

MODELLING SOLUTE TRANSPORT WITH PREFERENTIAL FLOW PATHS

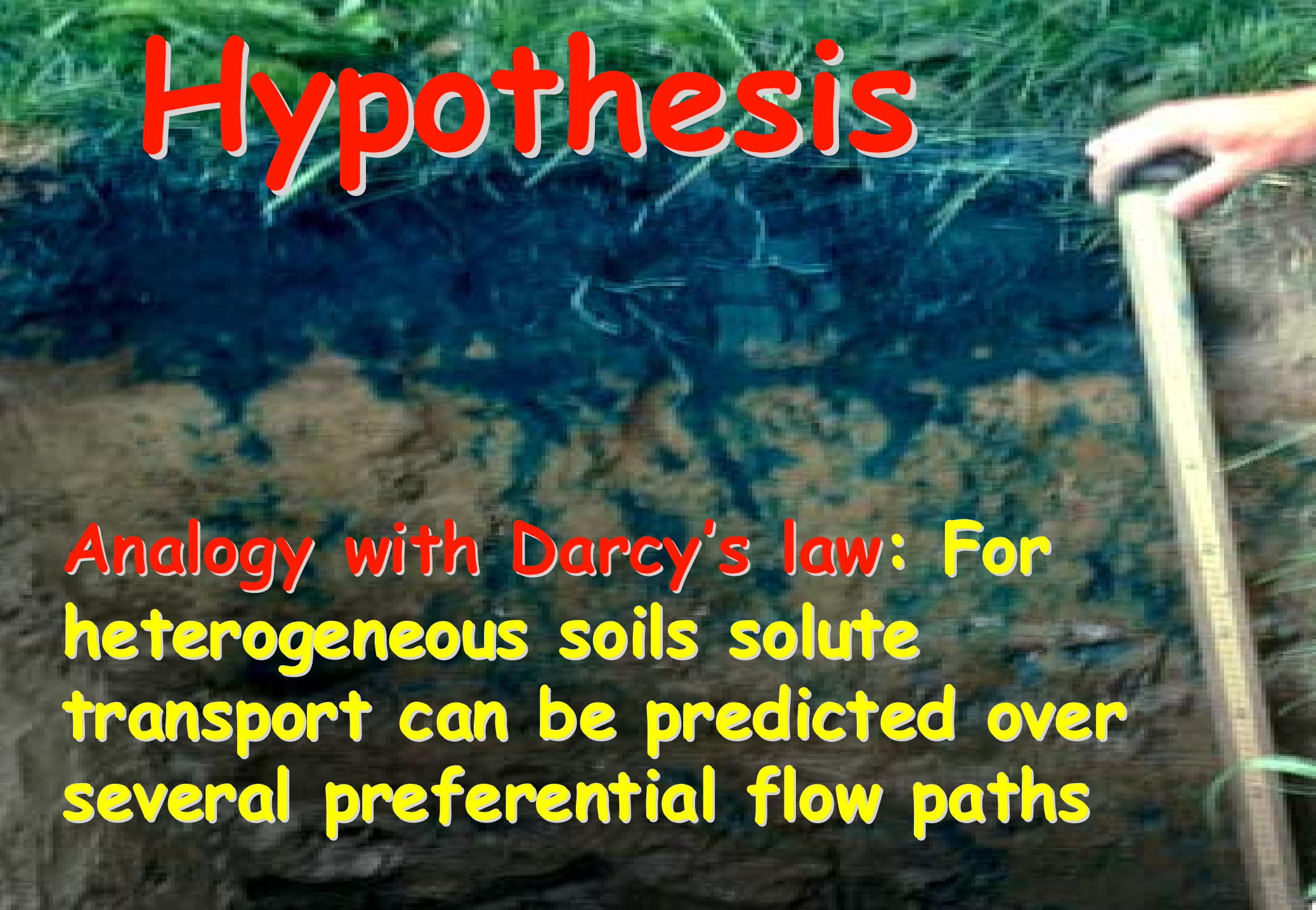
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Akhtar, B.K. Richards, K.-J.S. Kung, J. Boll,
C. Darnault, T.J. Gish, L.W. Dekker,
C.J.Ritsema, S.O. Aburime, and many others



For homogeneous
soils Darcy's law is
valid only for
several pores

Fact

Hypothesis

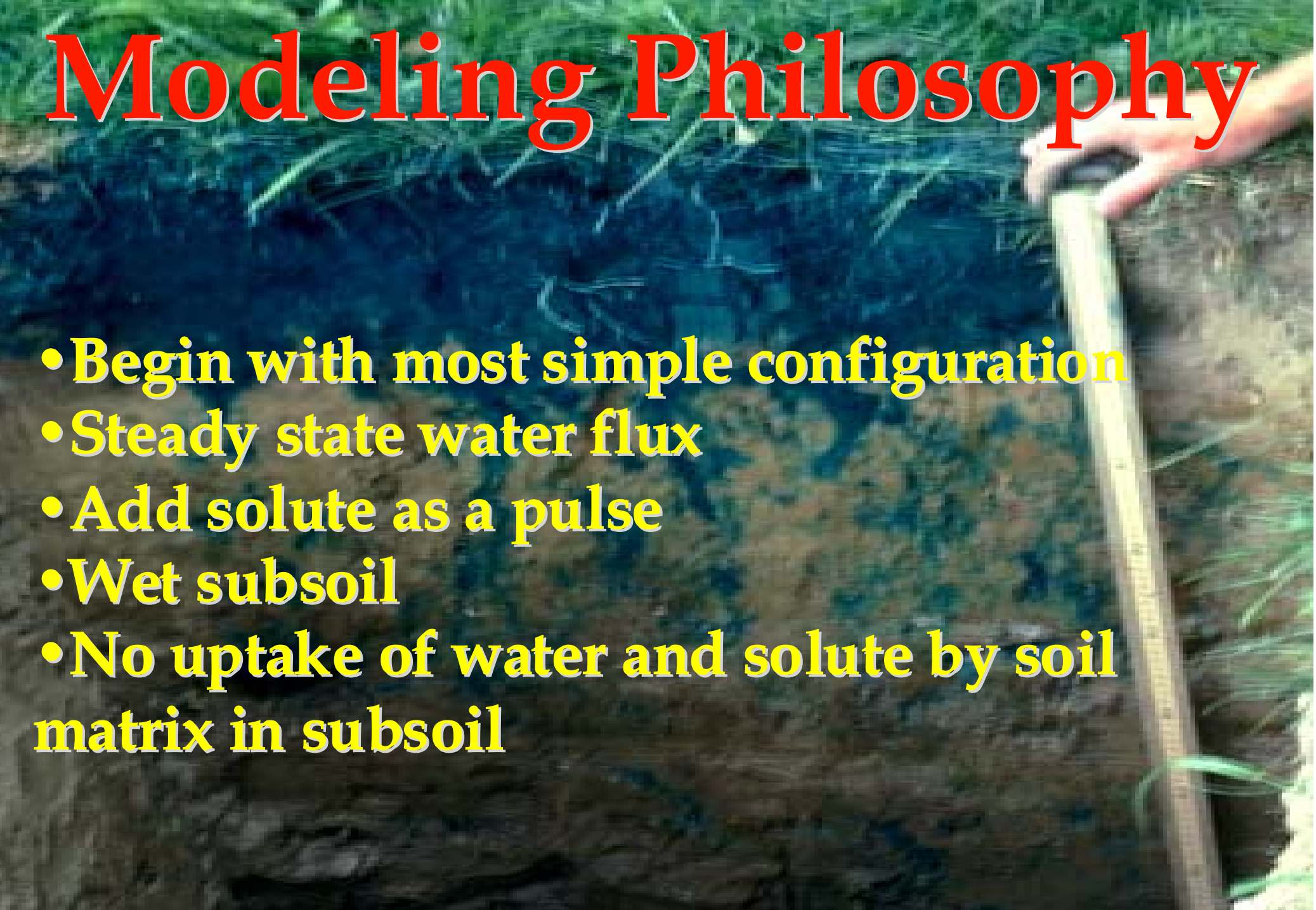
The background image shows a close-up of dark, moist soil. A hand is visible on the right side, holding a yellow measuring tape vertically. The soil surface is uneven, and there are visible root channels or preferential flow paths running through it, which are the focus of the hypothesis being presented.

Analogy with Darcy's law: For heterogeneous soils solute transport can be predicted over several preferential flow paths

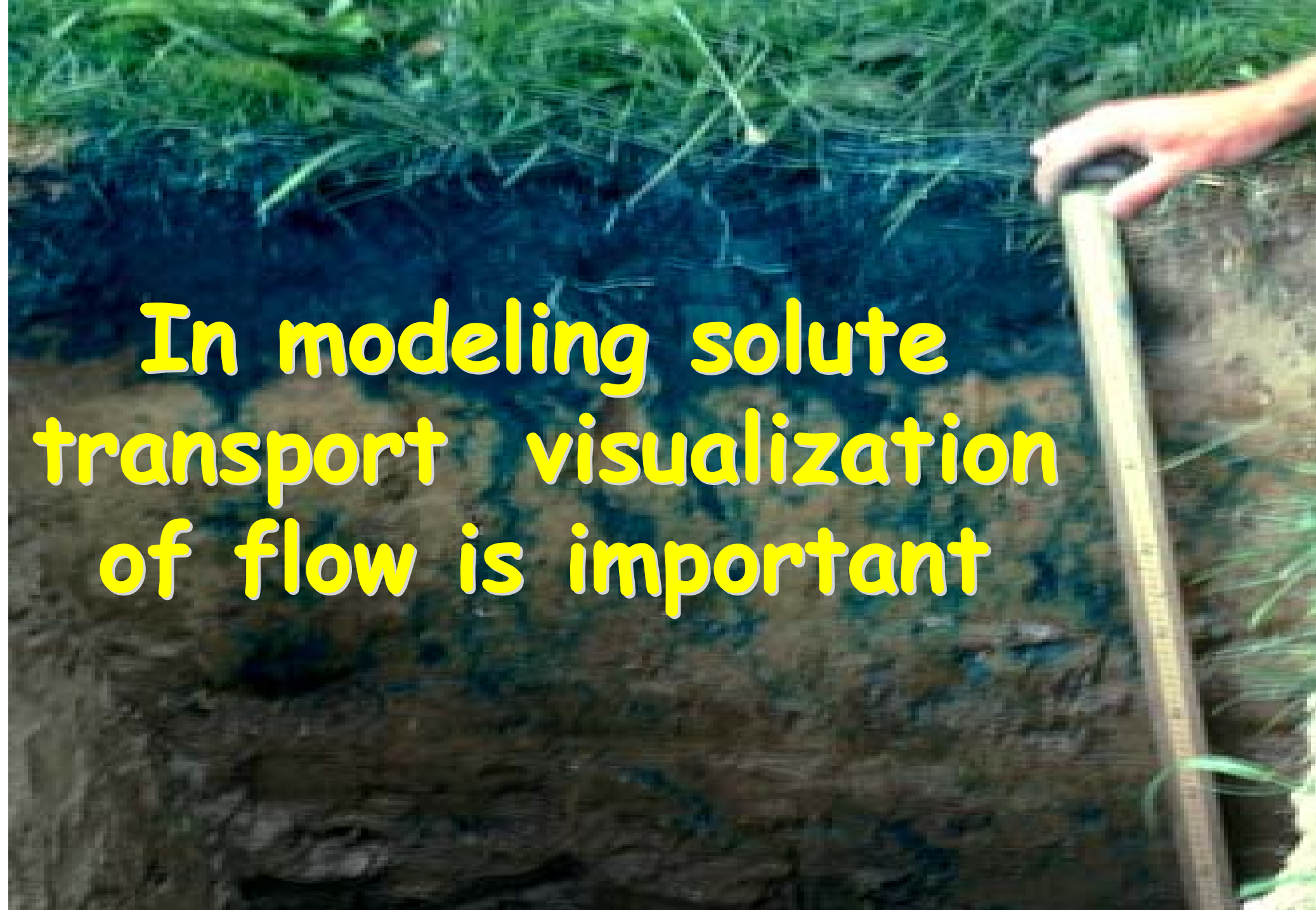
Hypothesis

Field scale solute transport
can not be predicted by
modeling individual pores

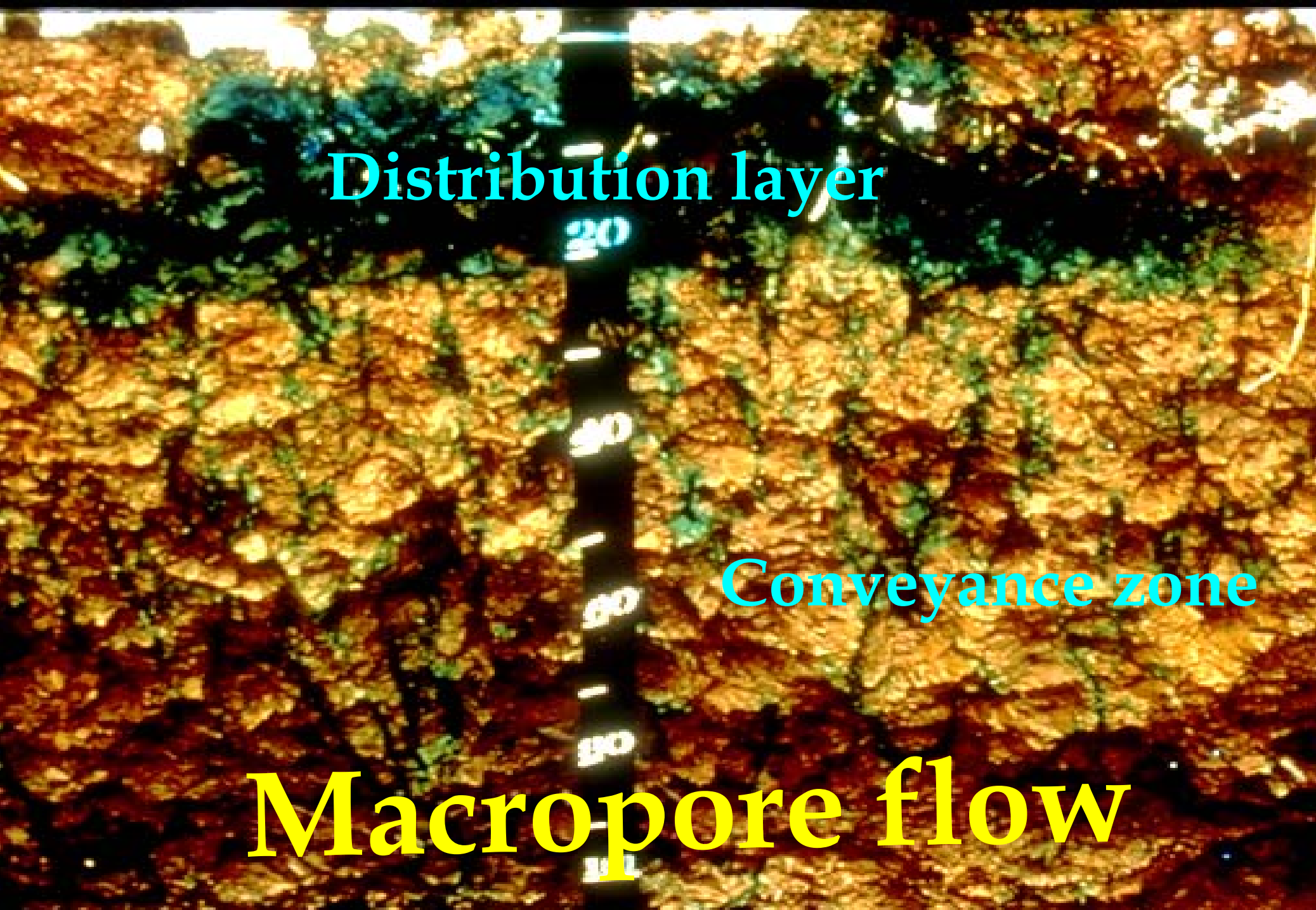
Modeling Philosophy

A background image showing a hand holding a measuring tape vertically against a dark, moist soil surface. The soil is dark brown and appears wet, with some green grass visible at the top and bottom edges. The measuring tape is yellow and has black markings. The hand is light-skinned and is positioned on the right side of the frame.

- **Begin with most simple configuration**
- **Steady state water flux**
- **Add solute as a pulse**
- **Wet subsoil**
- **No uptake of water and solute by soil matrix in subsoil**

A photograph showing a cross-section of soil. The top layer is dark brown, moist soil. Below it is a lighter, more textured layer. A hand is visible on the right side, holding a yellow measuring tape vertically against the soil profile. The background is a dense patch of green grass.

**In modeling solute
transport visualization
of flow is important**

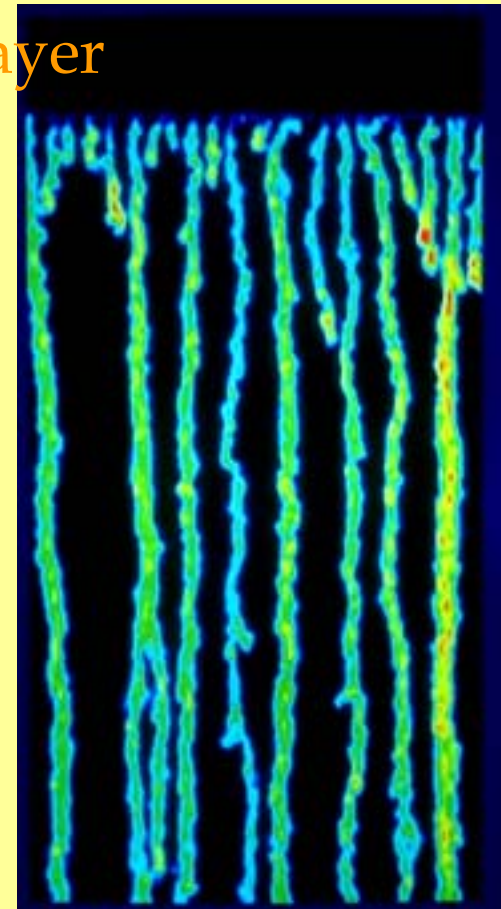
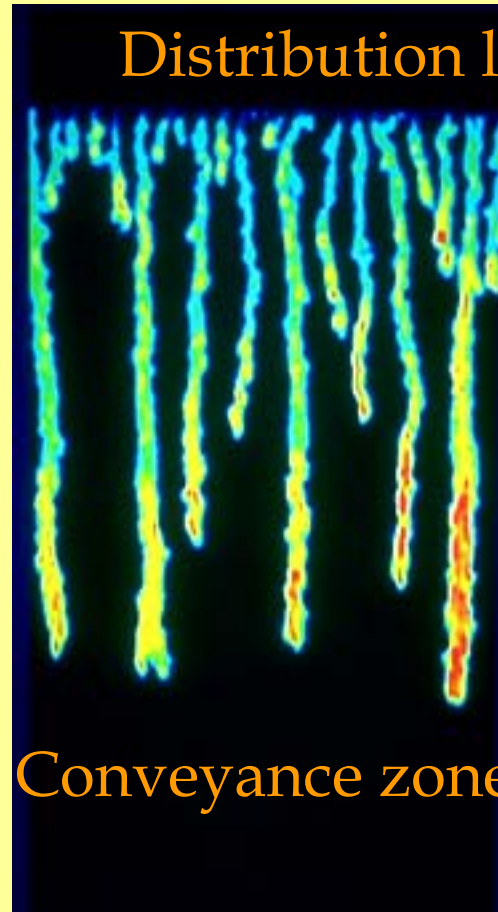
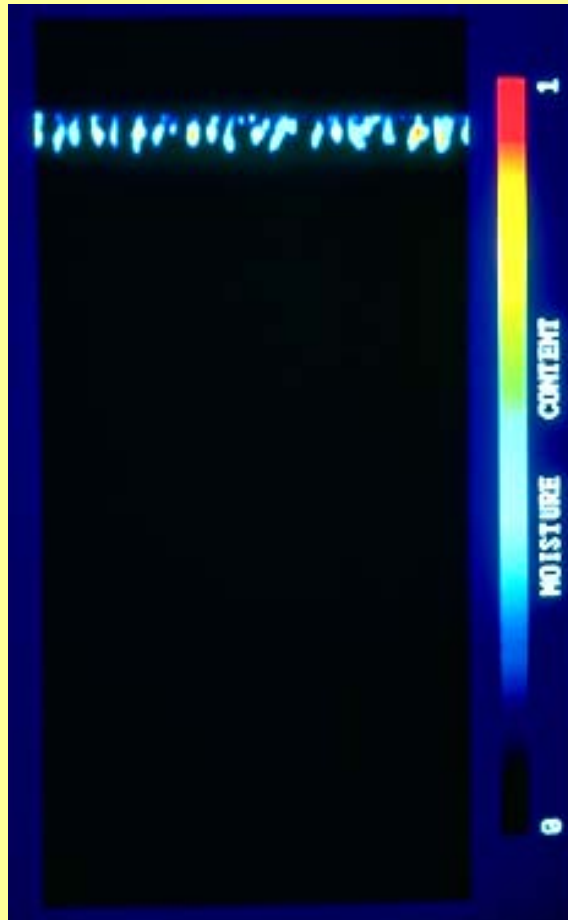
A photograph of a soil profile, likely from a field or laboratory setting. A vertical black scale with white markings is positioned in the center. The soil is dark brown and appears to have a crumbly texture. The scale has markings at 20, 40, 60, 80, and 100. The text 'Distribution layer' is written in red at the top, 'Conveyance zone' is written in red in the middle, and 'Macropore flow' is written in yellow at the bottom.

Distribution layer

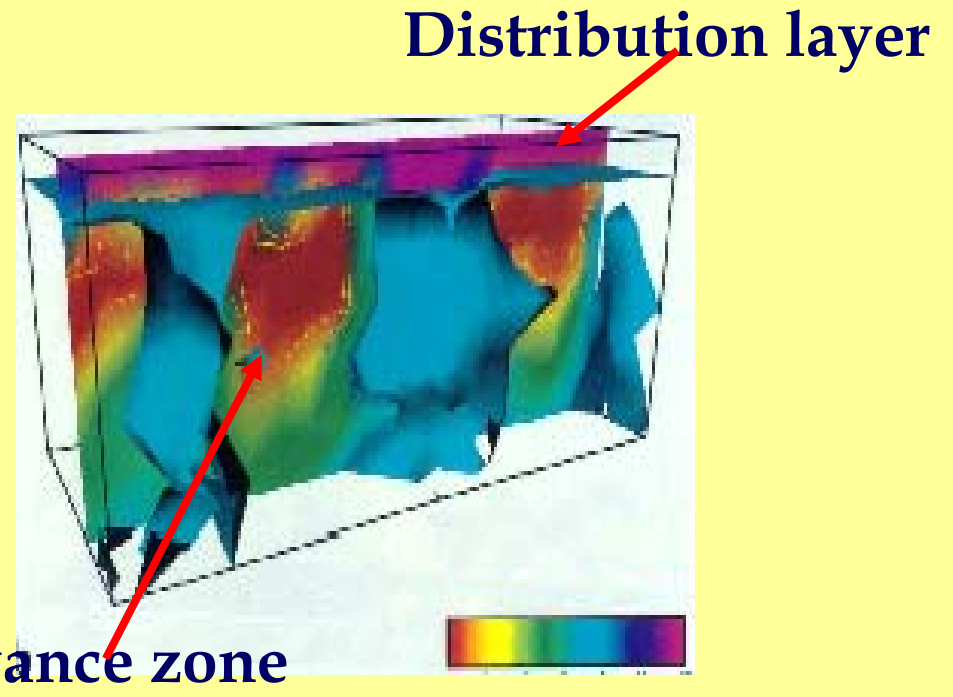
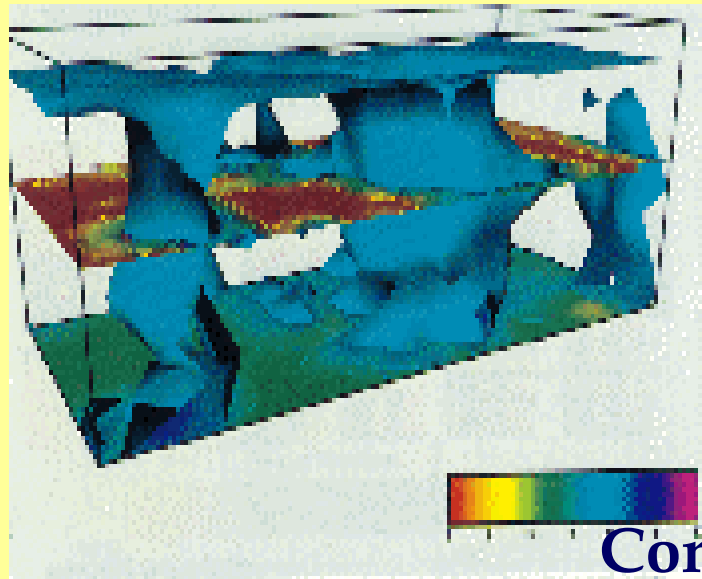
Conveyance zone

Macropore flow

Finger Flow in Homogenous Sand



Finger Flow in Water repellent sand



Funneled Finger Flow



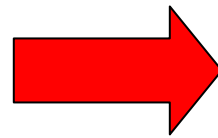
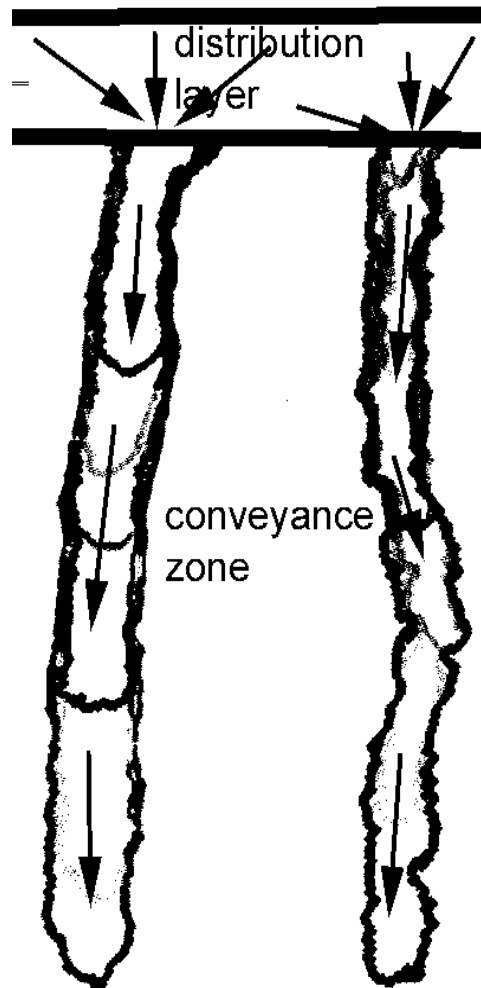


Preferential flow models must have two layers:

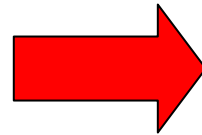


- Distribution layer**
- Conveyance zone**

Preferential flow model



$$C = C_0 \exp(-\lambda t)$$



$$\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial x^2} - v \frac{\partial C}{\partial x}$$

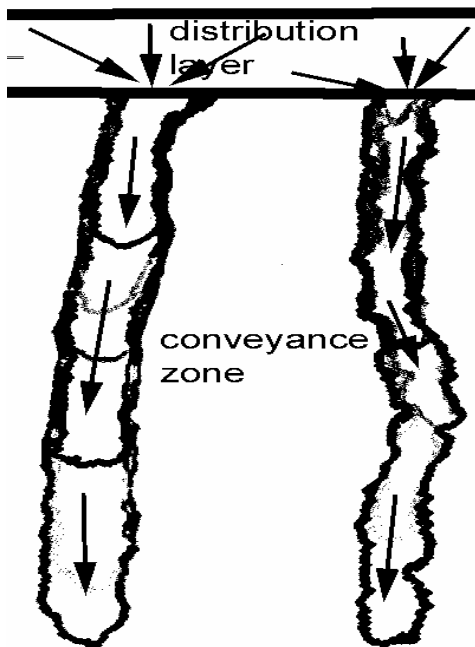
Preferential flow model

No flow outside preferential flow path in conveyance zone

$$C = \frac{1}{2} C_o \left[\operatorname{erfc} \left(\frac{x - Vt}{\sqrt{4Dt}} \right) - \exp \left[\frac{Vx}{2D} (1 - \alpha) - \lambda t \right] \operatorname{erfc} \left(\frac{x - V\alpha t}{\sqrt{4Dt}} \right) \right]$$

$$\alpha = \sqrt{1 - \frac{4D\lambda}{V^2}},$$

$$\lambda = \int \frac{q dt}{W}$$



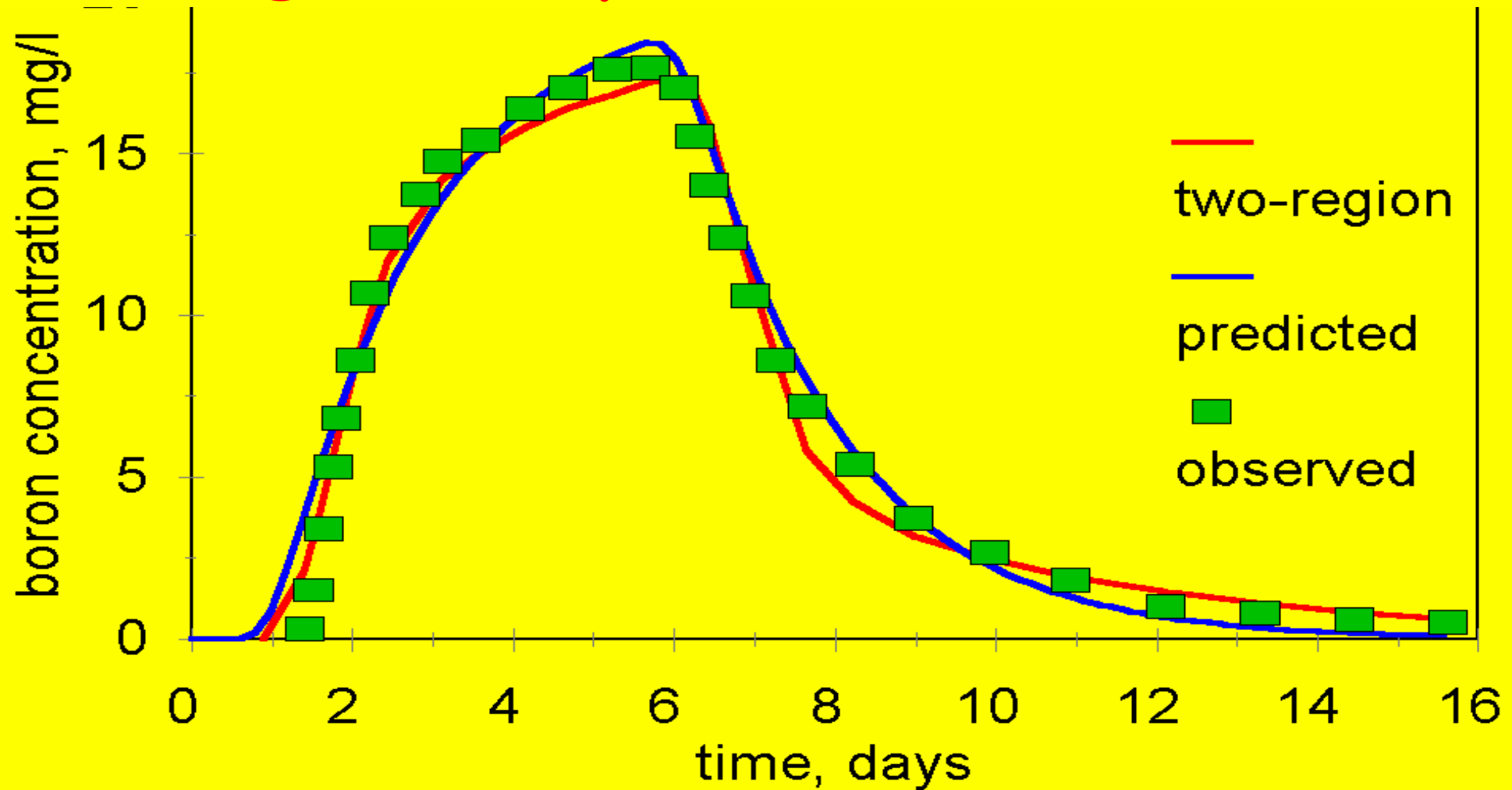
Input parameters for soil

W = water content distribution layer

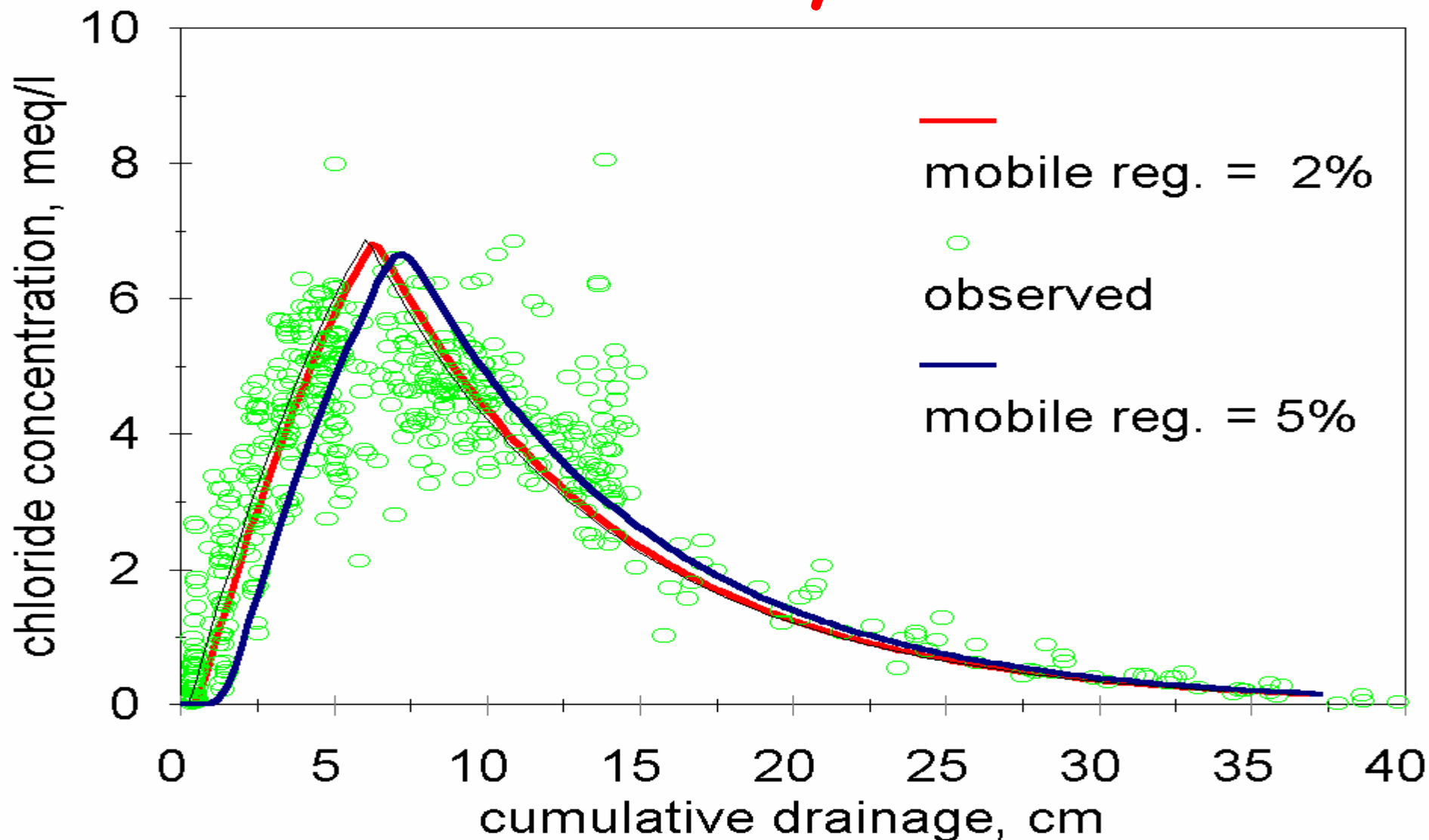
V = velocity in preferential flow paths, or
fraction of preferential flow path in soil

D = dispersion coefficient

Comparison of the two region and preferential flow model



Predicting chloride breakthrough through undisturbed 39 sandy loam columns



Experiments

Two sets of soil column experiments with were performed. Rain was applied with rainfall simulator.

1) instantaneous Cl application on homogeneous sand columns (**fingering flow** experiments)

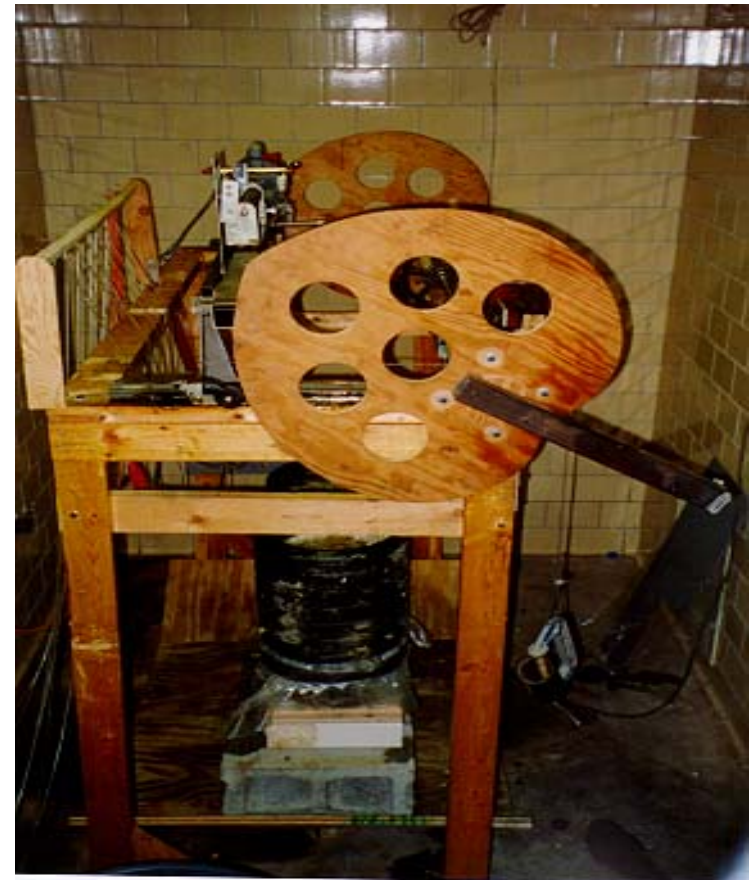
2) Pulsed application on undisturbed soil columns (**macropore flow** experiments)

EXPERIMENTAL SETUP

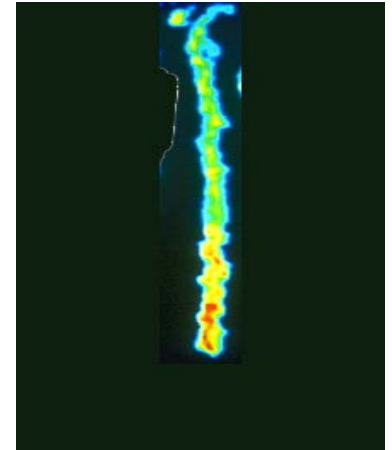
for studying conveyance zone transport

40 cm long undisturbed
clay loam or coarse sand

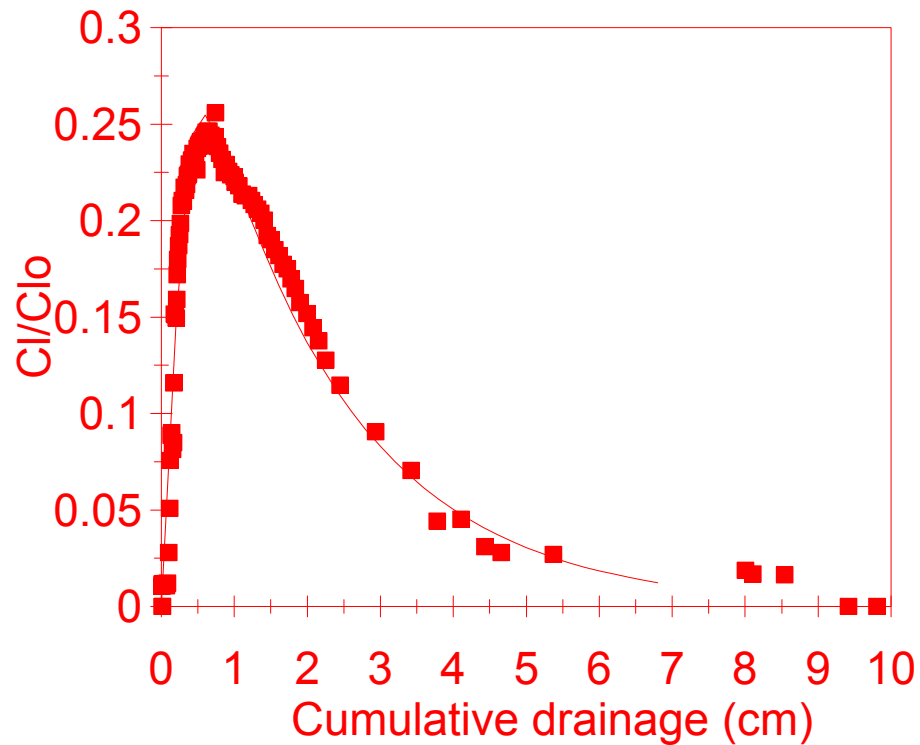
Rainfall rate varied from
0.002 to 2 cm/hr



fingered flow



$q=0.002$



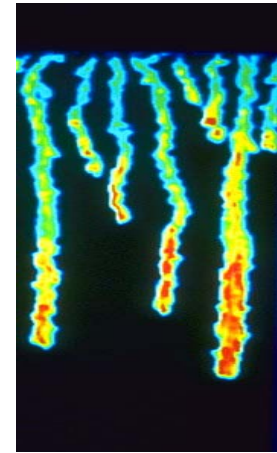
$q = 0.002 \text{ cm/min}$

$v = 0.3 \text{ cm/min}$

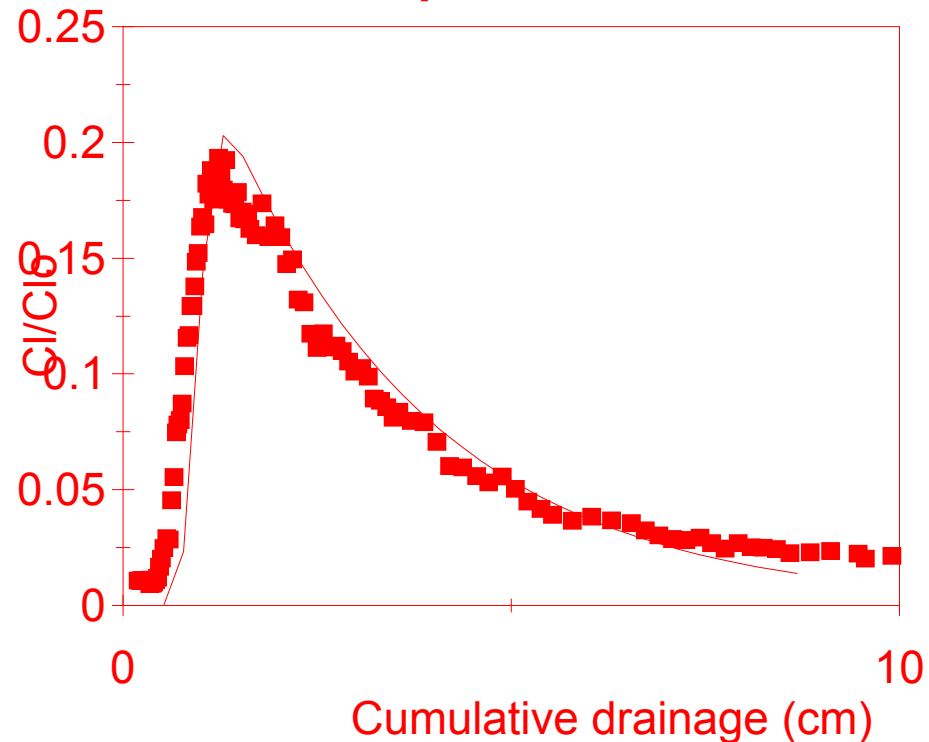
$D = 3 \text{ cm}^2/\text{min}$

$W = 2$

fingered flow



$q=0.017$



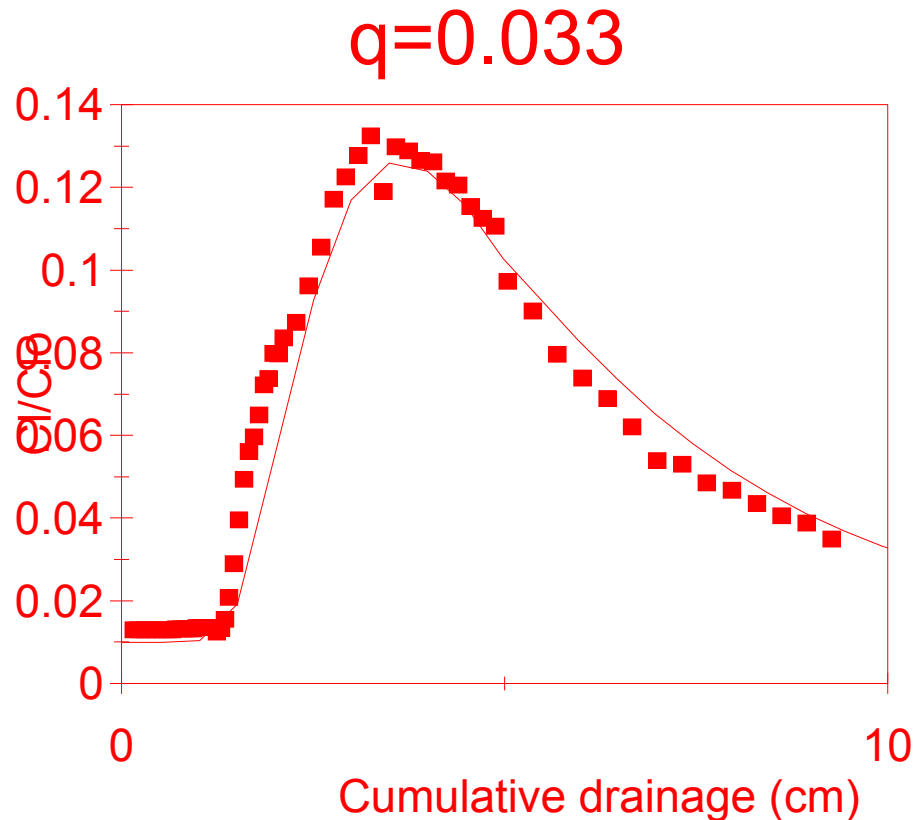
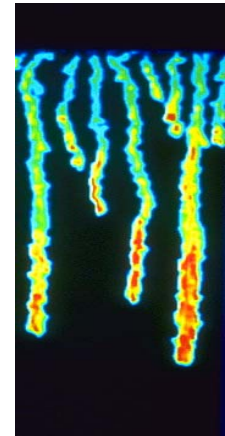
$q = 0.017 \text{ cm/min}$

$v = 0.7 \text{ cm/min}$

$D = 0.4 \text{ cm}^2/\text{min}$

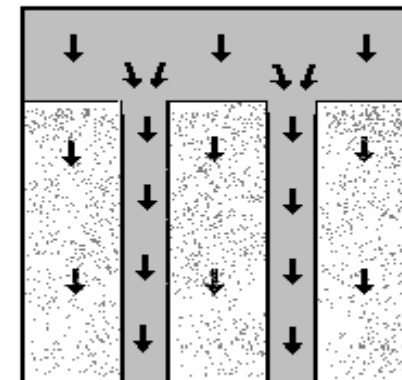
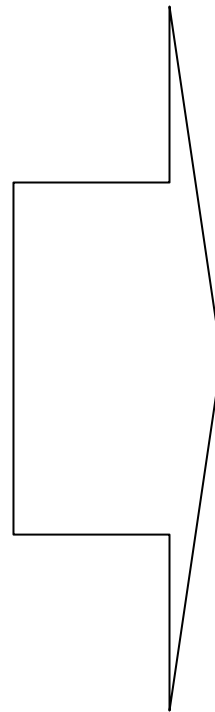
$W = 2.7$

fingered flow



- $q = 0.033$ cm/min
 $v = 0.5$ cm/min
 $D = 1.2$ cm²/min
 $W = 3.4$

Solute transport in structured soil



Distribution zone
(Preferential
mixing)

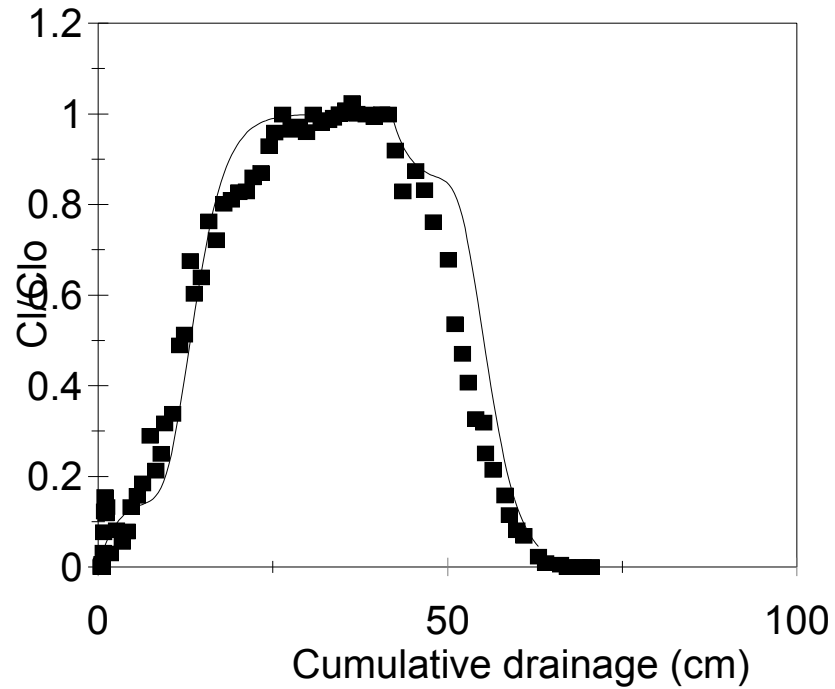
**Conveyance
zone**
(Matrix flow with
preferential flow
paths)

Preferential flow model for structured soil

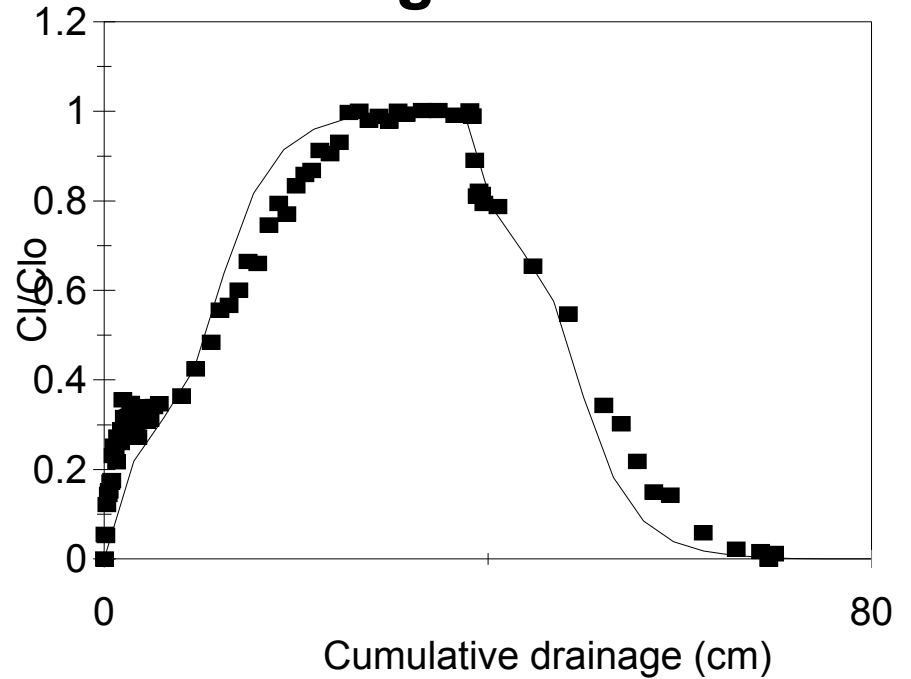
$$C = \frac{1}{2} a C_0 \left[\operatorname{erfc} \left(\frac{x - v_p t}{2\sqrt{Dt}} \right) - \exp \left\{ \frac{v_p x}{2D} (1 - \alpha_p) - \lambda t \right\} \operatorname{erfc} \left(\frac{x - v_p t \alpha_p}{2\sqrt{Dt}} \right) \right] +$$
$$\frac{(1-a)}{2} C_0 \left[\operatorname{erfc} \left(\frac{x - v_m t}{2\sqrt{Dt}} \right) - \exp \left\{ \frac{v_m x}{2D} (1 - \alpha_m) - \lambda t \right\} \operatorname{erfc} \left(\frac{x - v_m t \alpha_m}{2\sqrt{Dt}} \right) \right]$$

Where a is the fraction of the flow through the macro pores

Low rate



High rate



Rate	a	q	v_p	v_m	D	w	α_p	α_m
Low	0.15	0.003	2	0.01	0.01	25	0.99	0.721
High	0.38	0.025	2	0.1	0.1	4	0.99	0.866

Conclusions

- The generalized model was able to describe the breakthrough of solutes with three parameters (v , D , and W)
- Apparent water contents, W , increased proportional to the flow rate
- For fingered flow the velocity was almost independent of flow rate

References:

Steenhuis, T.S., Y.-J. Kim, J.-Y. Parlange, M.S. Akhtar, B.K. Richards, K.-J.S. Kung, T.J. Gish, L.W.Dekker, C.J. Ritsema, and S.O.Aburime. An equation for describing solute transport in field soils with preferential flow paths. In: Proceeding of the 2nd ASAE International Symposium on Preferential Flow: Water Movement and Chemical Transport in the Environment. Honolulu, HI. January 3-5, 2001.

Kim, Y.J., C.J.G. Darnault, N. Bailey, J.-Y. Parlange, and T.S. Steenhuis. 2003. An equation for describing solute transport in field soils with preferential flow paths. Submitted to Soil Sci. Soc. Am. Journal.