Critical Role of High Permeability Zones on Field-Scale Pathogen Transport and Retention, Infection Risk, and Setback Distance

Scott A. Bradford[1], Feike J. Leij[2], Jack Schijven[3], and Saeed Torkzaban[4]

[1]US Salinity Laboratory, USDA, ARS, Riverside, CA

[2]Department of Civil Engineering, California State University, Long Beach, CA

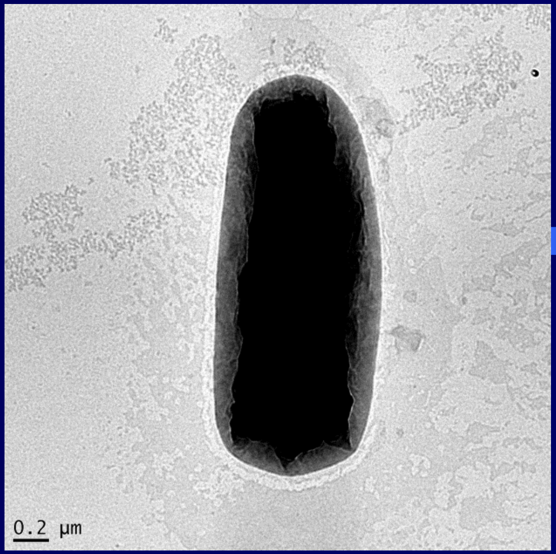
[3]Faculty of Geosciences, Utrecht University, The Netherland

[4]CSIRO Land and Water, Glen Osmond, Australia

Funding Sources: USDA NP 212

Pathogens

E. coli O157:H7

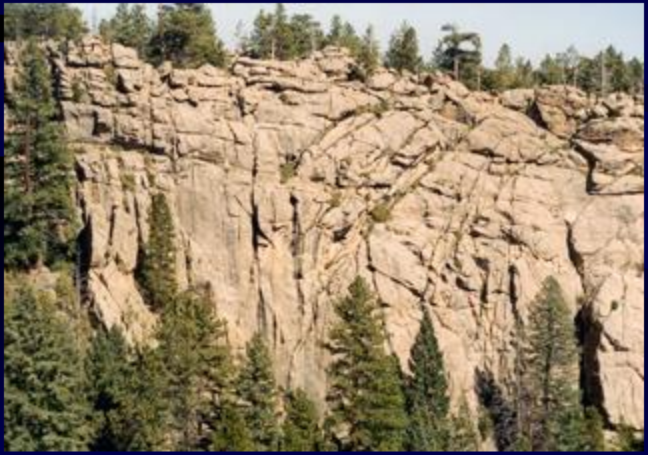


- Groundwater is the principal source of drinking water for as many as 2 billion people worldwide (50% in US and 75% in Europe).
- 52% of drinking-water outbreaks are associated with groundwater in the US.
- 15% of groundwater systems in the US and Canada tested positive for enteric pathogens (bacteria, virus, and protozoan parasites).
- Waterborne illnesses have been estimated to kill 2-3 million people worldwide every year.

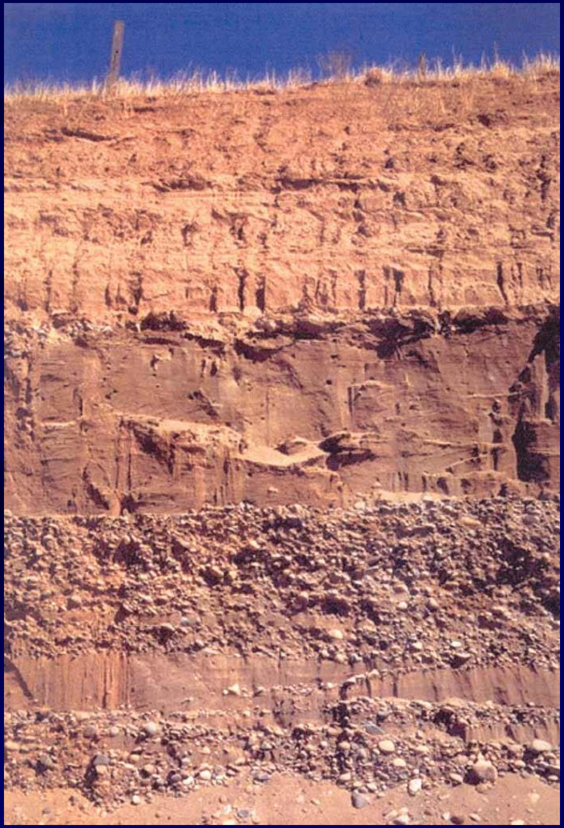
Cryptosporidium parvum

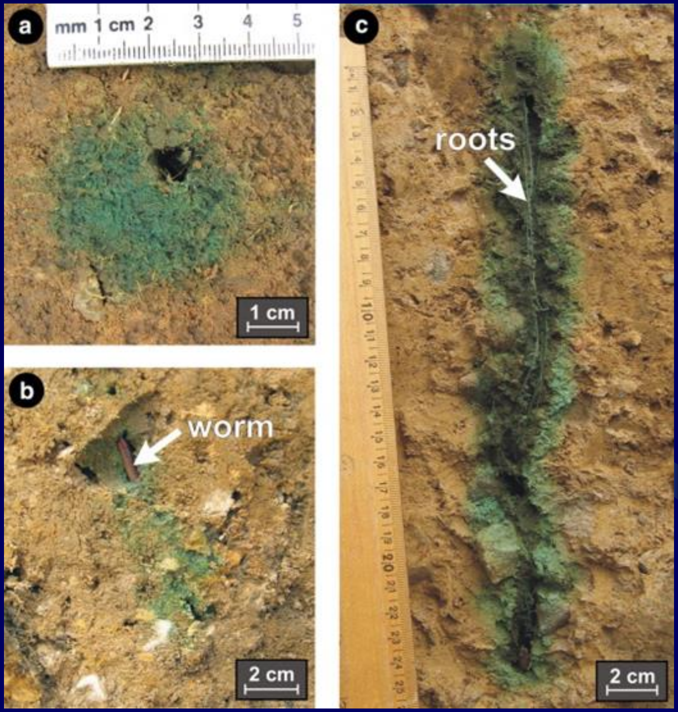
Objective

- Develop mathematical models to examine the role of high permeability zones on pathogen transport and fate.
- Examples of high permeability zones:
  - Preferential flow paths
  - Sand and gravel layers and lenses
  - Fractured rock
  - Karst systems



USGS





Cey et al. (2009)

Deterministic Pathogen Transport

- **Advective-dispersion equation with retention, release, and decay**

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial z^2} - v_w \frac{\partial C}{\partial z} - (\mu_w + k_{sw})C + \frac{\rho_b k_{rs}}{\theta} S_r$$

$$\rho_b \frac{\partial S_r}{\partial t} = \theta F_{rev} k_{sw} C - \rho_b (\mu_s + k_{rs}) S_r$$

$$\rho_b \frac{\partial S_i}{\partial t} = \theta (1 - F_{rev}) k_{sw} C - \rho_b \mu_s S_i$$

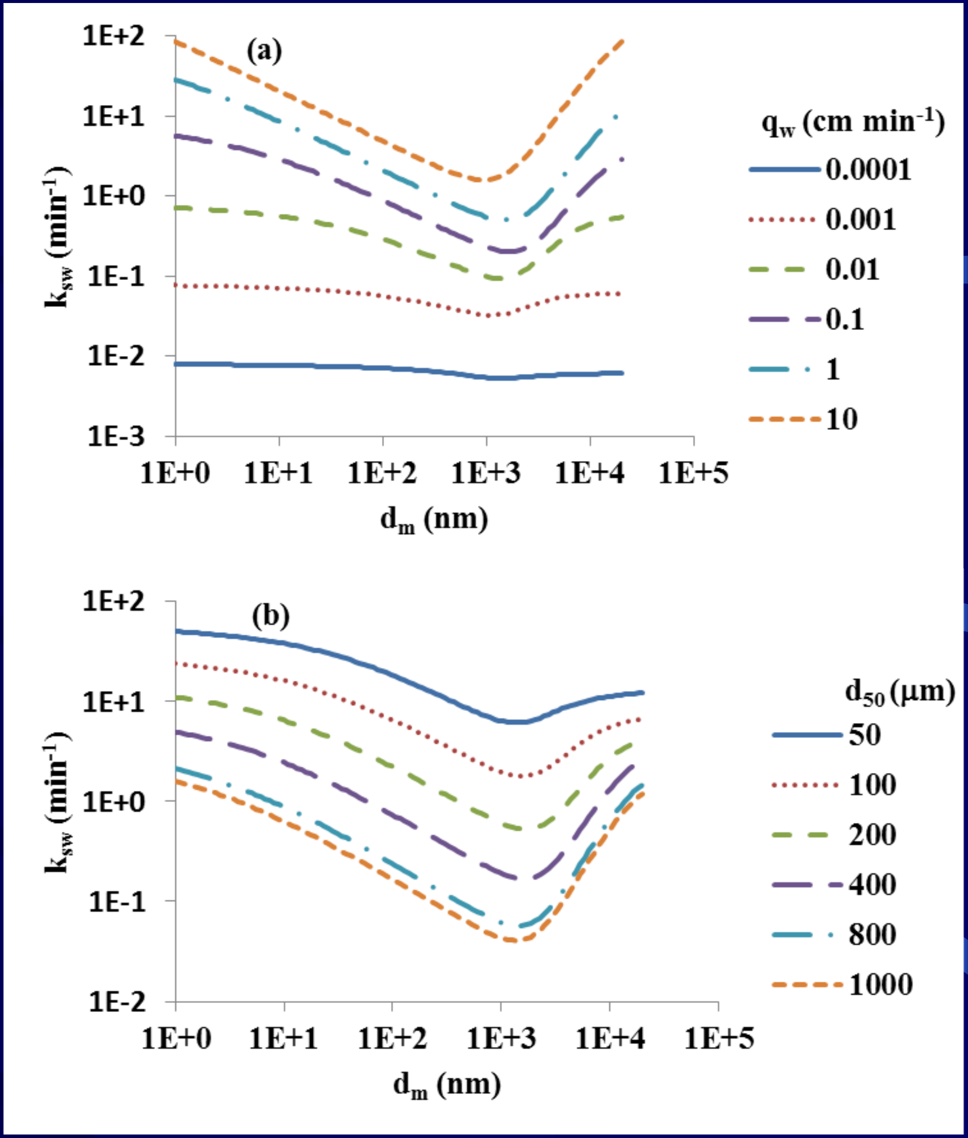
- **We use an analytic solution from Toride et al. (1995)**

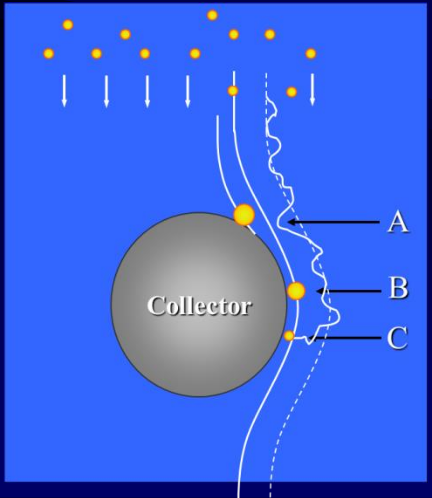
- **Filtration theory**

$$k_{sw} = \frac{3(1-\theta)}{2d_{50}} \eta \alpha v_w$$

Filtration Theory

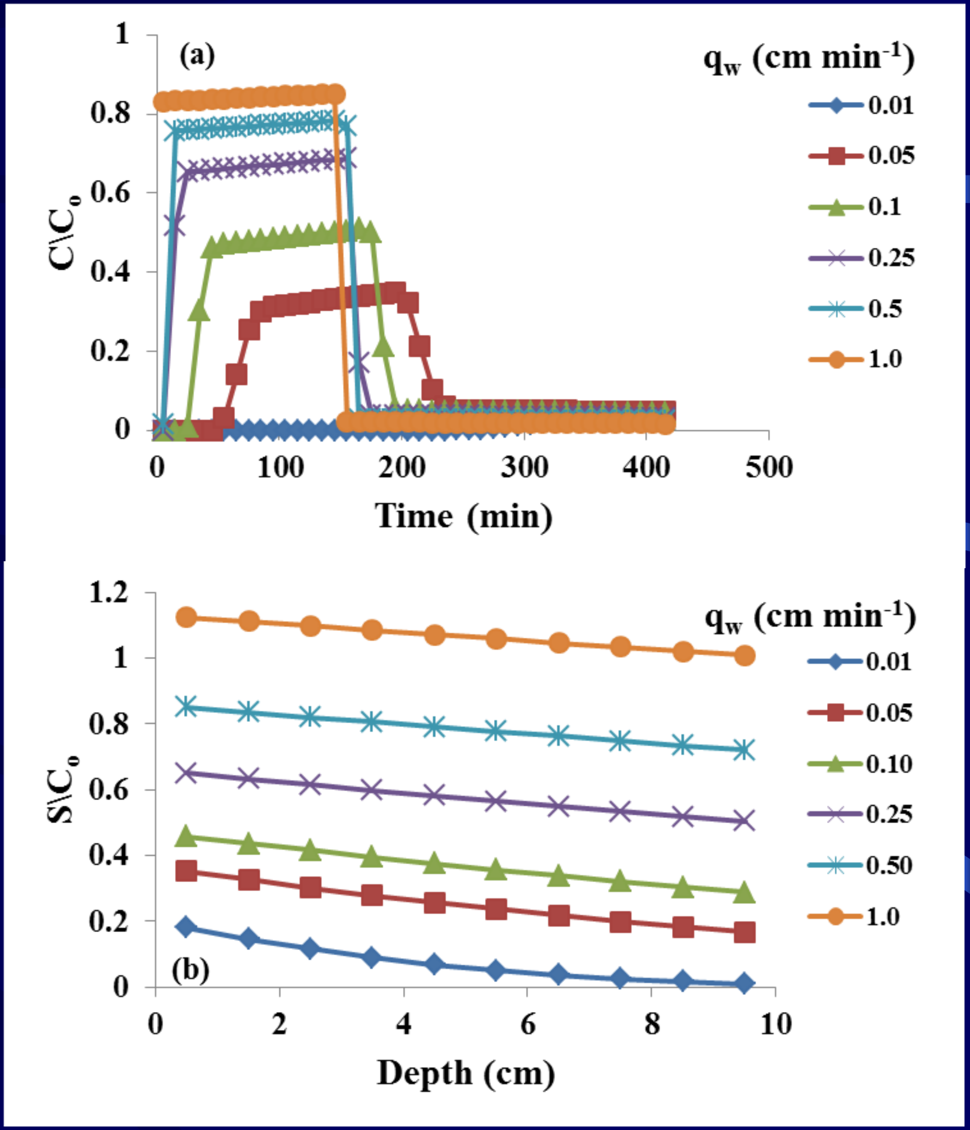
- Mass transfer occurs via sedimentation (A), and interception (B), and diffusion (C).
- Mass transfer is quantified by solution of the convective diffusion equation.





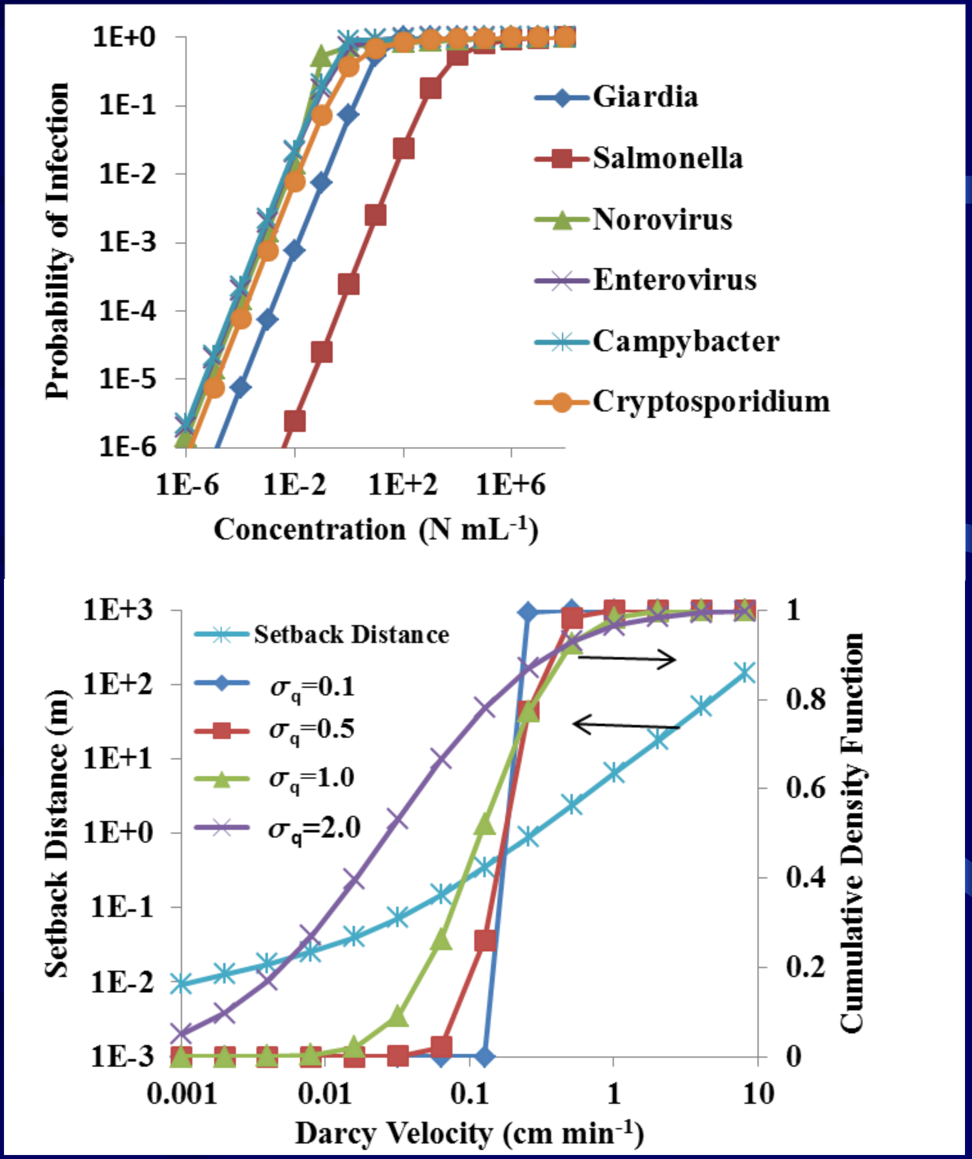
Filtration Theory Prediction

- Filtration theory predicts that k_{sw} increases with velocity.
- However, there is a decrease in residence with increasing q_w that produces less retention.
- Retention profile is exponential with transport distance.



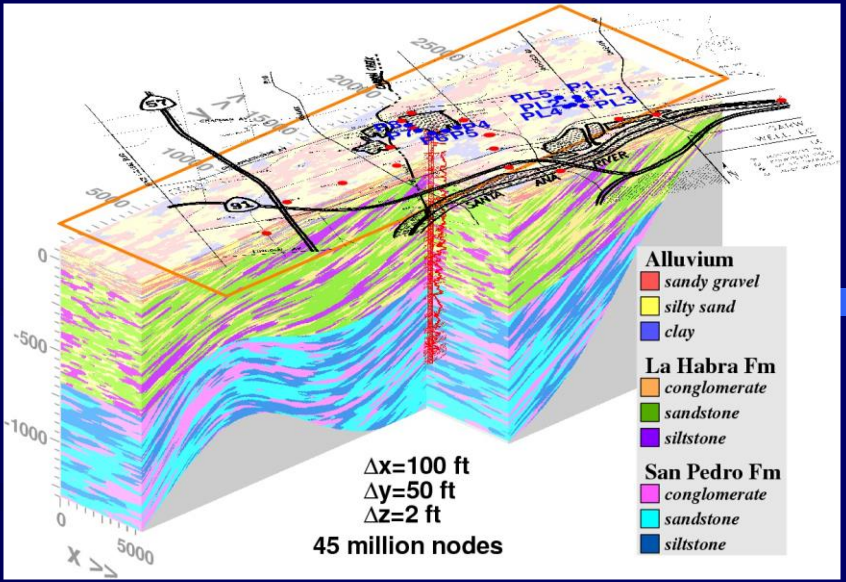
Setback Distance and Velocity

- Probability of infection depends on the amount of water consumed, the concentration of pathogens, and dose-response model.
- Transport (setback) distance is needed to remove pathogens (> 6 logs) from source water.
- Setback distance increases with velocity.
- High velocity regions will control the risk of infection.



Deterministic Models

- **Deterministically model subsurface heterogeneity in flow and transport properties.**
- **Does not account for uncertainty.**
- **Alternative deterministic models**
  - ➢ **Dual permeability models**
  - ➢ **Analytic solution from Leij and Bradford (2013)**



Maxwell et al. (2003)

$$\theta_1 \frac{\partial C_1}{\partial t} = \theta_1 D_1 \frac{\partial^2 C_1}{\partial z^2} - \theta_1 v_1 \frac{\partial C_1}{\partial z} - \theta_1 \left(\mu_w + k_{sw1}\right) C_1 + \rho_b k_{rs1} S_{r1} - \theta_1 \Gamma \left(C_1 - C_2\right)$$

$$\theta_2 \frac{\partial C_2}{\partial t} = \theta_2 D_2 \frac{\partial^2 C_2}{\partial z^2} - \theta_2 v_2 \frac{\partial C_2}{\partial z} - \theta_2 \left(\mu_w + k_{sw2}\right) C_2 + \rho_b k_{rs2} S_{r2} + \theta_1 \Gamma \left(C_1 - C_2\right)$$

$$\rho_b \frac{\partial S_{r1}}{\partial t} = \theta_1 F_{rev} k_{sw1} C_1 - \rho_b \left(\mu_s + k_{rs1}\right) S_{r1}$$

$$\rho_b \frac{\partial S_{i1}}{\partial t} = \theta_1 \left(1 - F_{rev}\right) k_{sw1} C_1 - \rho_b \mu_s S_{i1}$$

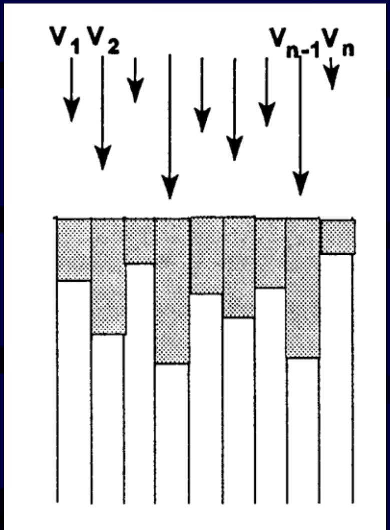
$$\rho_b \frac{\partial S_{r2}}{\partial t} = \theta_2 F_{rev} k_{sw2} C_2 - \rho_b \left(\mu_s + k_{rs2}\right) S_{r2}$$

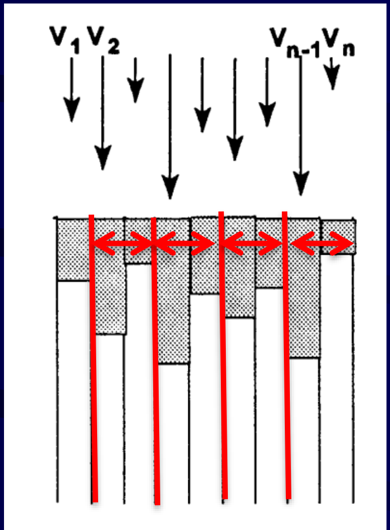
$$\rho_b \frac{\partial S_{i2}}{\partial t} = \theta_2 \left(1 - F_{rev}\right) k_{sw2} C_2 - \rho_b \mu_s S_{i2}$$

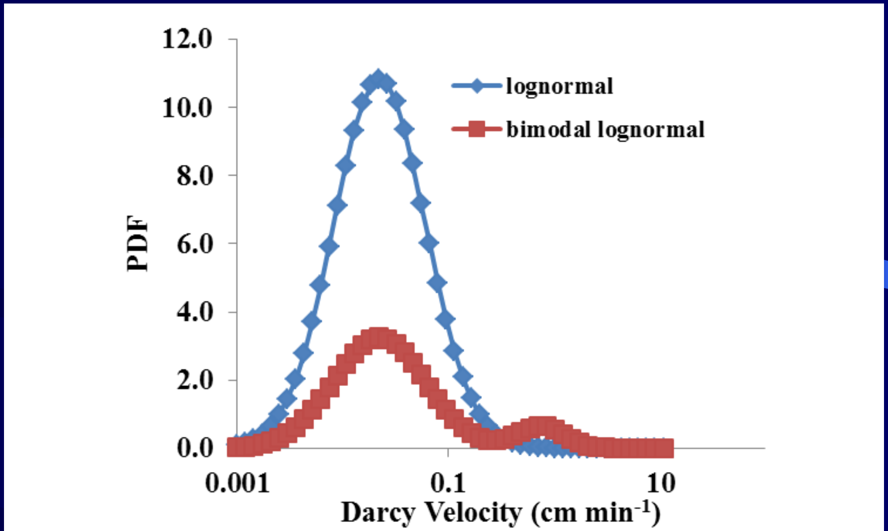
Wang et al. (2014)

Stochastic Stream Tube Model (SSTM)

- Field-scale flow and transport are described using a series of independent stream tubes.
- Local-scale transport is described deterministically using single or dual permeability models.
- Field-scale parameters are described with PDFs.







- More complex geometries (variable width and tortuous) may be considered.
- Mean <u>and variance</u> of field-scale concentrations can be calculated.

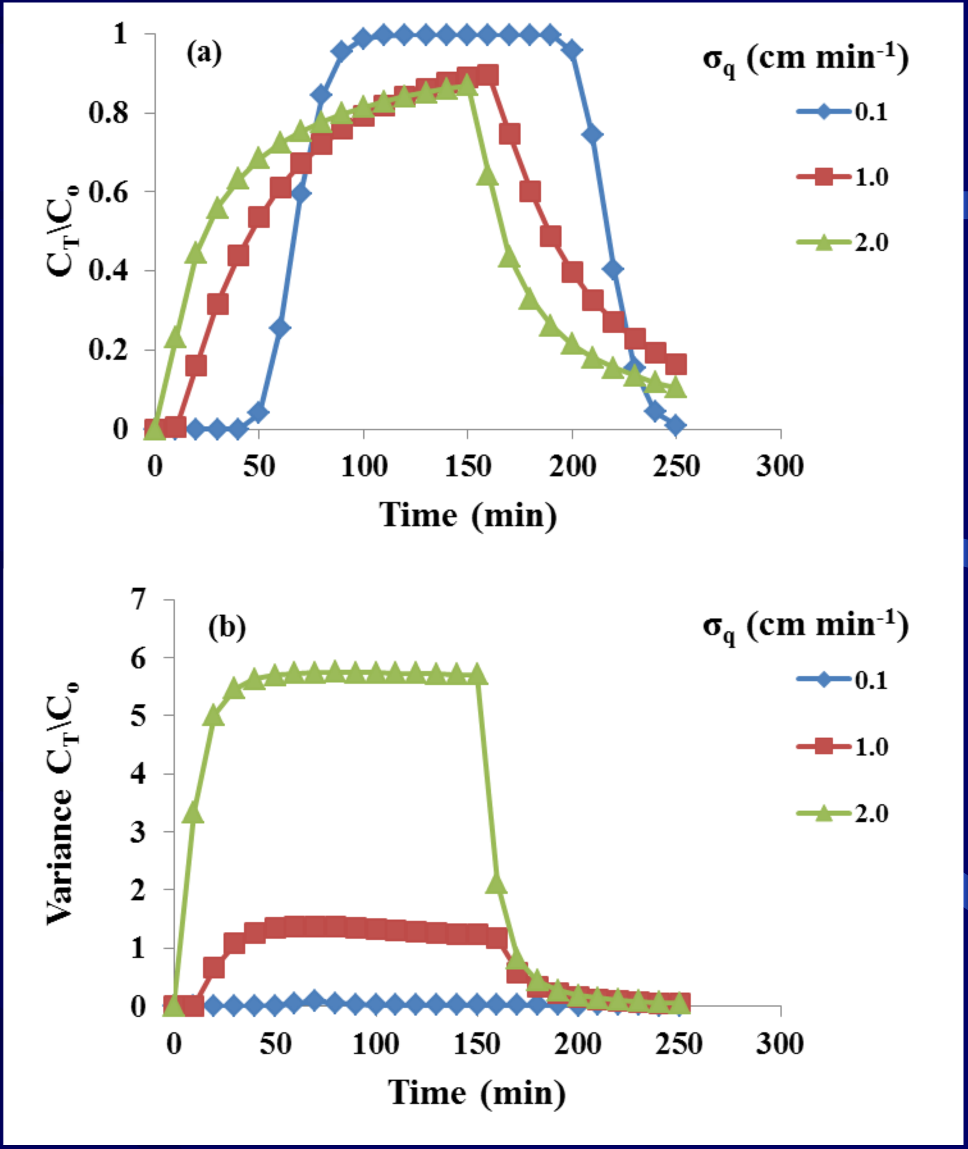
$$C_T(z,t) = \frac{\langle q_w C(z,t;q_w)\rangle}{\langle q_w \rangle} = \frac{\int_0^\infty q_w f(q_w) C(z,t;q_w)\, dq_w}{\int_0^\infty q_w f(q_w)\, dq_w}$$

$$C_T(z,t) = \frac{\langle q_1 C_1(z,t;q_w) + q_2 C_2(z,t;q_w)\rangle}{\langle q_w \rangle} = \frac{\int_0^\infty f(q_w)\left[q_1 C_1(z,t;q_w) + q_2 C_2(z,t;q_w)\right] dq_w}{\int_0^\infty q_w f(q_w)\, dq_w}$$

- Dual permeability stream tube model allows for mixing!

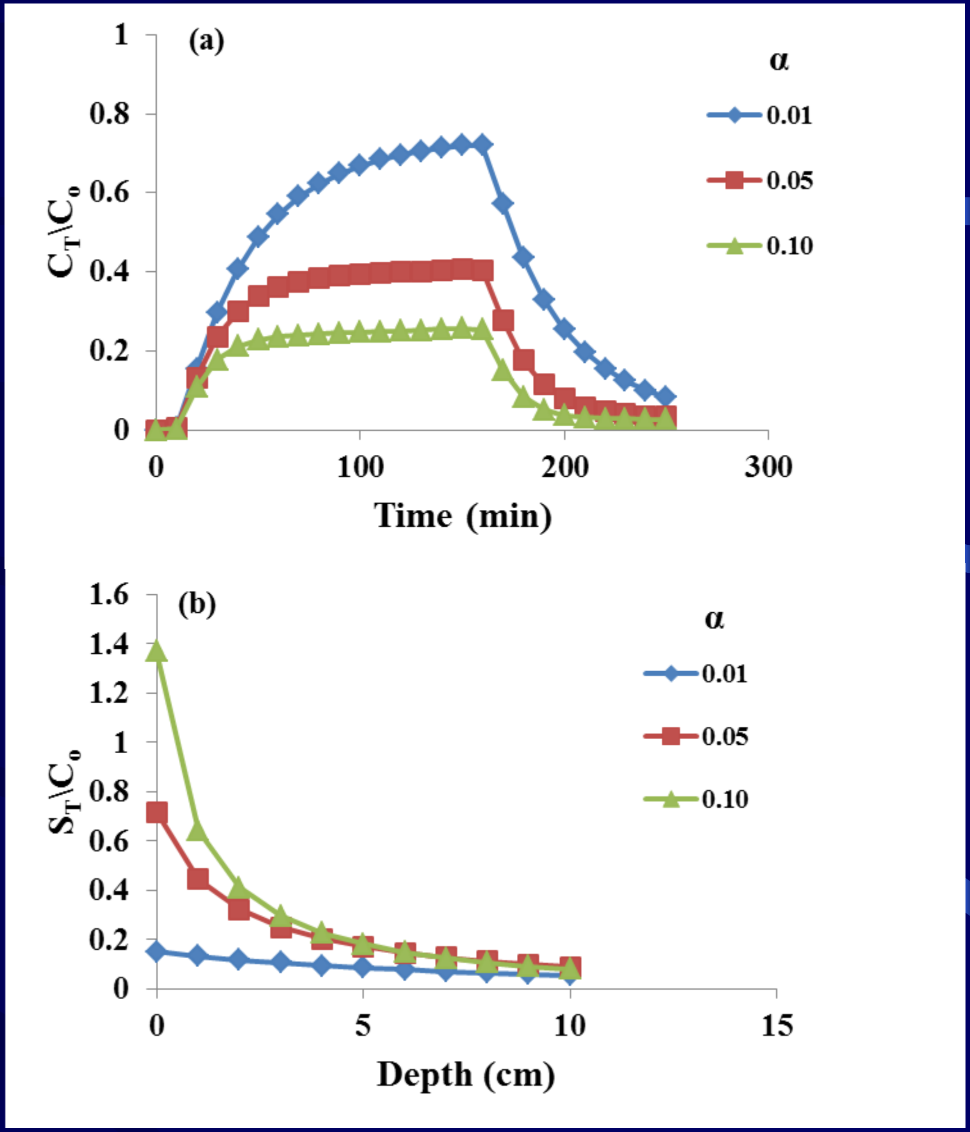
SSTM – Single Permeability Per Tube

- Ex. – Conservative tracer
- Earlier breakthrough and concentration variance with increasing velocity variance.
- Tailing is due to physical non-equilibrium.



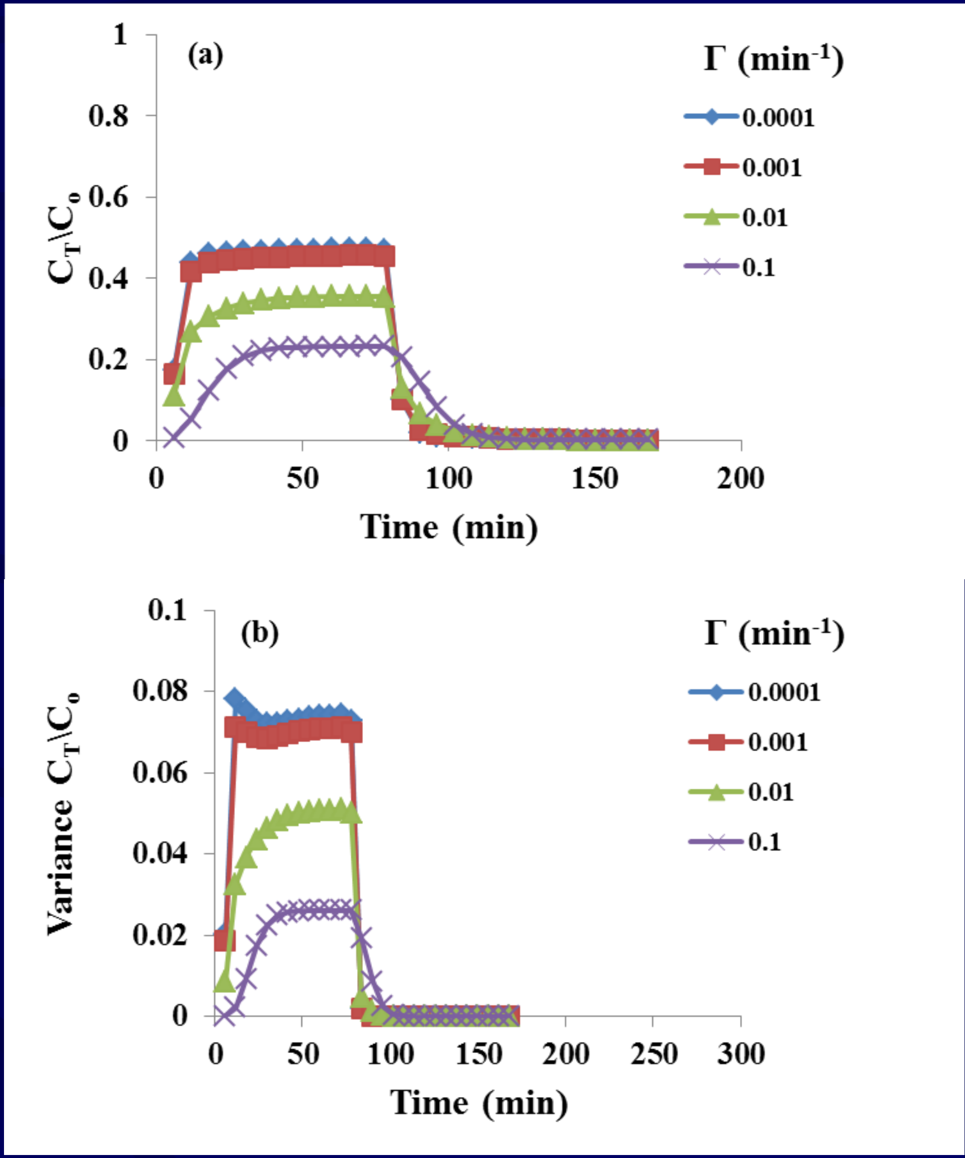
SSTM – Single Permeability Per Tube

- Example of pathogen transport
- Pathogens are quickly removed from low velocity regions.
- Pathogen transport continues for greater distances in high velocity regions.
- This produces hyper-exponential retention profiles, especially for greater retention rates and large velocity distributions.



SSTM – Dual Permeability Per Tube

- Example of pathogen transport
- Greater exchange produces less transport and lower variance in concentration.
- SSTM with single permeability per tube provides a worst case pathogen transport scenario, but is may be too conservative.



Conclusions

- The setback distance increases with velocity.
- High velocity regions will control the risk of infection.
- Stream tube models have several advantages over deterministic approaches (PDFs instead of explicit description of heterogeneity; mean and variance).
- Stream tube models may also account for mixing (dual permeability), hyper-exponential RPs, early breakthrough, and concentration tailing.
- SSTM with single permeability per tube provides a worst case transport scenario.