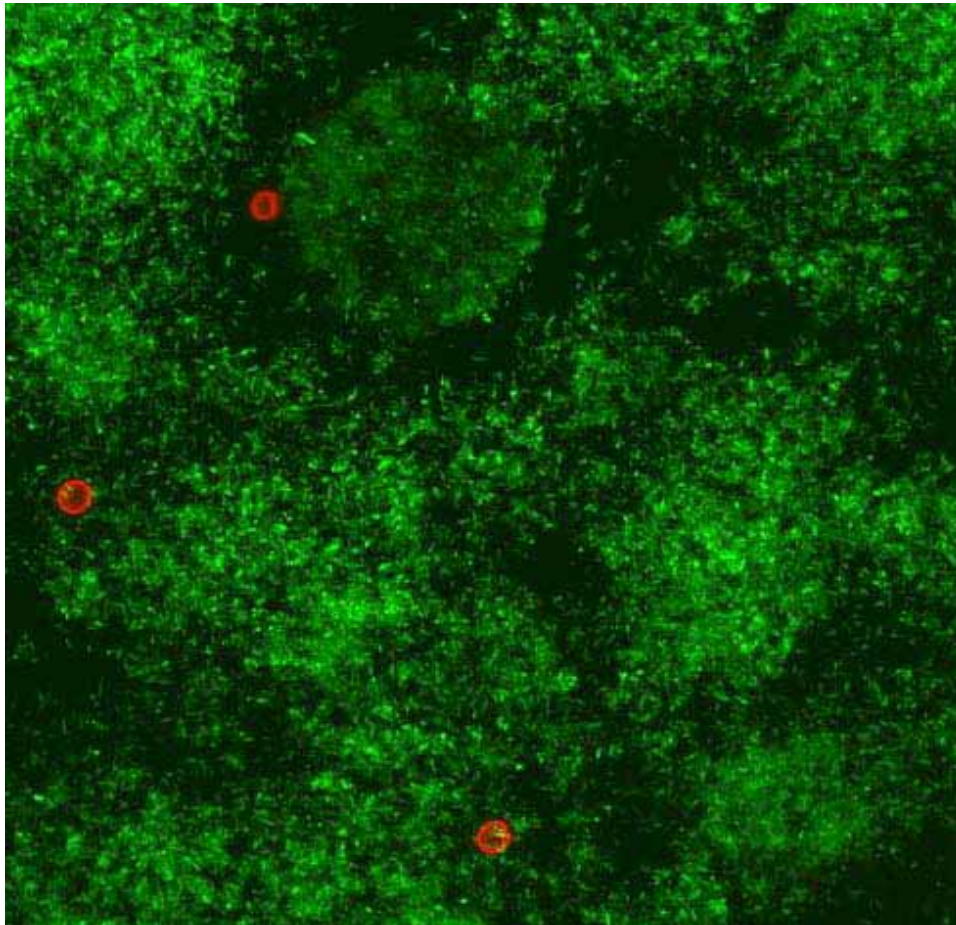


# Flow Cell Experiments with Biofilms



Schematic by J. Haagenen, courtesy M. Parsek, Univ. Washington

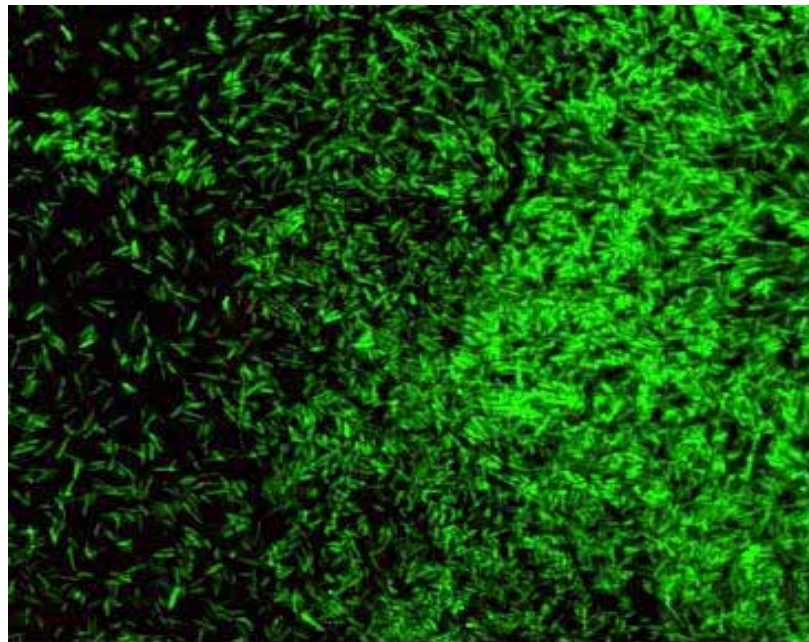
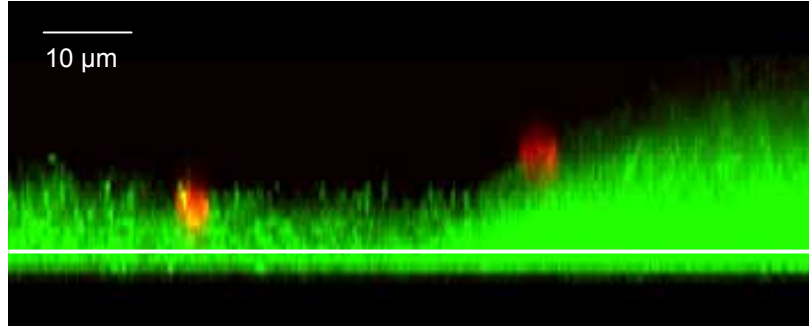
# *Cryptosporidium* attachment to *P. aeruginosa* biofilm



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

Confocal microscopy resolves  
3D spatial structure

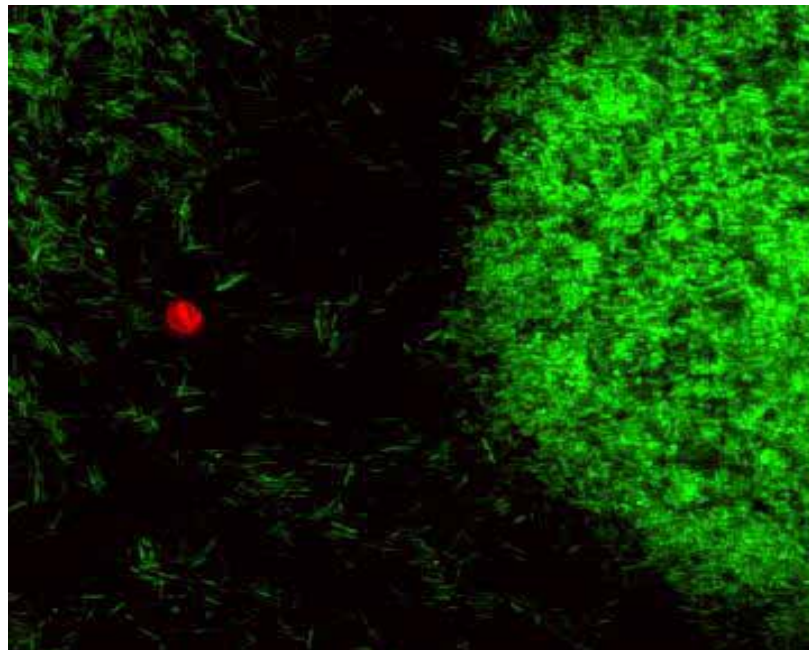
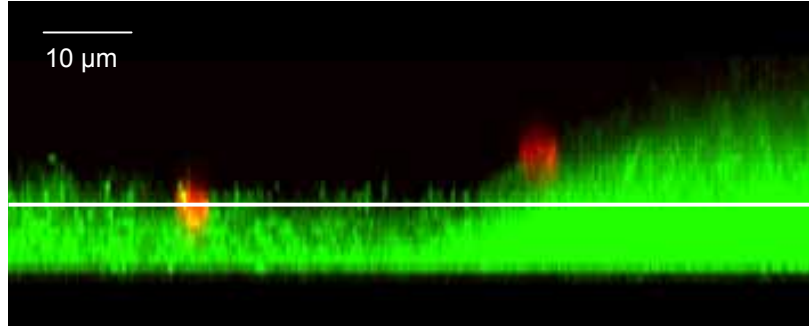
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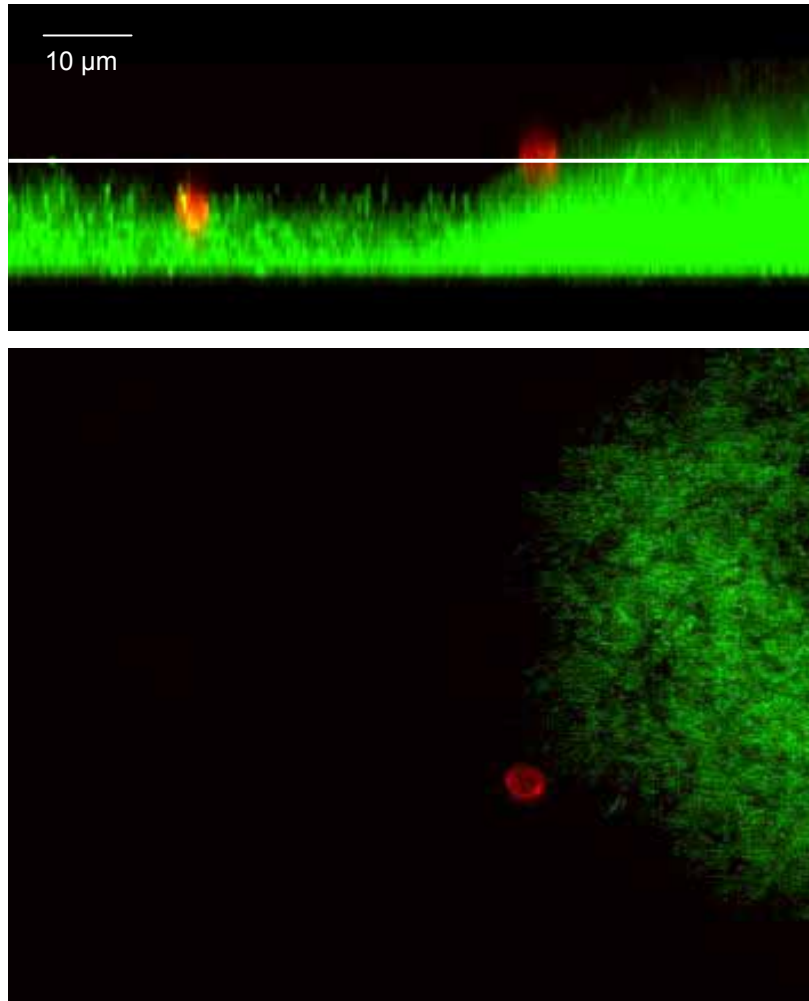
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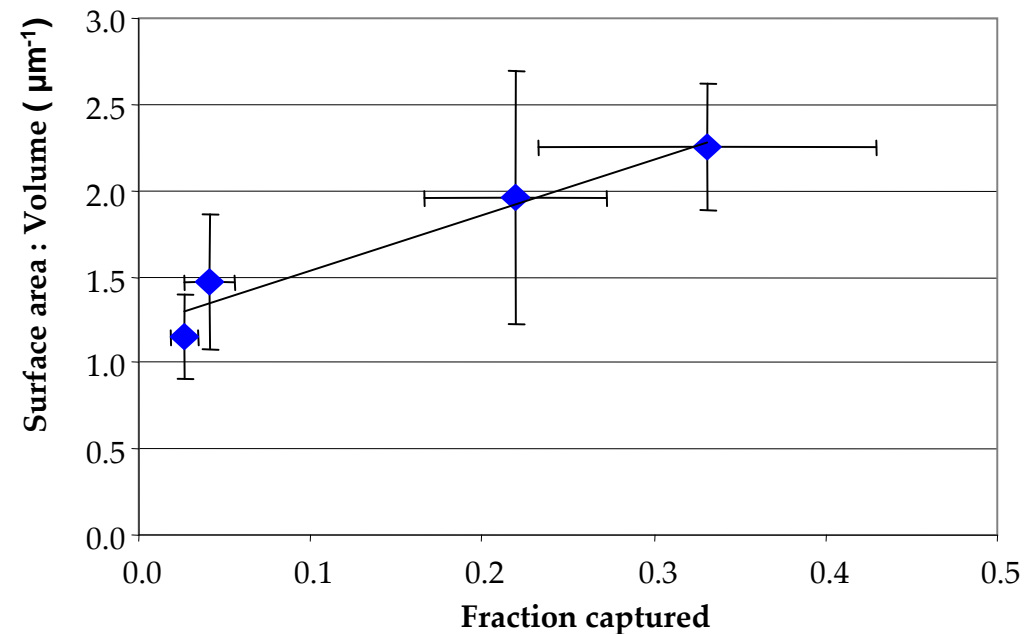
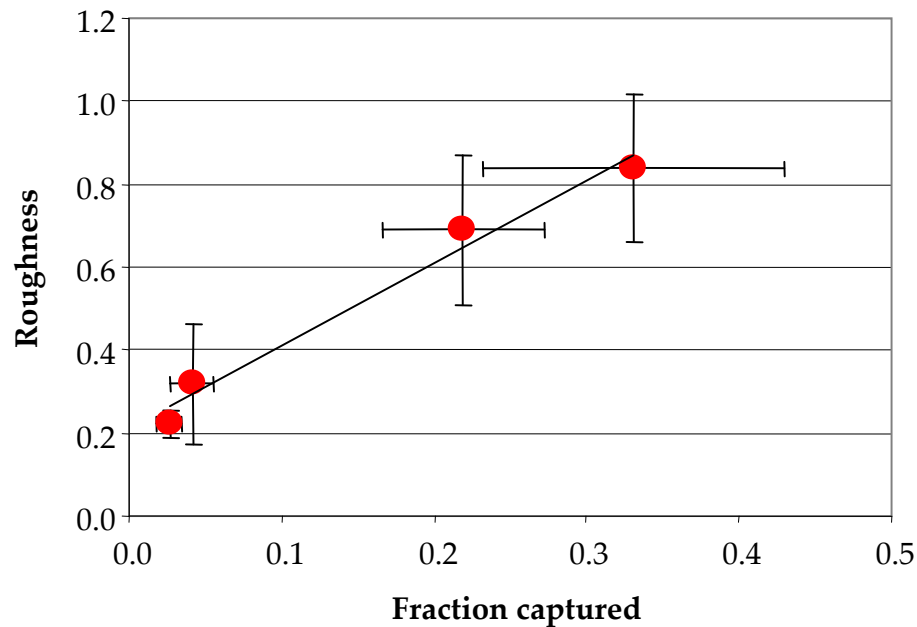
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# Oocyst Capture vs. Biofilm Architecture



**Oocyst capture is positively related to biofilm architecture (roughness and surface-area-to-volume ratio)**

# *Cryptosporidium* transport in porous media

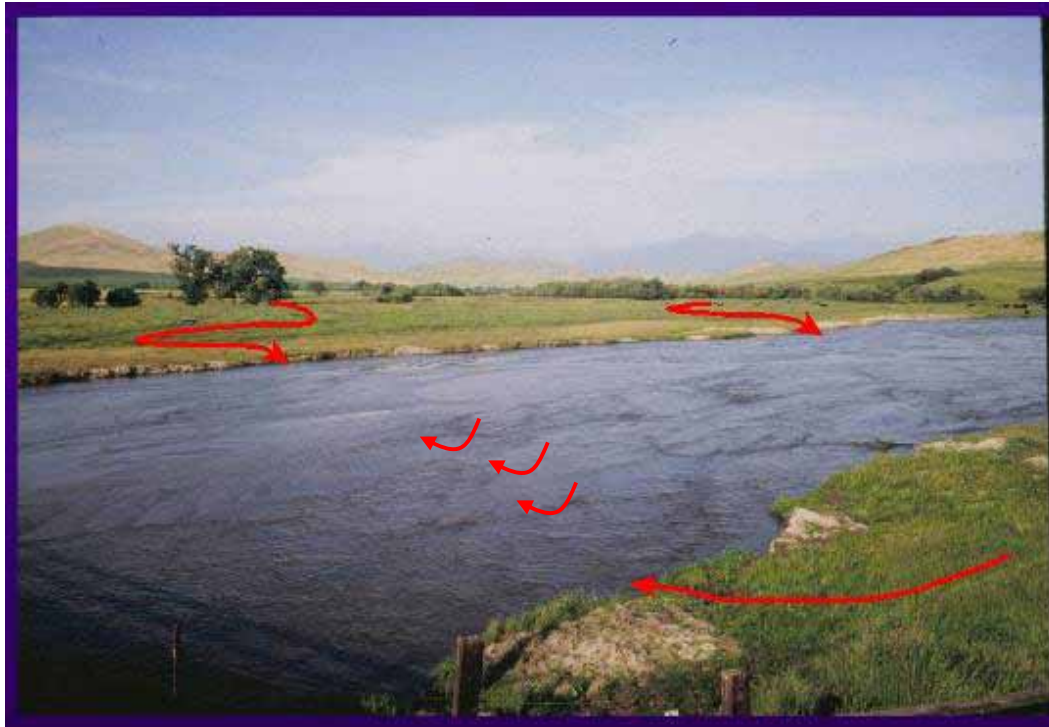


Image by T. Harter

# Column filtration experiments with *C. parvum*

Column length = 0.20 m  
Column diameter = 0.05 m  
Volumetric flux = 10 ml/min  
Injection time = 1.5 PV  
Ottawa Silica sand,  $d_g = 480 \mu\text{m}$



# CTRW model for *Cryptosporidium* transport

- ◆ Generalized random walk described by pdf  $\psi(s, t)$
- ◆ Can be used to represent multiple processes

$$\psi(\mathbf{s}, t) = \int_0^t \psi_0(\mathbf{s}, t - t') \phi(t' | t - t') dt'$$

- ◆ 1D Transport with filtration (in Laplace space)

$$u\tilde{c}(x, u) - c_0(x) = -\tilde{M}(u)v_\psi \left[ \lambda\tilde{c}(x, u) + \frac{\partial}{\partial x}\tilde{c}(x, u) - \alpha_\psi \frac{\partial^2}{\partial x^2}\tilde{c}(x, u) \right]$$

**Memory Function**

$$\tilde{M}(u) = \bar{t}u \frac{\tilde{\psi}(u)}{1 - \tilde{\psi}(u)}$$

**Average Velocity**

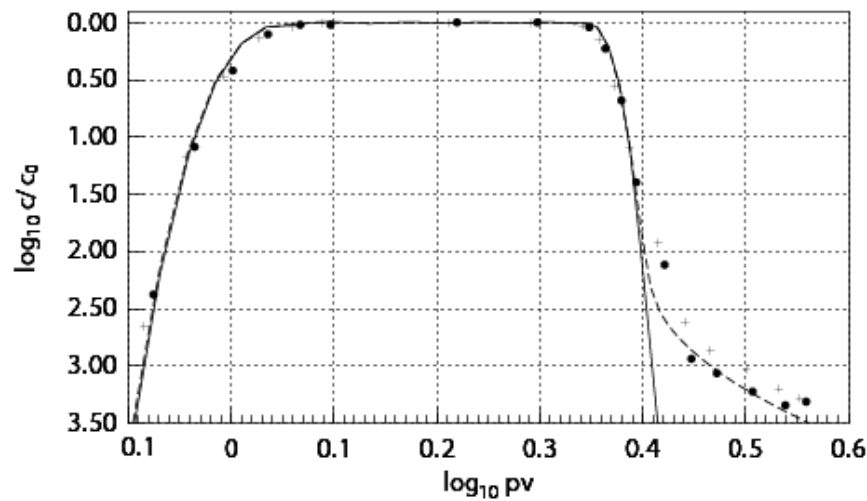
$$v_\psi = \bar{t}^{-1} \sum_s p(s)s$$

**Dispersivity**

$$\alpha_\psi = \frac{1}{2} \bar{t}^{-1} \sum_s p(s)s^2$$

# Application to *C. parvum* transport in porous media

**Bromide**

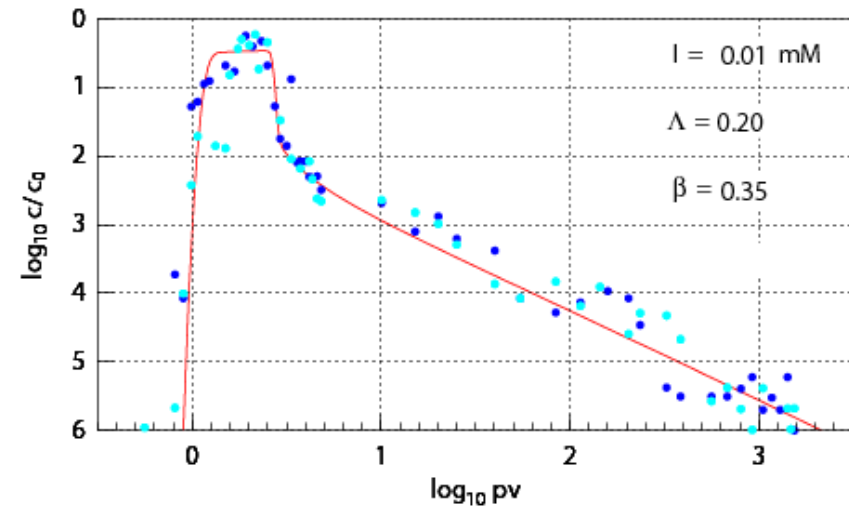


**Almost Fickian**

$$\tilde{\psi}_0(u) = 1/(1 + u^\gamma)$$

$$\gamma = 0.9992$$

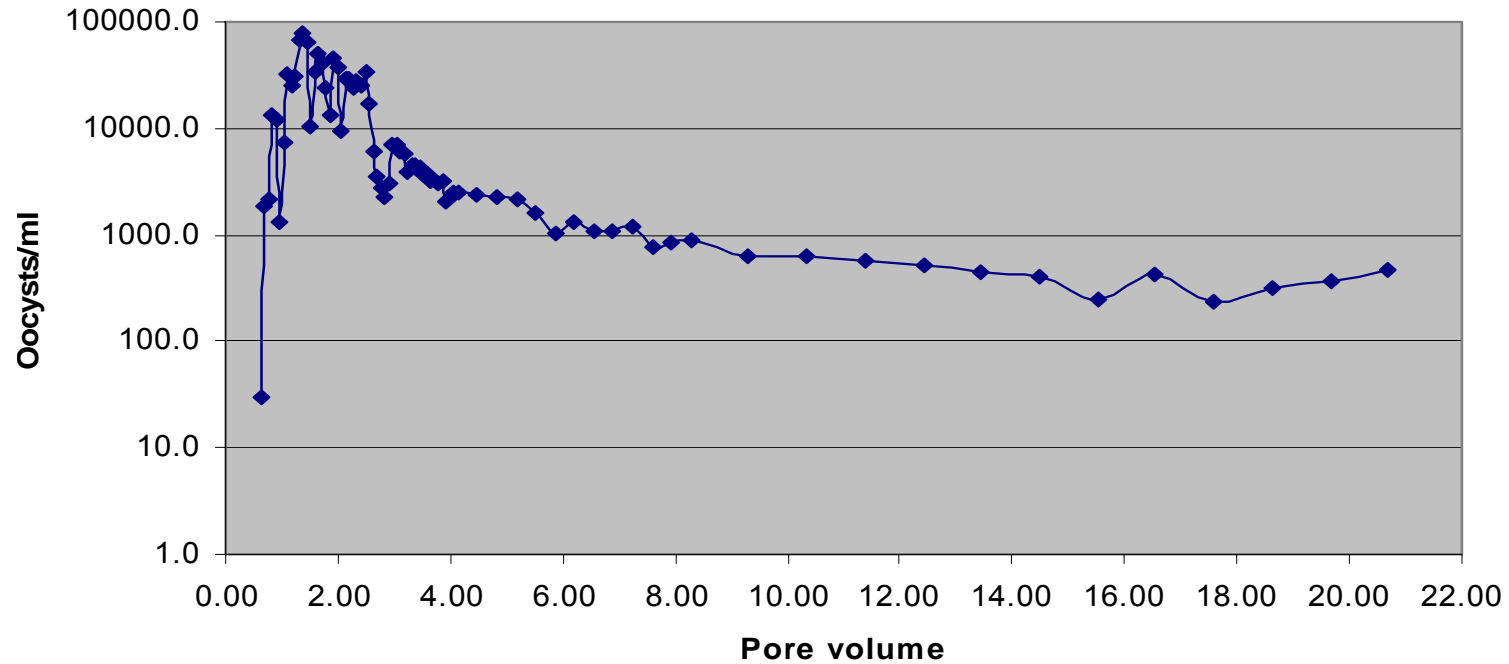
***C. parvum***



**Power-Law Tailing**

$$\tilde{\psi}(u) = \frac{1}{1 + u + \Lambda(1 - \tilde{\phi}(u))}$$

# Column experiments with biofilm



## ***C. parvum* oocysts remain infective after transport, filtration, and association with biofilm**

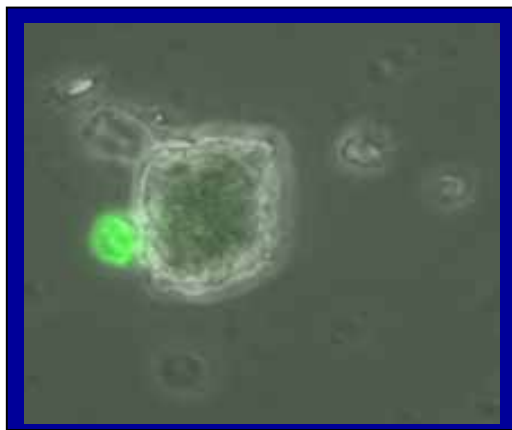
| <i>C. parvum</i><br>source (subsample) | Pore<br>Volumes | Inoculum size<br>(No. oocysts) | No. inoculated<br>mice | No. of infected<br>mice |
|--|-----------------|--------------------------------|------------------------|-------------------------|
| Initial effluent                       | 0.8~1.0         | 1000                           | 10                     | 10                      |
| Peak concentration                     | 1.0~2.0         | 1000                           | 10                     | 10                      |
| Tail concentration                     | 4.0~8.0         | 1000                           | 10                     | 10                      |
| Sand (filtered)                        | -               | 1000                           | 10                     | 10                      |
| Control                                | -               | 1000                           | 10                     | 10                      |

# Attachment of *C. parvum* to suspended sediments

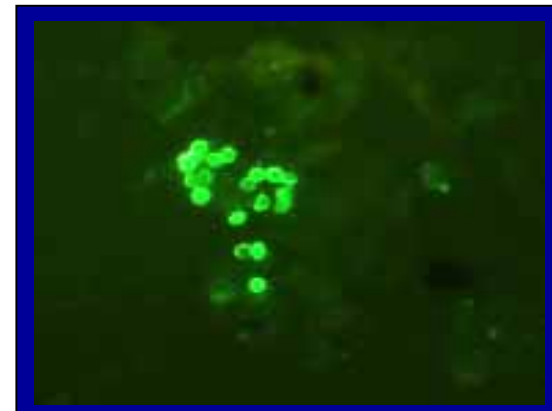
## Kaolinite



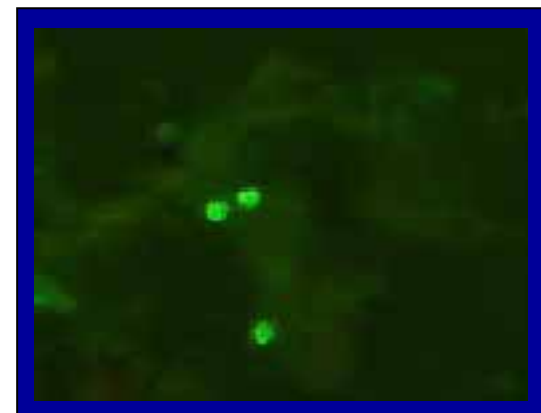
10  $\mu\text{m}$



## Natural Sediments

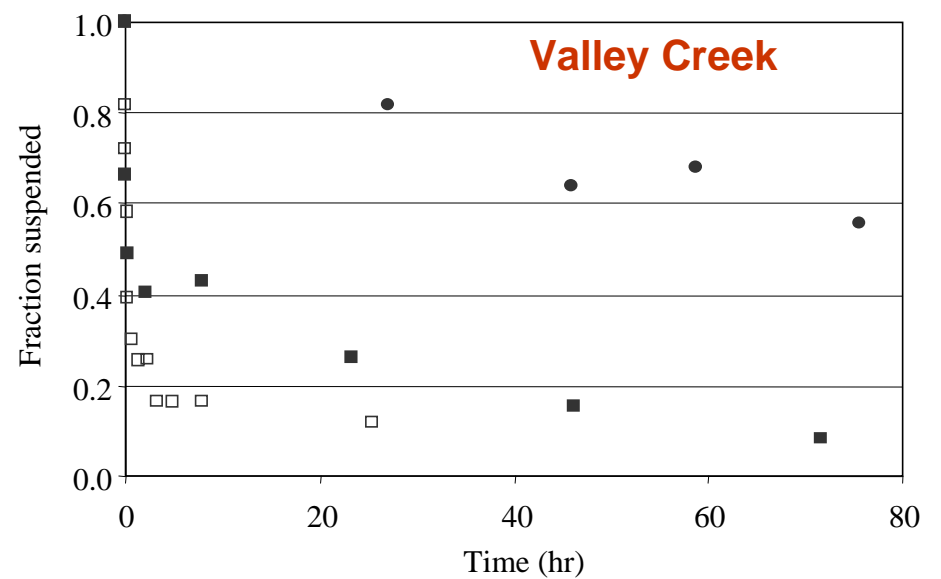
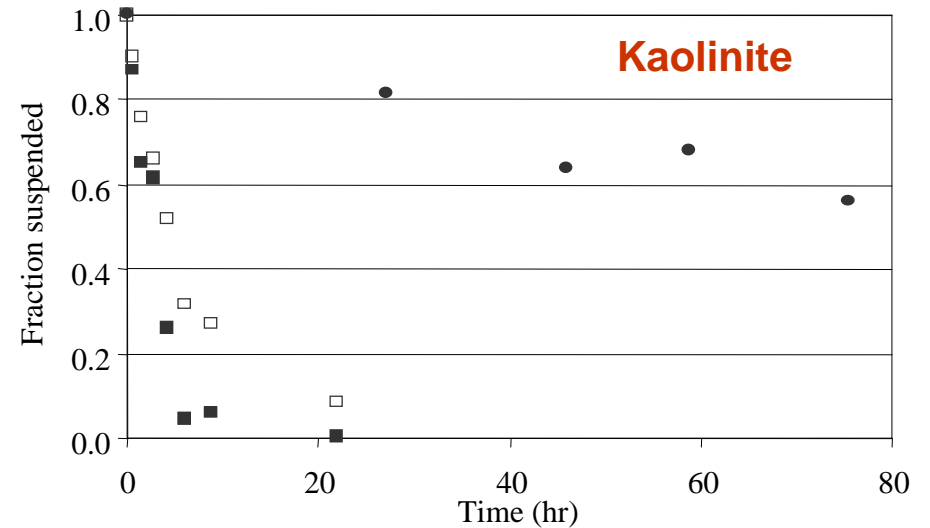
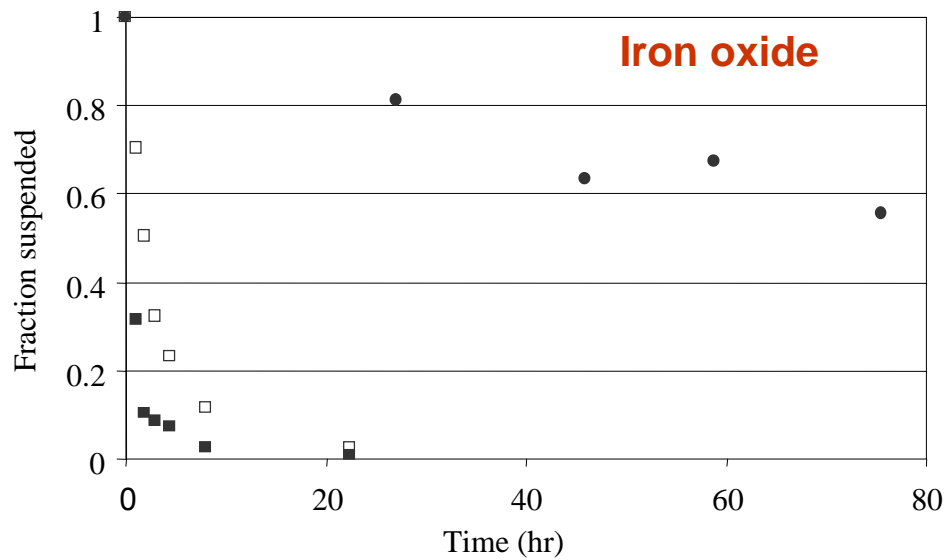


30  $\mu\text{m}$

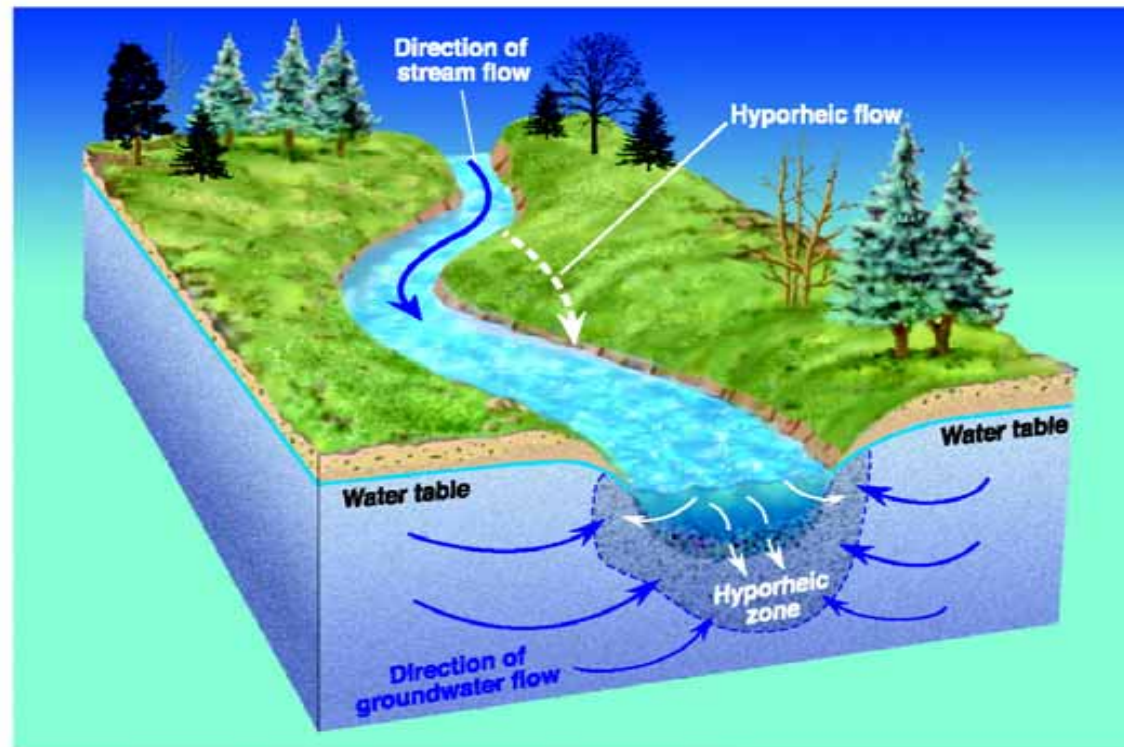


# Sedimentation of Oocyst-Particle Aggregates

- Free (unattached) oocysts
- Oocysts mixed with sediments
- Sediments



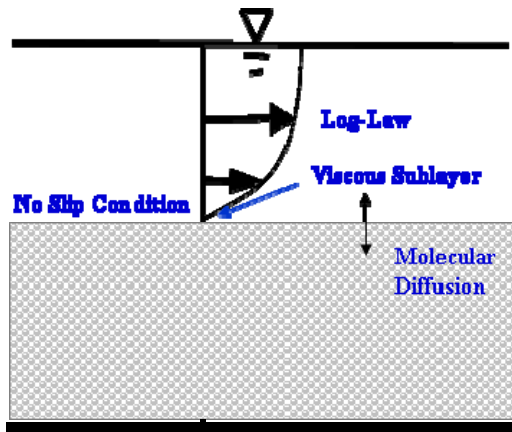
# Hyporheic exchange facilitates pathogen deposition in sediments



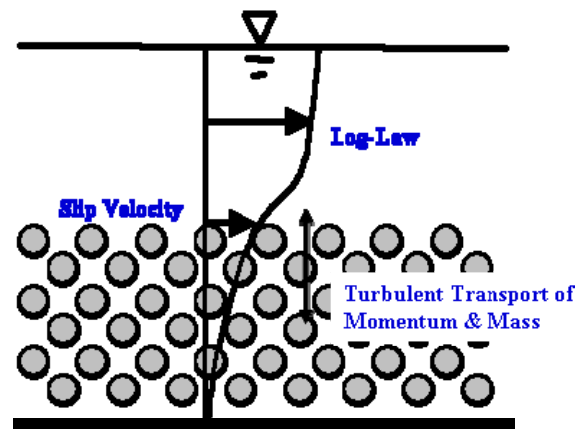
Alley et al., 2002

# Catalogue of interfacial exchange processes

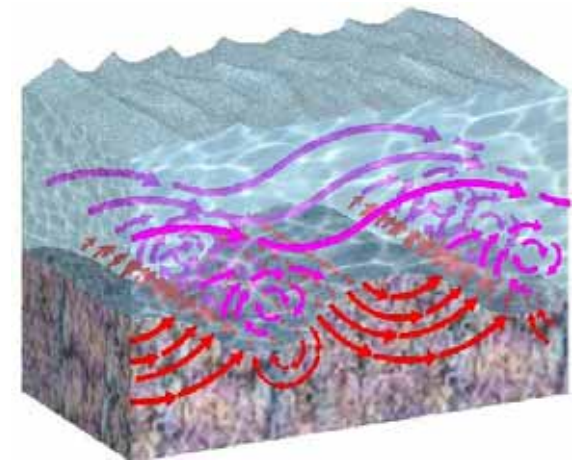
## Molecular Diffusion



## Turbulent Diffusion

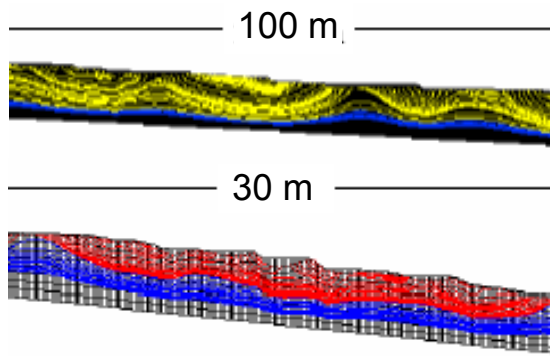


## Bedform-induced Advection

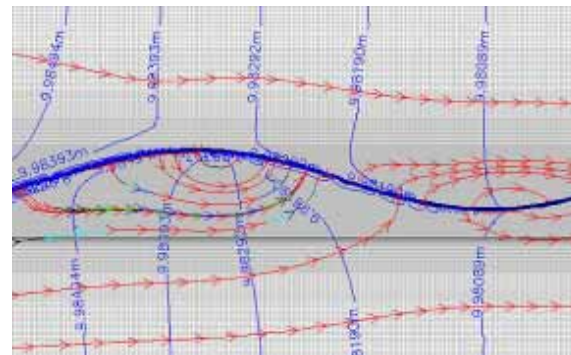


## Advection induced by larger channel morphology

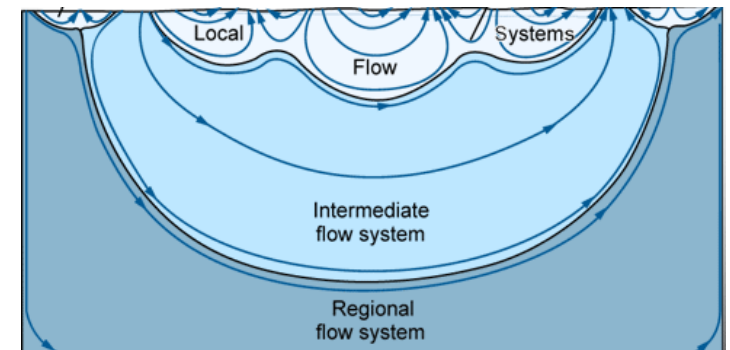
### Pool-Riffle Sequences



### Meanders



## Interaction with regional groundwater flow system

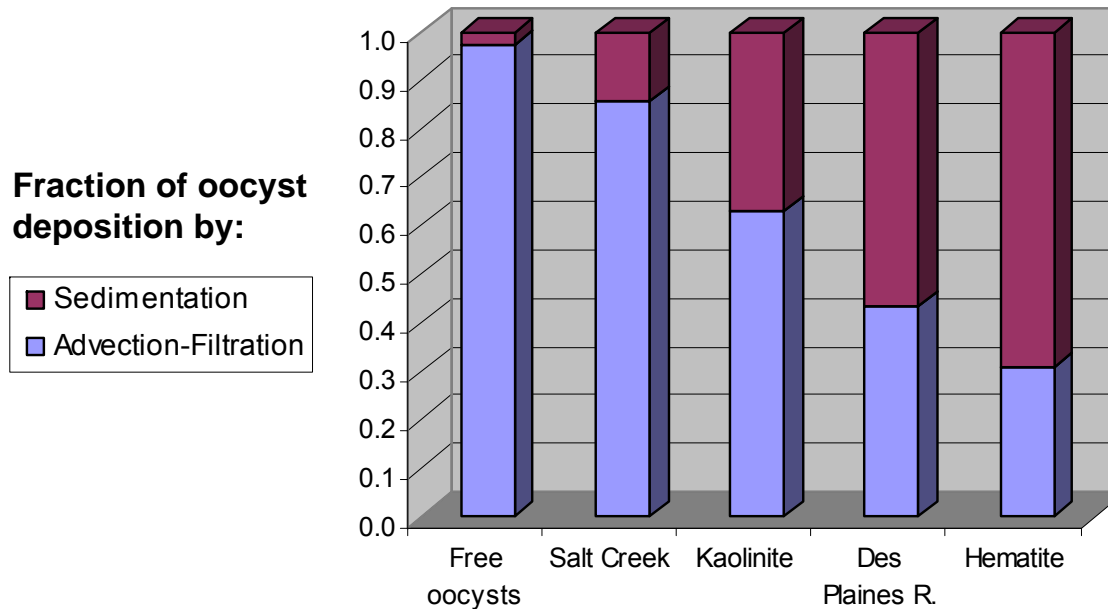
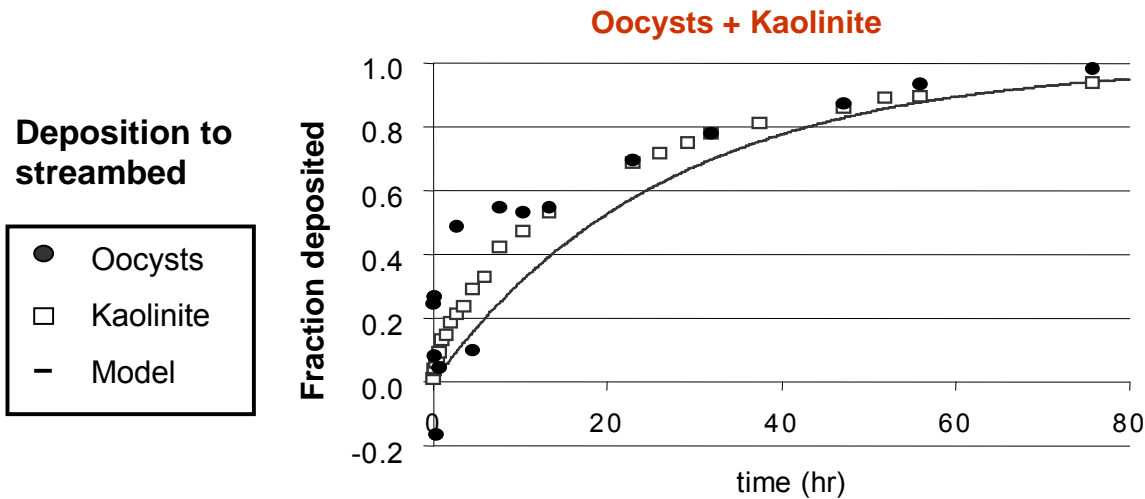


# Laboratory flume experiments with *C. parvum* and microspheres

**Sediment bed length = 2.5 m**  
**Sediment bed depth = 10 cm**  
**Bedform height  $\approx$  2 cm**  
**Bedform wavelength  $\approx$  15 cm**  
**Overlying flow depth = 15 cm**  
**Mean overlying velocity = 0.5 - 15 cm/s**  
**Ottawa Silica sand,  $d_g$  = 480  $\mu$ m**



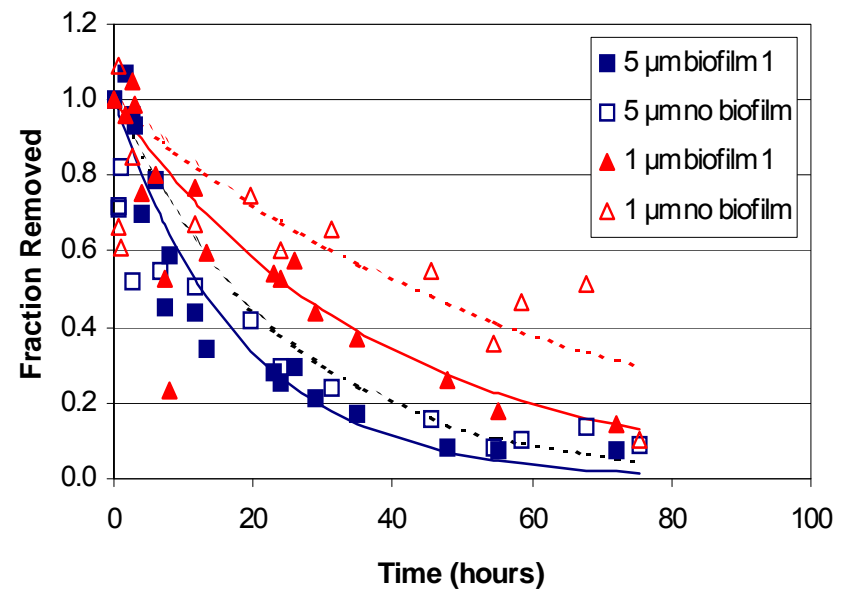
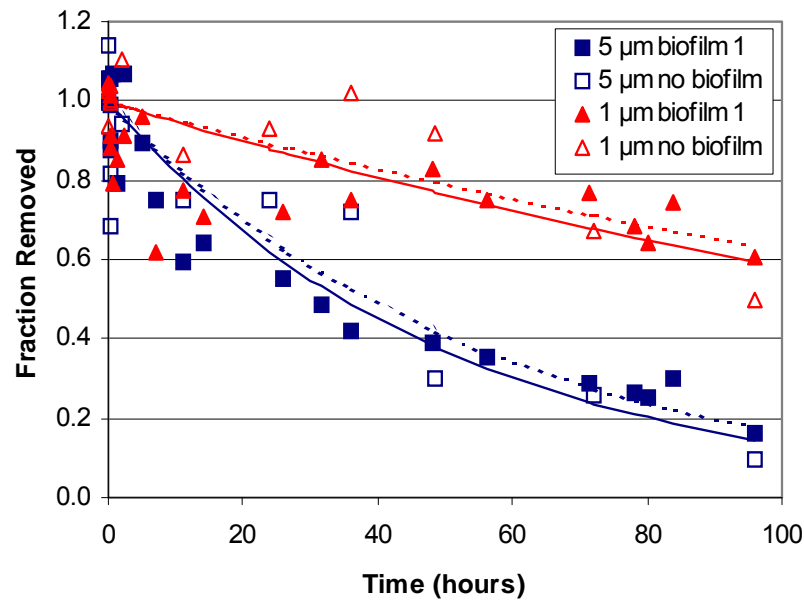
# Particle-Mediated Deposition of Oocysts from Overlying Flow



# Particle capture by biofilms

$U = 0.9 \text{ cm/s}$

$U = 5 \text{ cm/s}$



# Geomorphic & Hydrologic Complexity



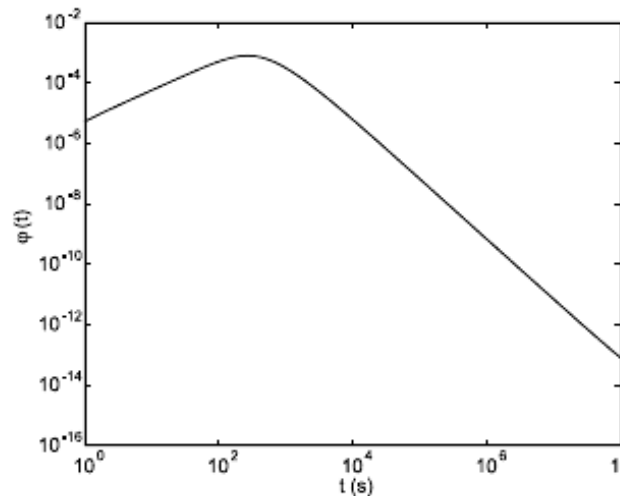
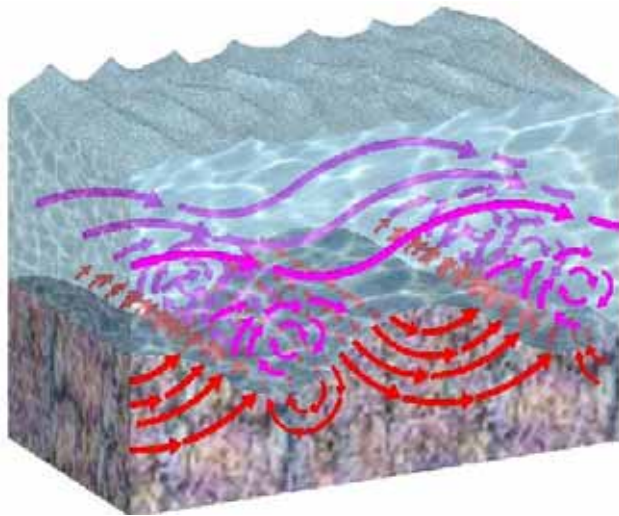
Whataroa River, New Zealand



# CTRW Model for Downstream Transport

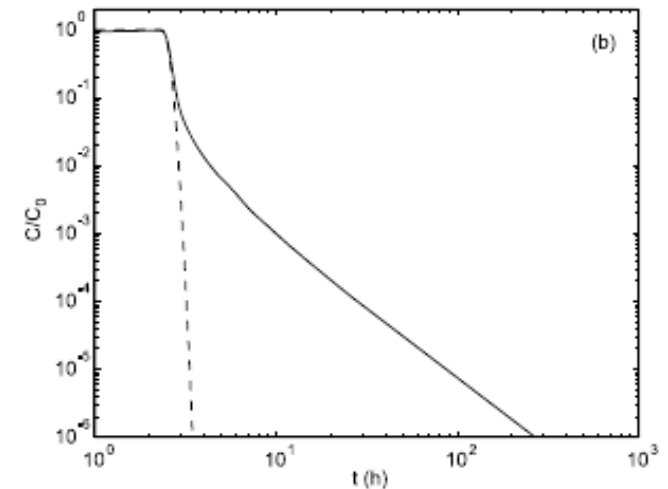
$$\frac{\partial C(x, t)}{\partial t} = \int_0^t M(t - t') \left[ -U_\psi \frac{\partial C(x, t')}{\partial x} + K_\psi \frac{\partial^2 C(x, t')}{\partial x^2} \right] dt'$$

**Subsurface residence  
time distribution**



**Evaluated from  
analytical solution**

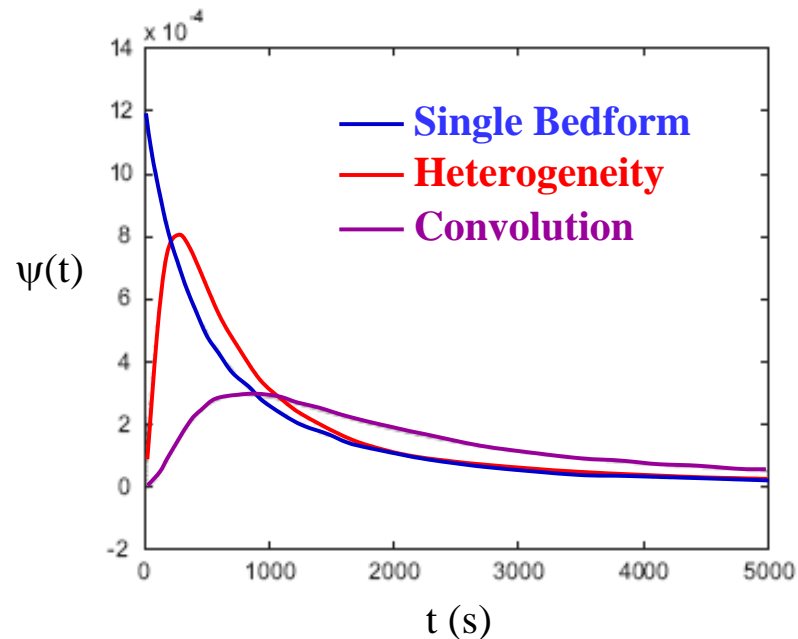
**In-stream solute  
breakthrough curve**



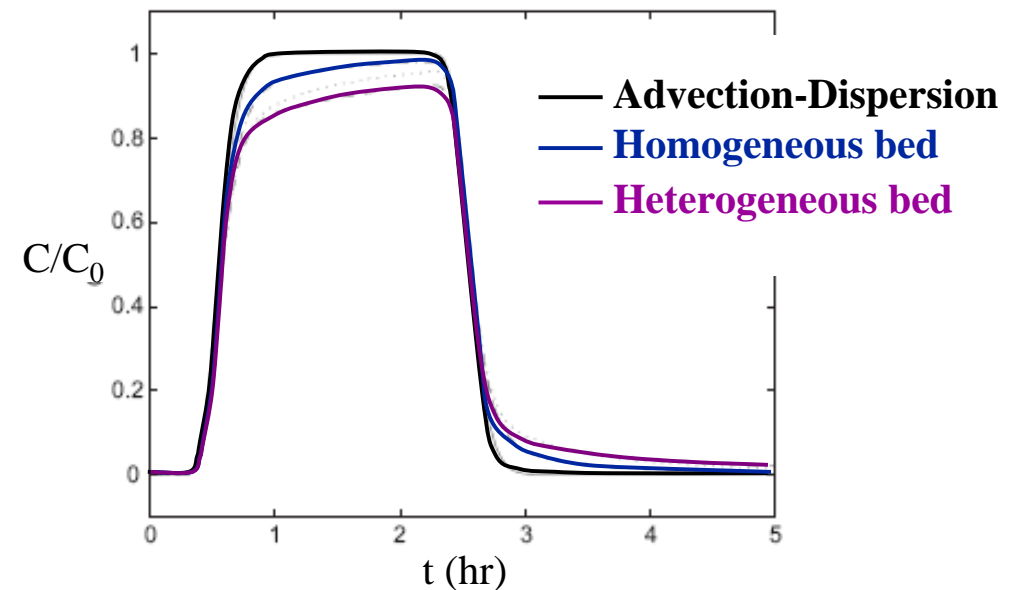
**Evaluated from probabilistic  
transport model (CTRW/FADE)**

# Can include effects of subsurface heterogeneity

## Subsurface Residence Time Distribution



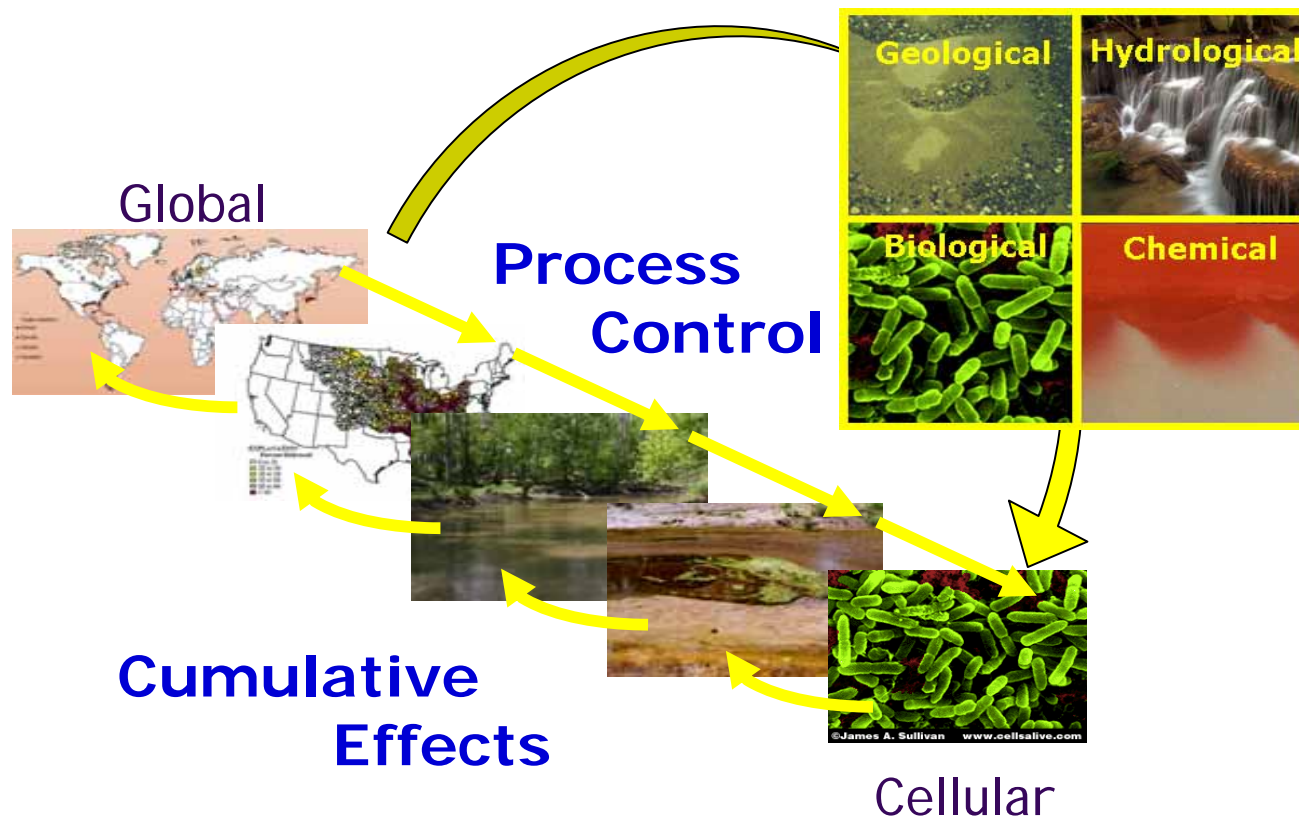
## Net Downstream Transport



$$\psi_H(t) = \int_0^t \psi_{\bar{K}}(t-\tau) \phi_H(\tau) d\tau$$

Heterogeneity represented by truncated power law,  $\phi_H(t)$

# Linking Scale and Process



**Need to link Structure, Transport, Transformation, and Microbial Activity across many spatial and temporal scales.**

- **From micron-scale to mega-scale ( $10^{-6}$  to  $10^6$  m) = 12 orders of magnitude!**

# Conclusions

- A variety of processes influence the propagation of pathogens derived from animal agriculture. Overland flow, groundwater, and surface water can all be important transmission pathways.
- Pathogens readily associate with a variety of background materials, including soil grains, suspended sediments, streambed sediments, and sedimentary biofilms. This association tends to reduce their mobility .
- *Cryptosporidium parvum* oocysts can reversibly attach to inorganic surfaces, resulting in a slow, long-term release following initial deposition in aquifers or sediment beds (i.e., both in groundwater and surface water).
- Pathogens associated with biofilms become incorporated into the EPS matrix, and can therefore be released in cell clusters whenever the host biofilm is disrupted, e.g., because of high shear or biological sloughing.
- Results to date suggest that transmission does not affect *C. parvum* infectivity. Oocysts remain viable after transmission through porous media and interaction with biofilms.