Development of multi-functional measurement devices for vadose zone characterization

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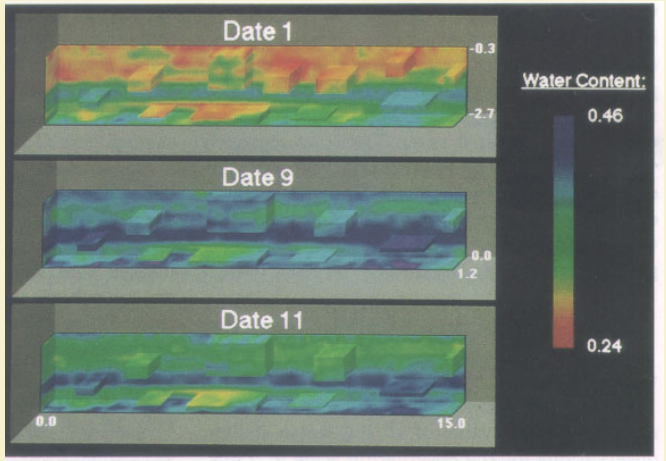
Keith Bristow
CSIRO, Townsville, Australia

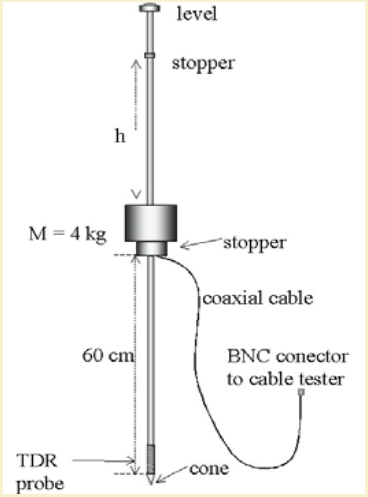
SOIL PROPERTIES ARE NOTORIOUSLY HETEROGENEOUS, IN BOTH SPACE AND TIME

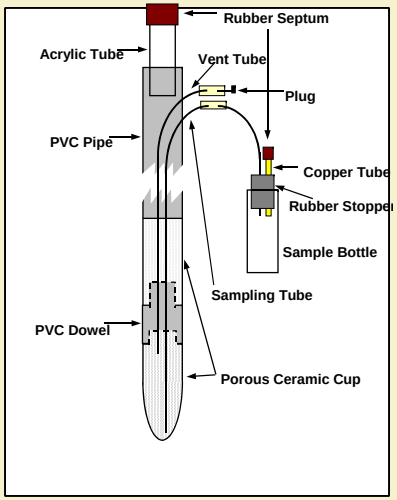


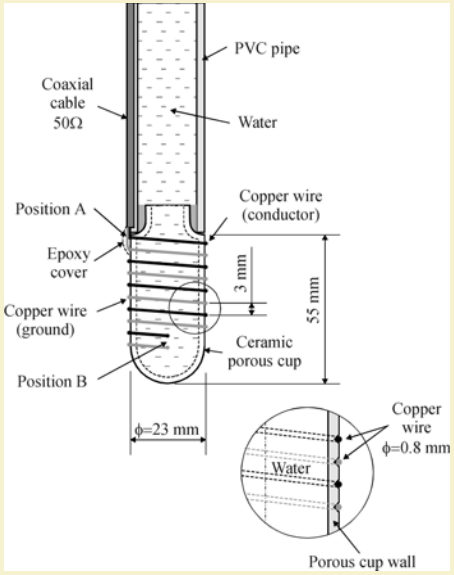
QUESTIONS:

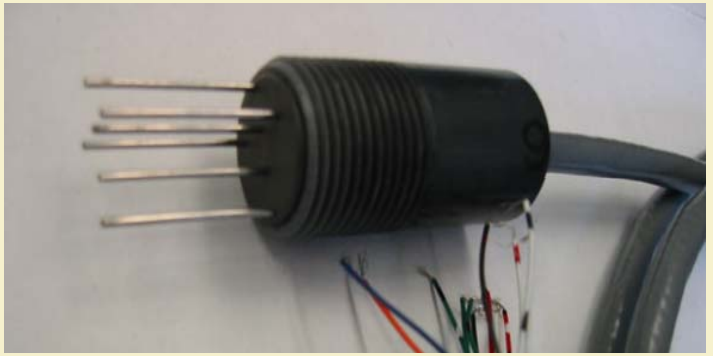
- Measurement Scale ????
- Measurement Types ???
- Measurement Instruments ??
- Measurement Locations ???
- Measurement Times ??????

MULTI-FUNCTIONAL instruments, ensuring identical measurement volumes

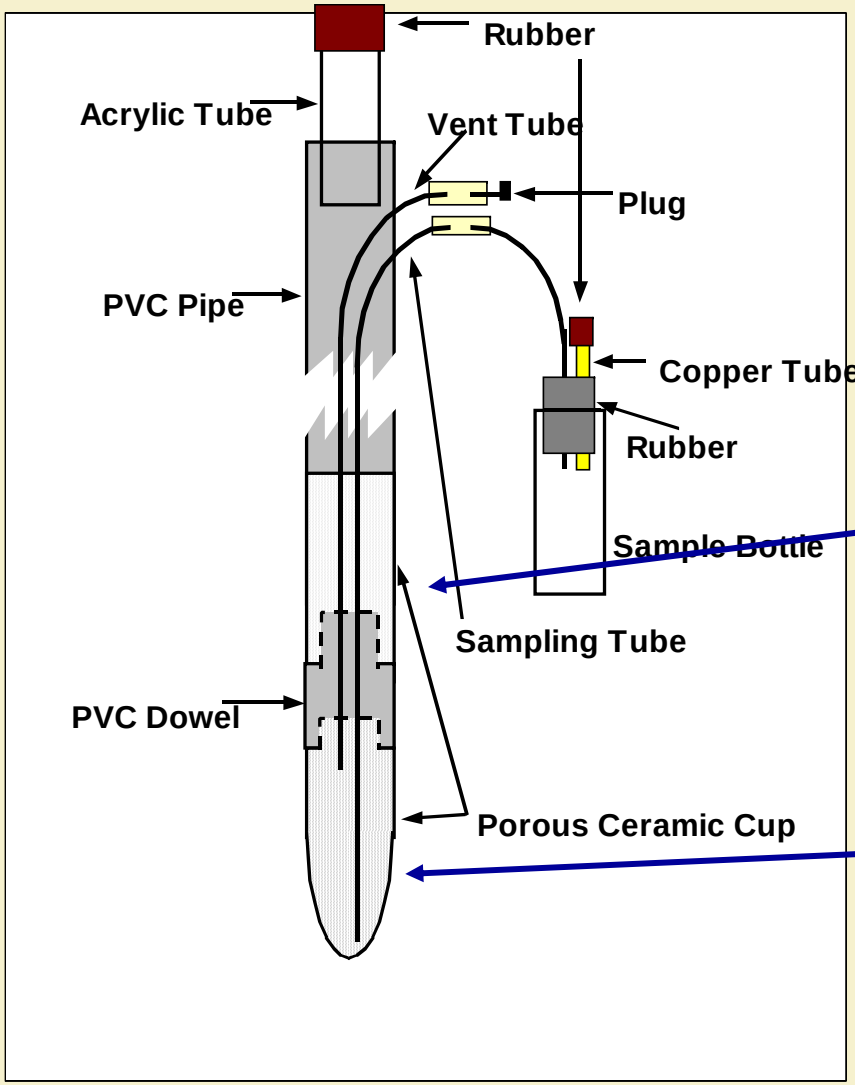








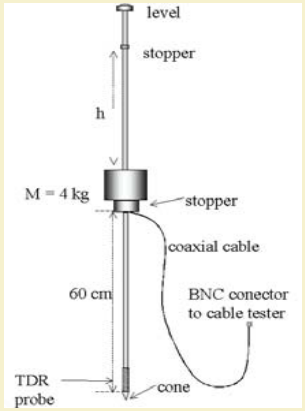
Combined tensiometer-solution sampling probe



Tensiometer

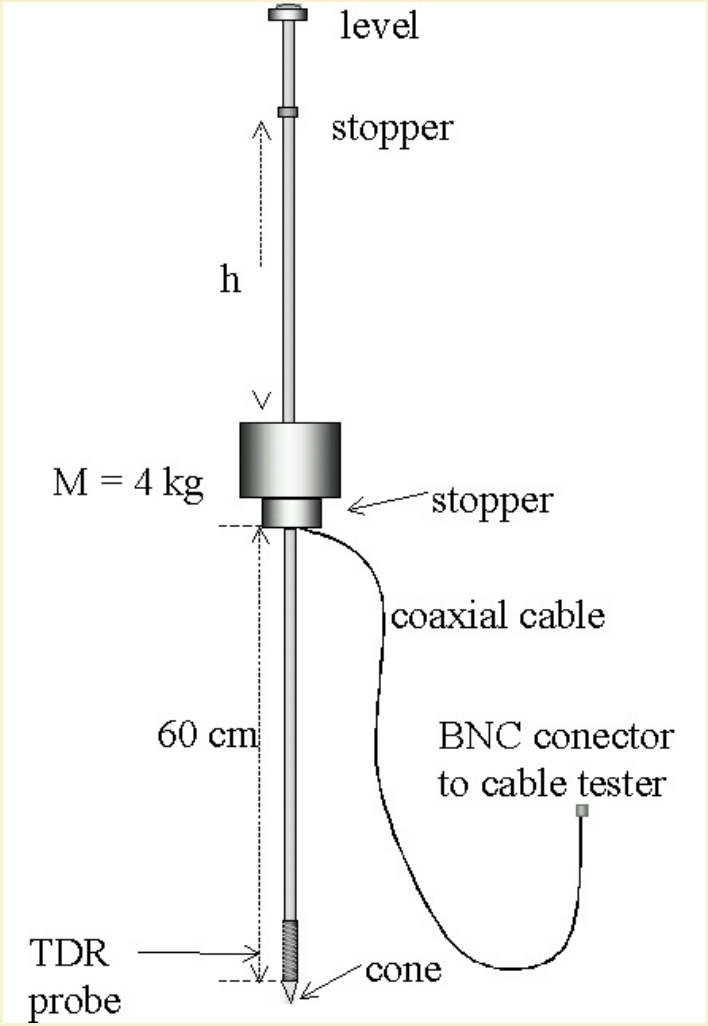
Soil Solution Sampling

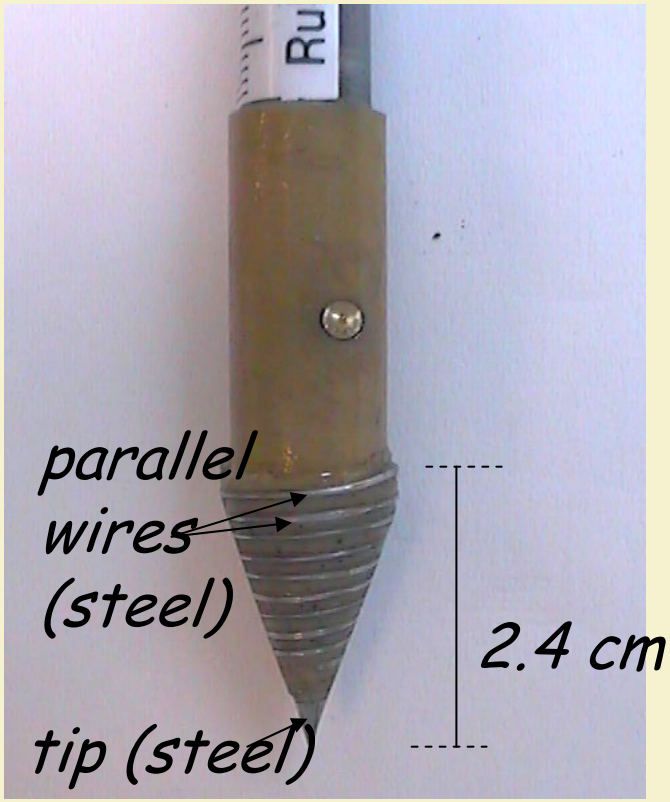
Coiled Cone Penetrometer-TDR Probe



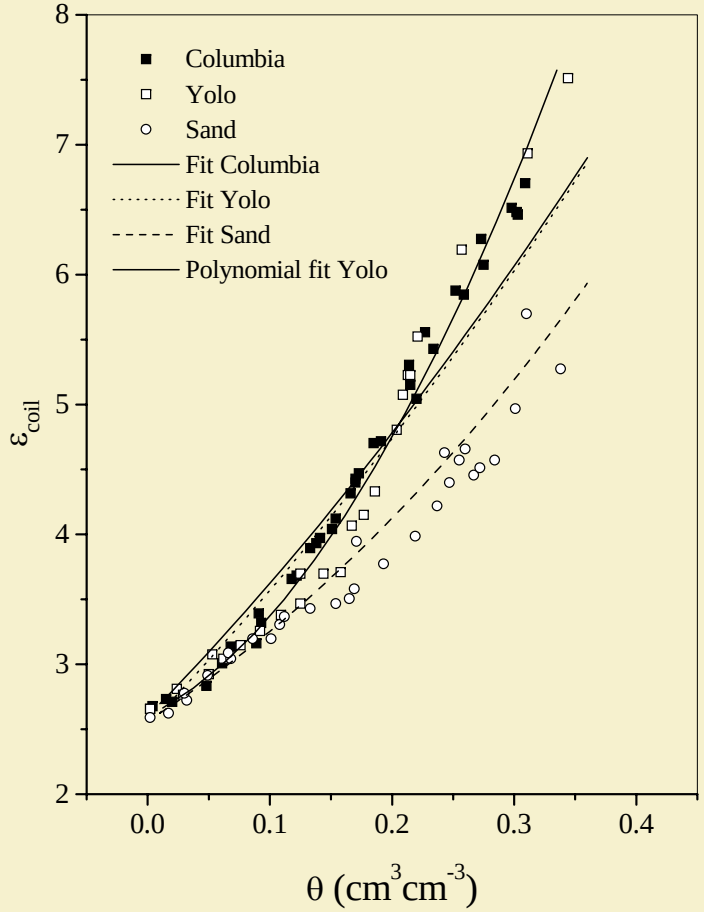
- **Two parallel copper wires are wrapped around inner core (as double helix);**
- **Wires are connected to conductor and ground of coaxial cable;**
- **Signal is analyzed by cable tester;**
- **Long wire length (about 30 cm) ensures accurate travel time measurement,and**
- **Narrow wire spacing ensure high depth resolution**

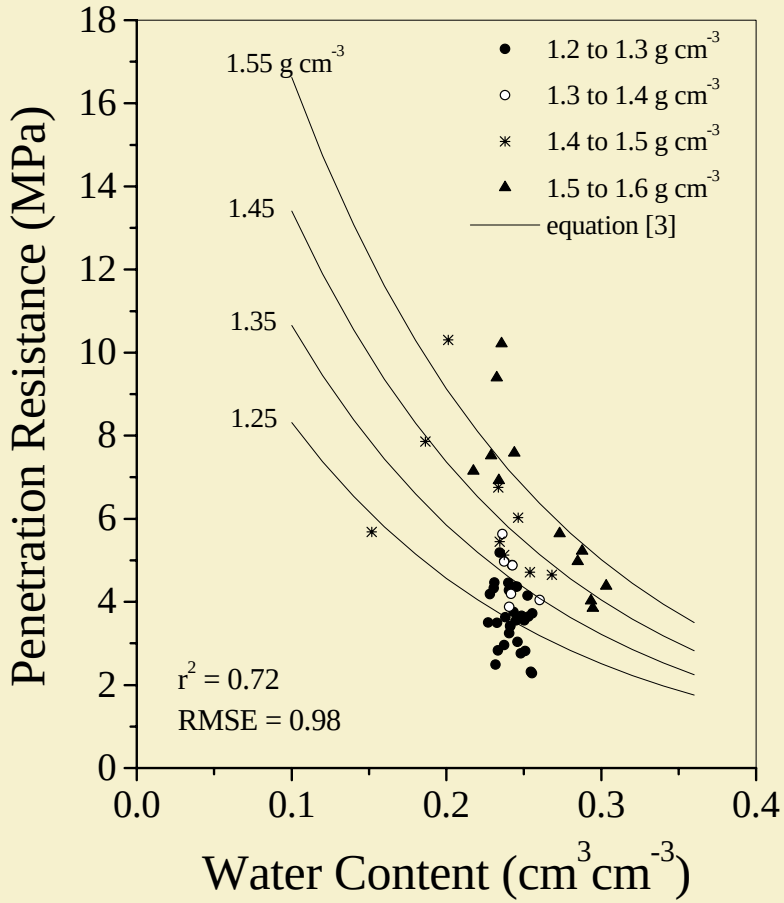
Hammer penetrometer





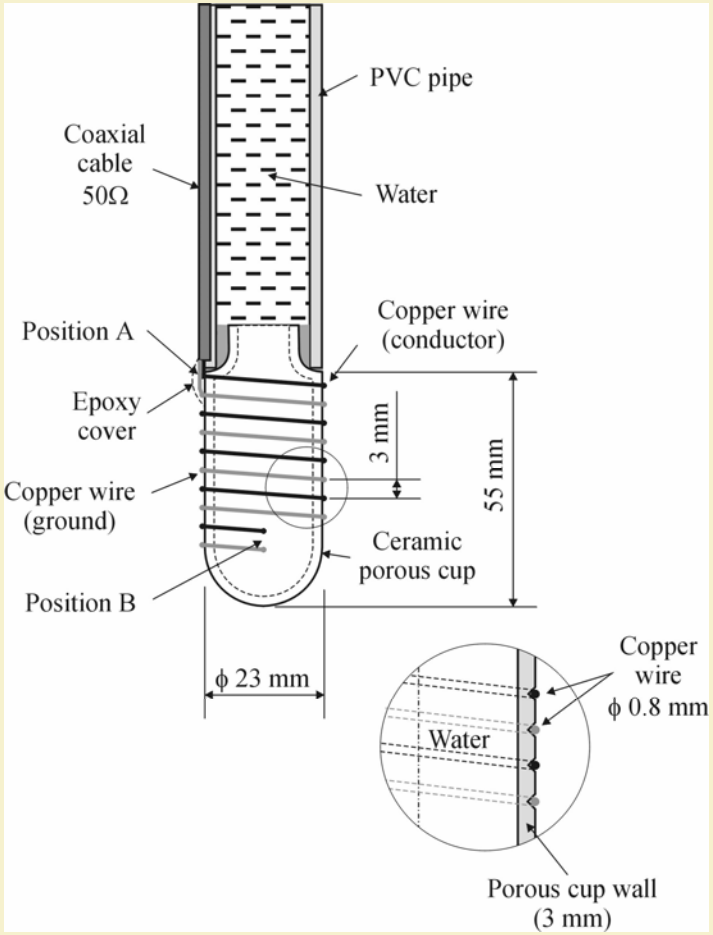
Calibration

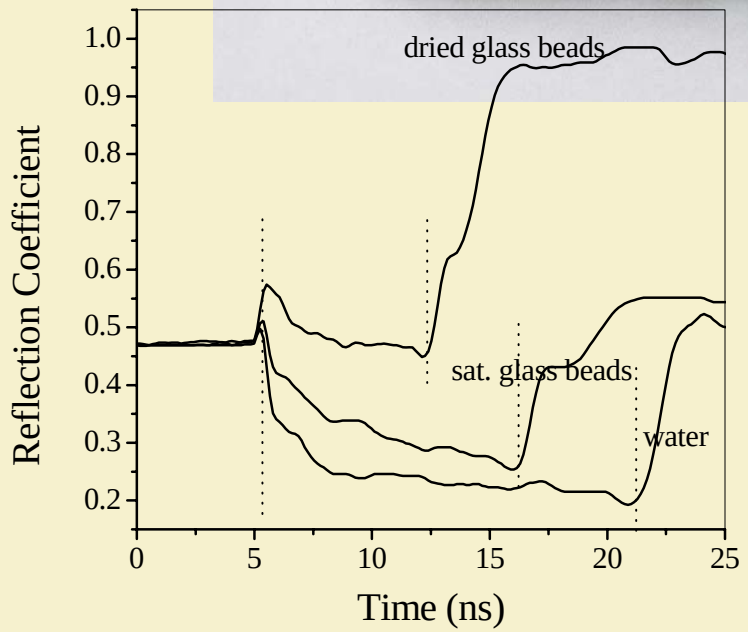




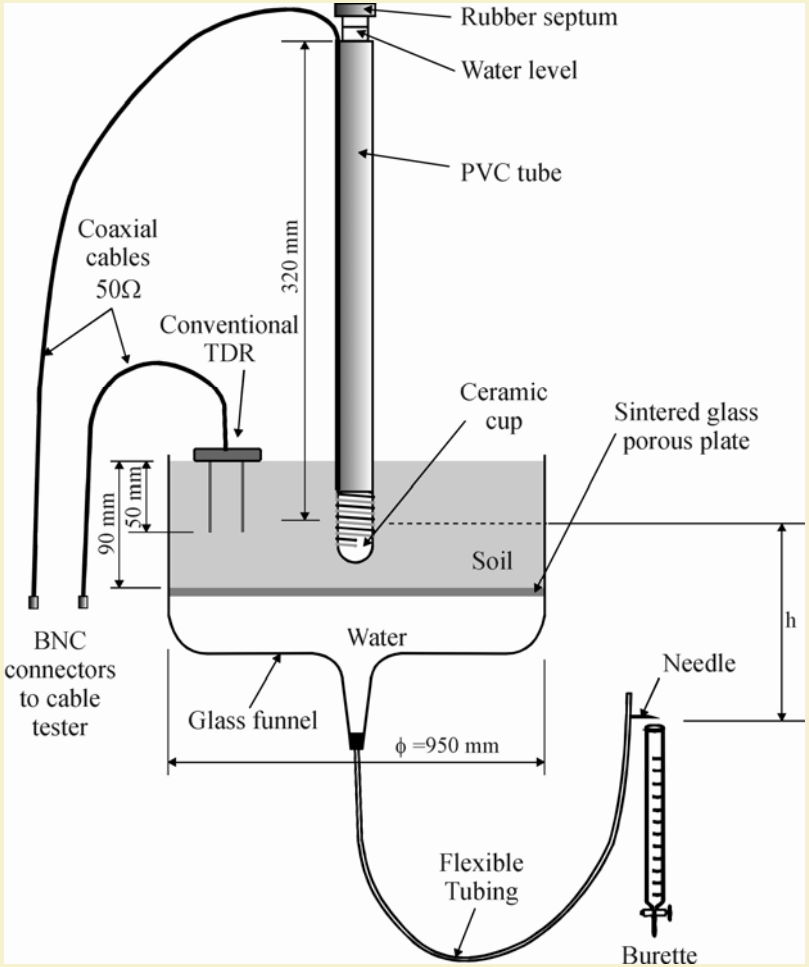
Field development, Brazil

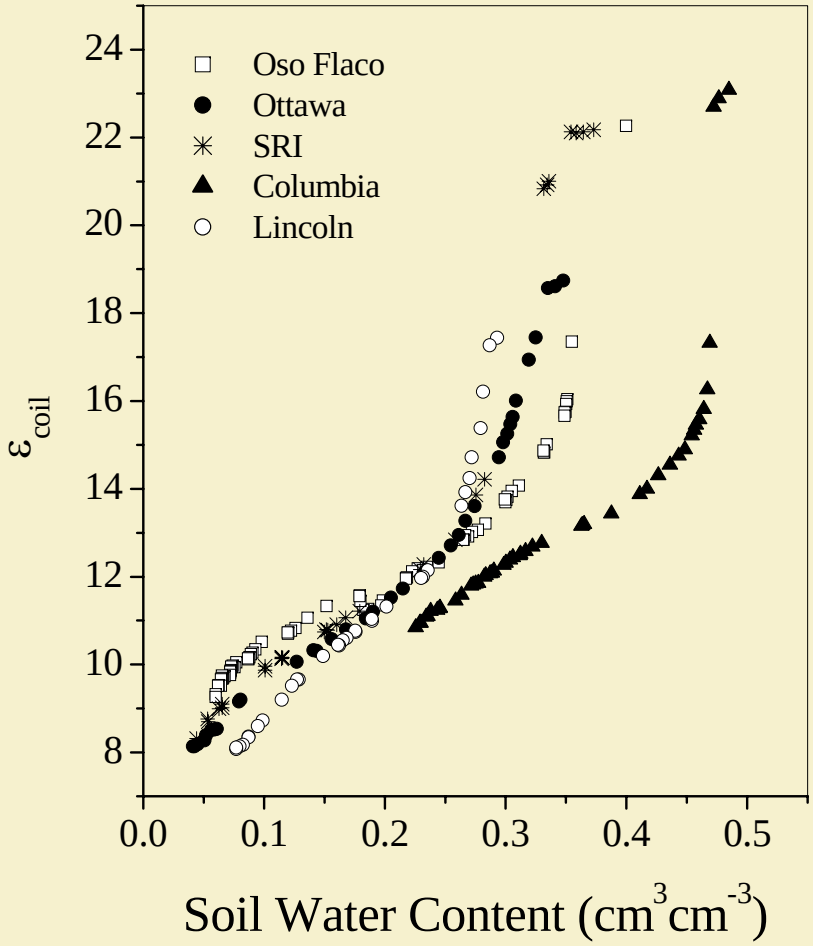
Combined Tensiometer-TDR





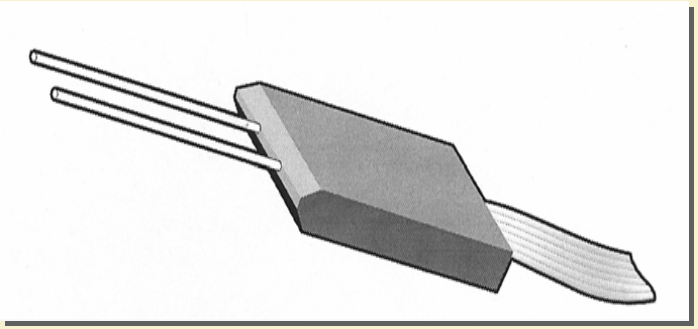
Laboratory Calibration

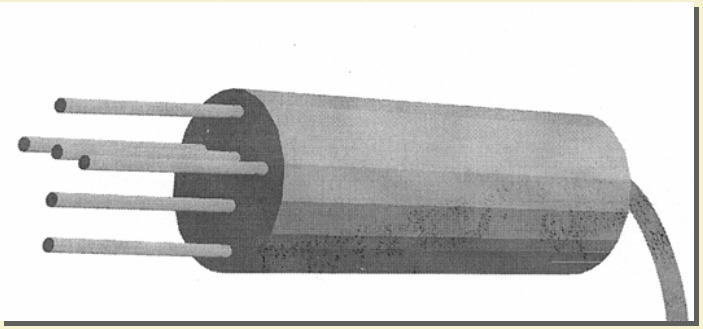




A heat pulse probe?

- Instrumentation in the vadose zone
  - → TDR – Time domain reflectometry
  - → Tensiometers
  - → Tracer experiments
- Heat pulse probe – multifunctional
  - → Apply heat as tracer
  - → Heat, water and solute transport



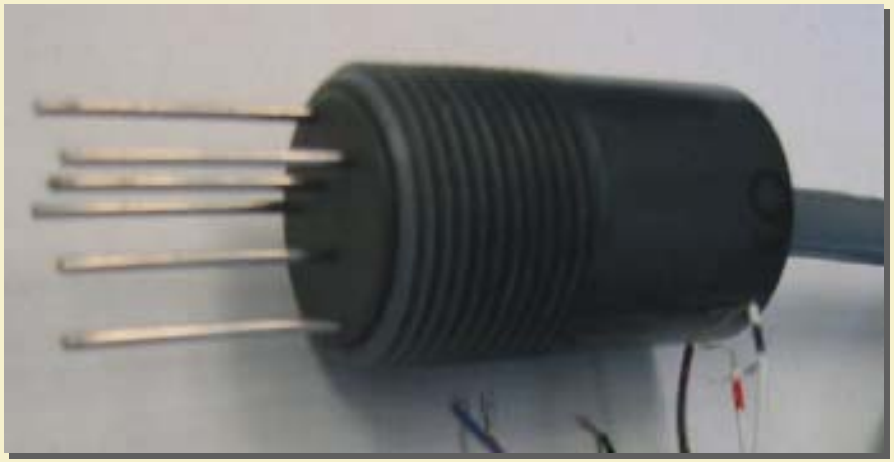


Multifunctional heat pulse probe

- Temperature, T
- Thermal properties
  - → Heat capacity, C
  - → Heat conductivity, λ_0
  - → Thermal diffusivity, κ
  - → Heat dispersion, D
- Hydraulic properties
  - → Water flux, q_w
  - → Water content, θ
  - → Electrical conductivity, EC_a

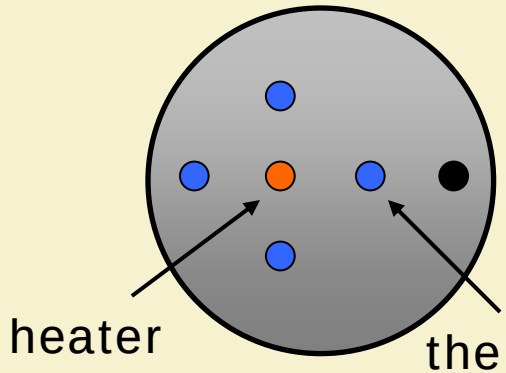
same time
+
same place
+
same scale

Heat pulse probe design

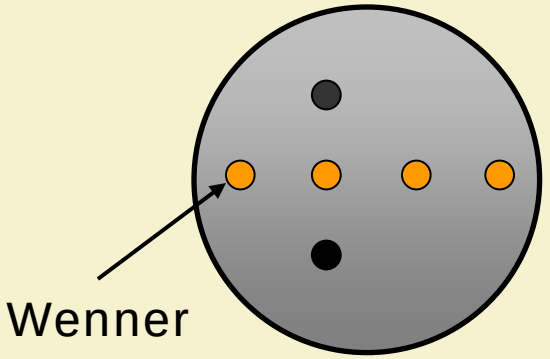


- 6 needles
- 1 mm diameter
- 6 mm spacing
- 28 mm long
- 25 mm wide

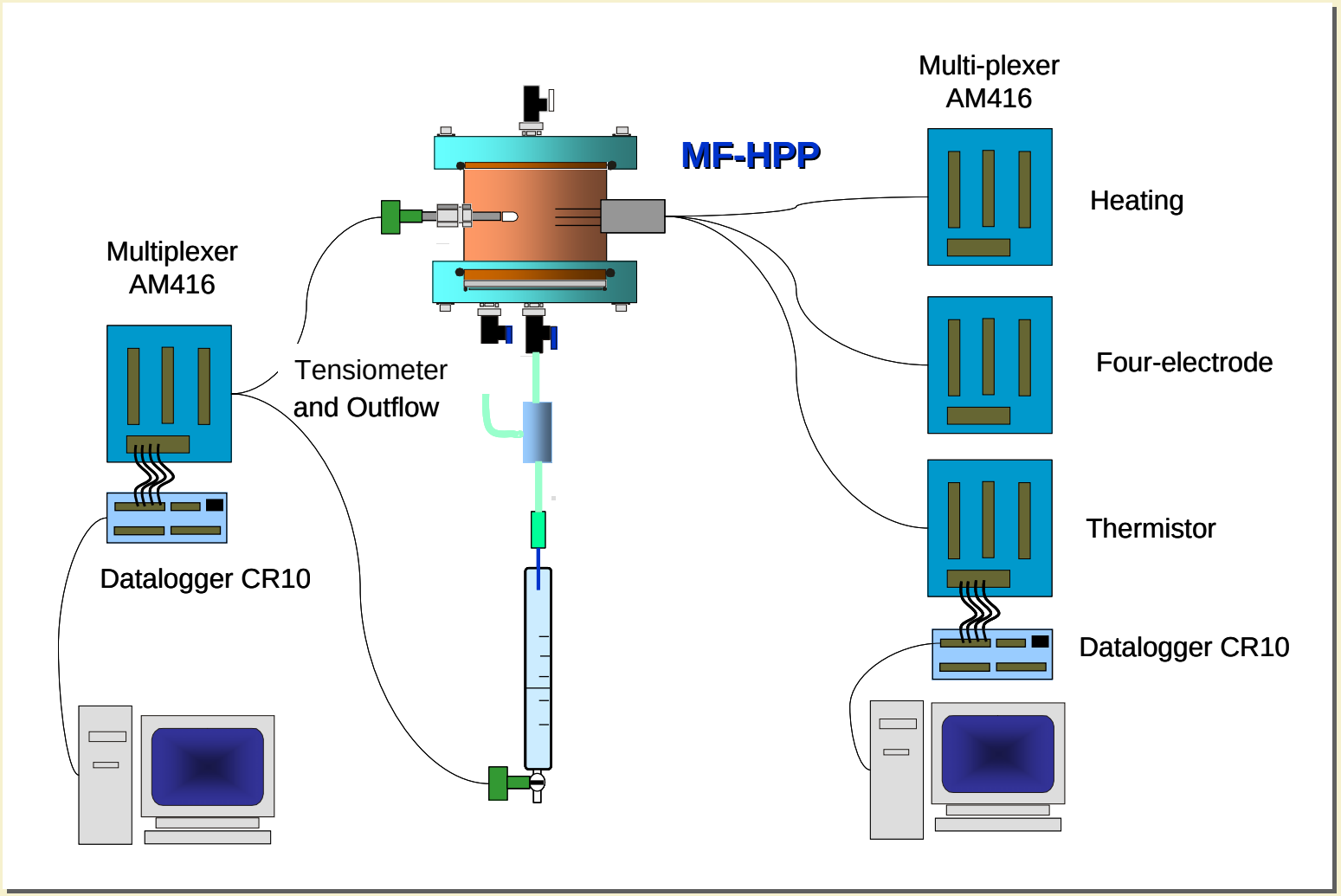
Heat pulse



Electrical conductivity



I. Multi-step outflow experiment



I. Analytical solutions of heat transport

- De Vries (1952)- Thermal Conduction

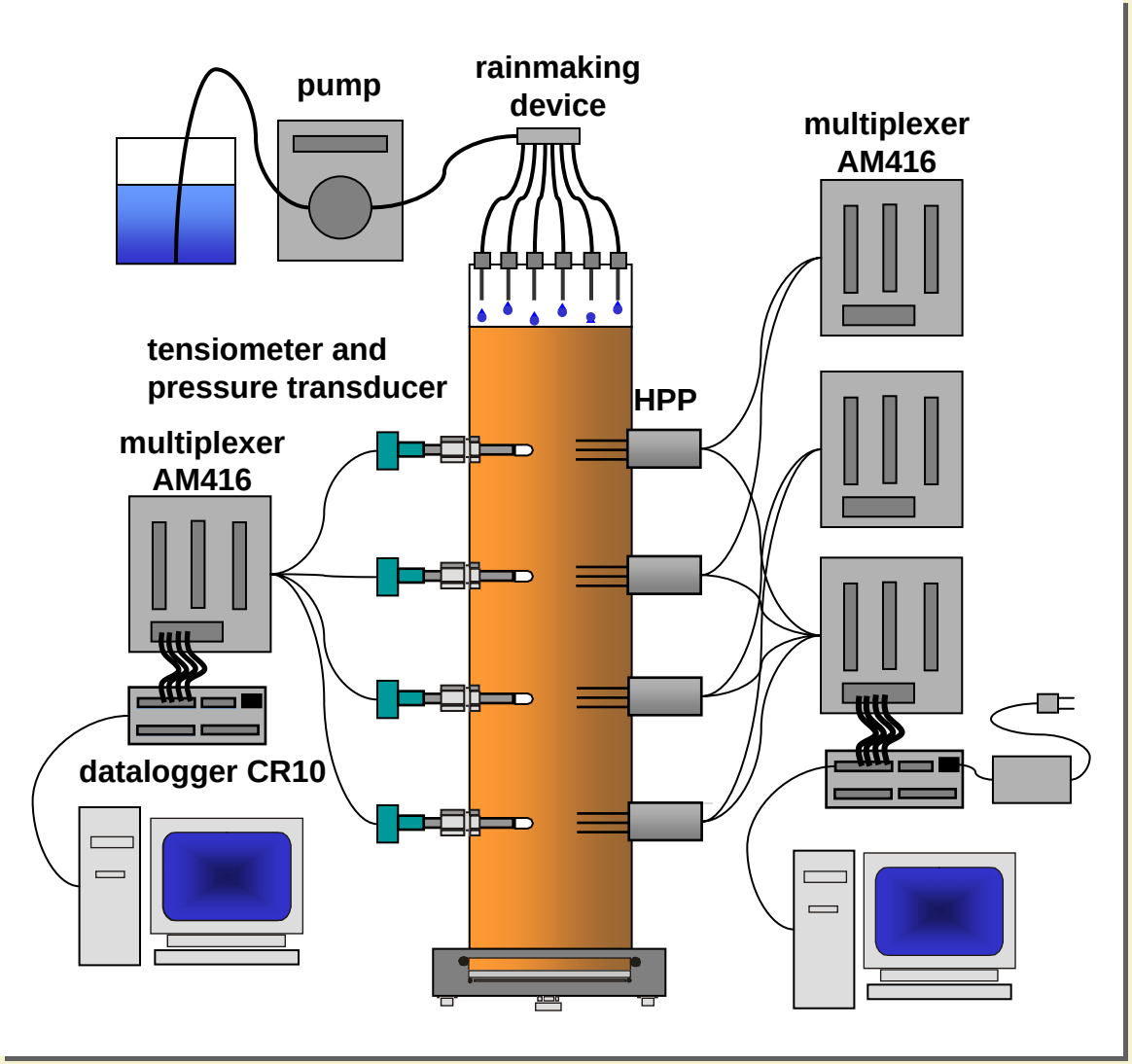
$$\Delta T(r,t) = \frac{q'}{4\pi C\kappa}\left[Ei\left(\frac{-r^2}{4\kappa(t-t_0)}\right) - Ei\left(\frac{-r^2}{4\kappa t}\right)\right]; \quad t > t_0$$

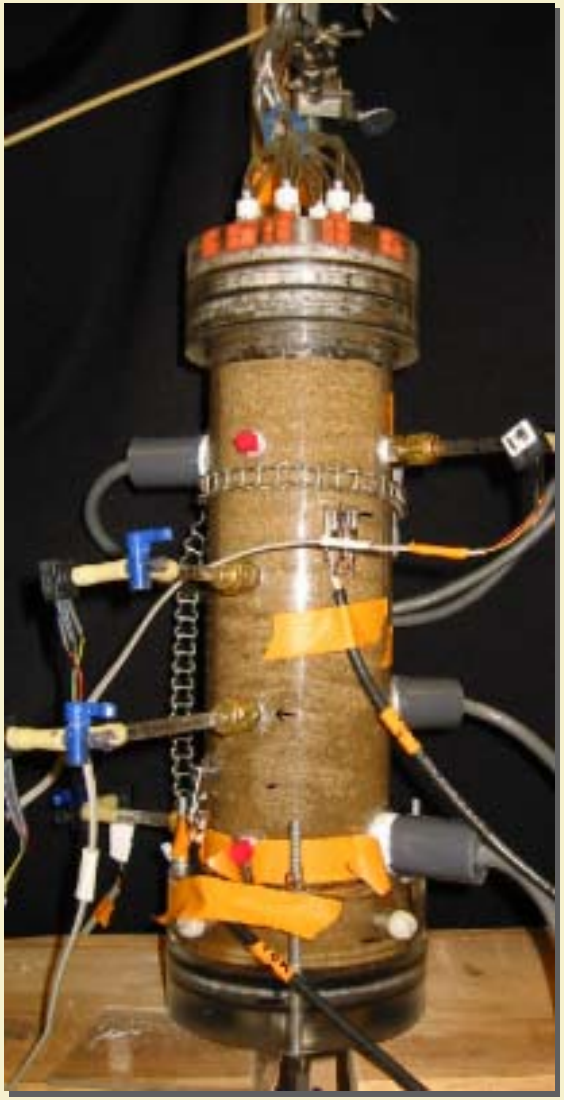
- Ren et al. (2000) – Thermal Convection

$$\Delta T_u = \frac{q'}{4\pi C\kappa}\left[\int_{t-t_0}^{t} s^{-1} exp\left\{-\frac{(r_u + V_h s)^2}{4\kappa\, s}\right\} ds\right]; \quad t > t_0$$

$$\Delta T_d = \frac{q'}{4\pi C\kappa}\left[\int_{t-t_0}^{t} s^{-1} exp\left\{-\frac{(r_d - V_h s)^2}{4\kappa\, s}\right\} ds\right]; \quad t > t_0$$

II. Experimental flow column





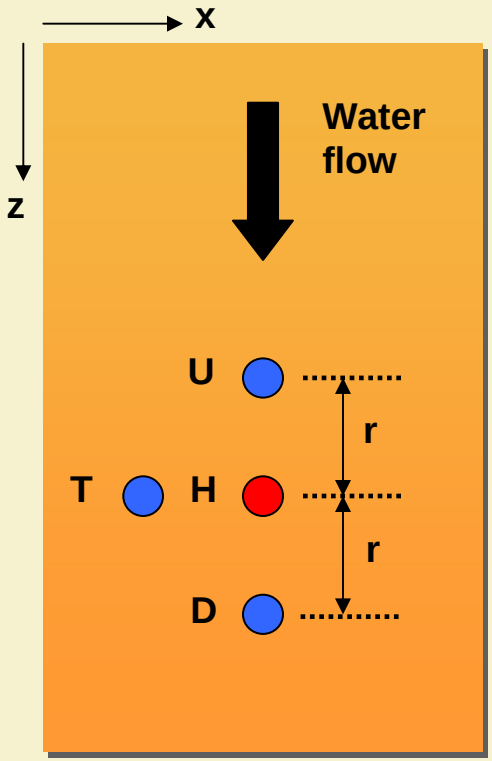
II. Numerical solution heat transport

- Heat conduction and convection
  - → Homogenoues and isotropic media
  - → Thermal equilibrium between phases

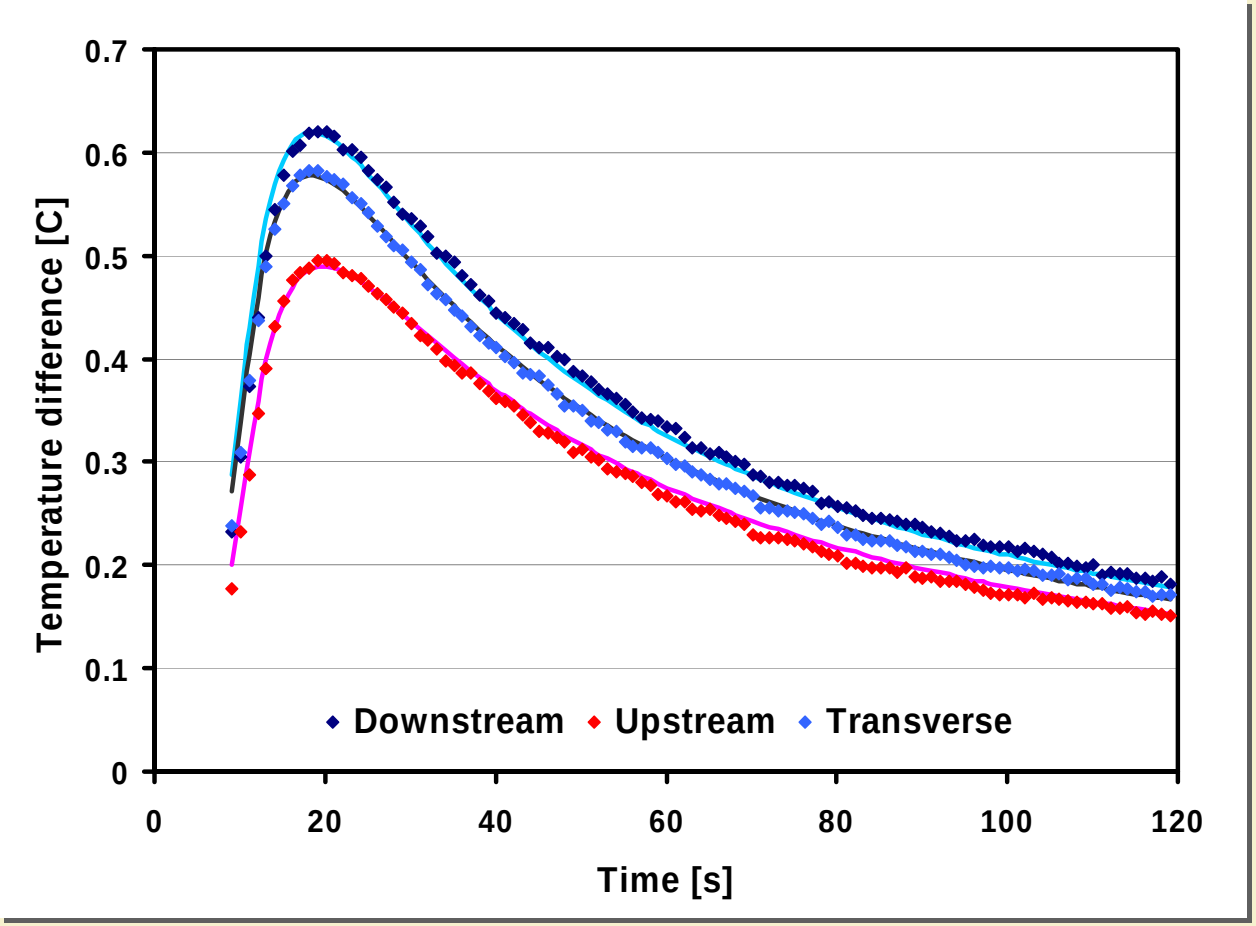
$$\frac{\partial T}{\partial t} = \kappa \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2} \right) - \theta V_w \frac{C_w}{C_b} \frac{\partial T}{\partial z}$$

$$V_h = \frac{C_w q_w}{C_{bulk}} = \frac{\theta C_w V_w}{C_b}$$

$$C_{bulk} = C_s (1 - \phi) + C_w \theta$$



Fitting of temperature response curve



Fitting

I. Analytical solution

II. Numerical solution (HYDRUS 2D)

Parameters

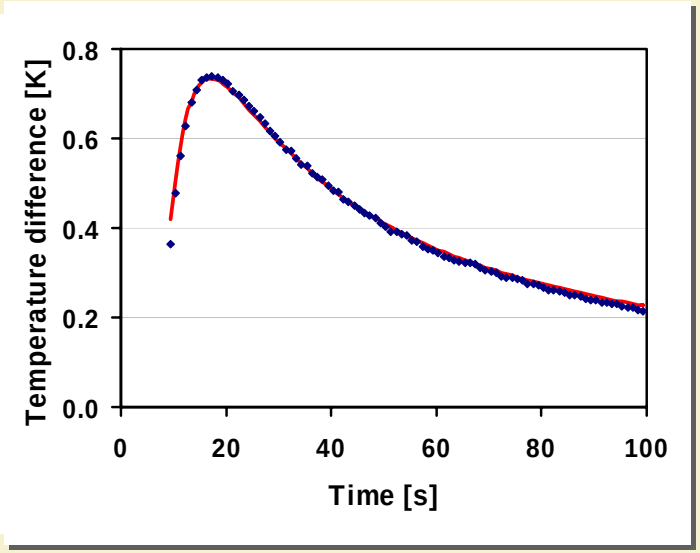
Thermal conductivity λ

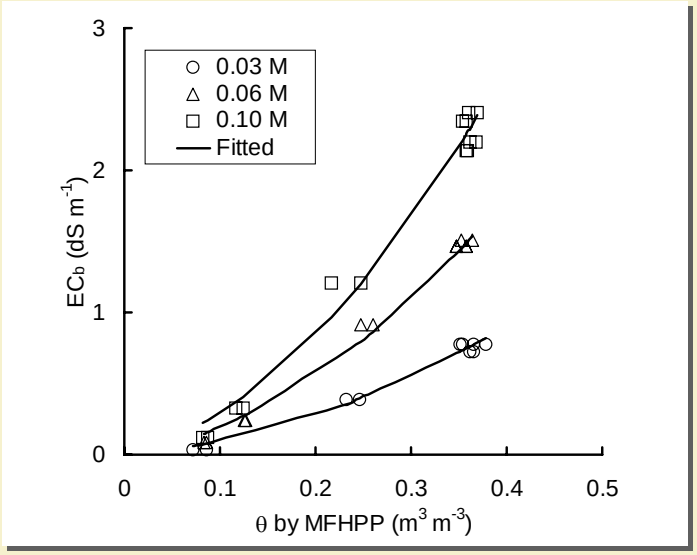
Water content θ

Water flux q_w

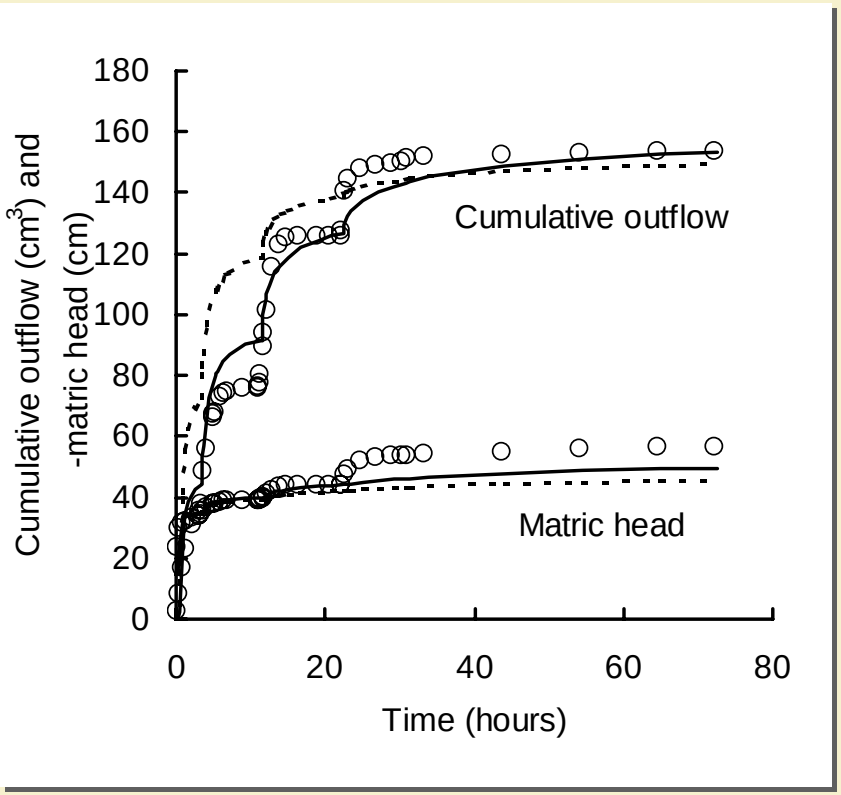
I and II: Calibration of MF-HPP

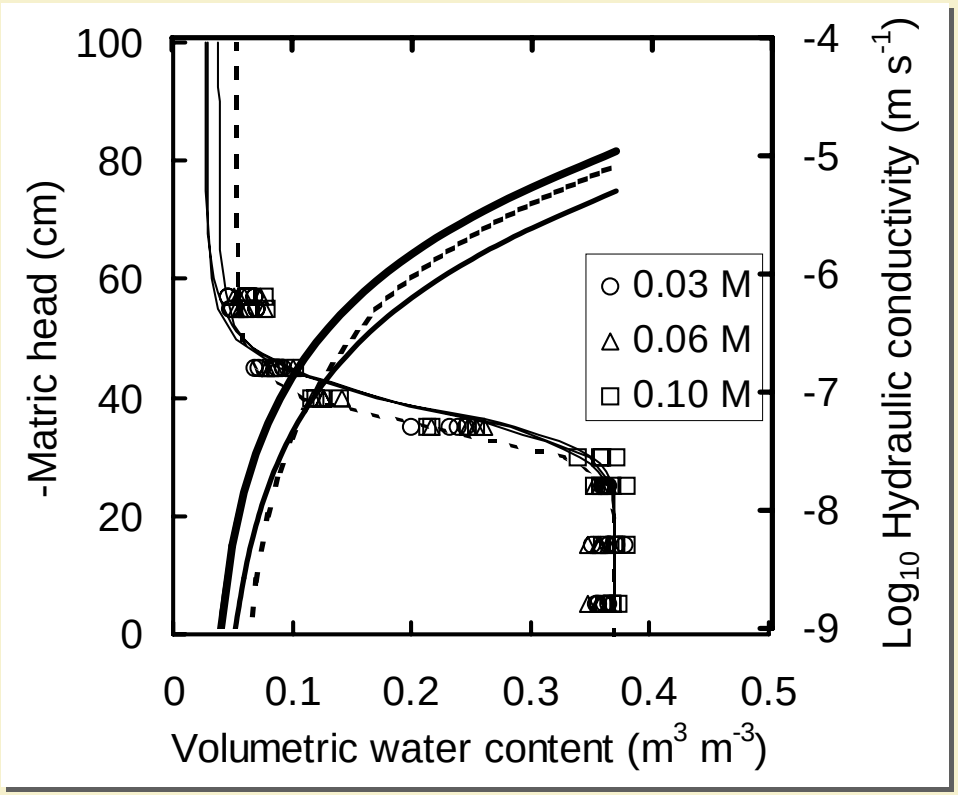
- Needle distance, r
  - → Calibration in agar solution
    - heat capacity for water
    - no convective heat transport
  - → Calibration in porous media
    - heat capacity for material
    - saturated conditions
- Wenner array
  - → Calibration in porous media
    - varying EC and water content





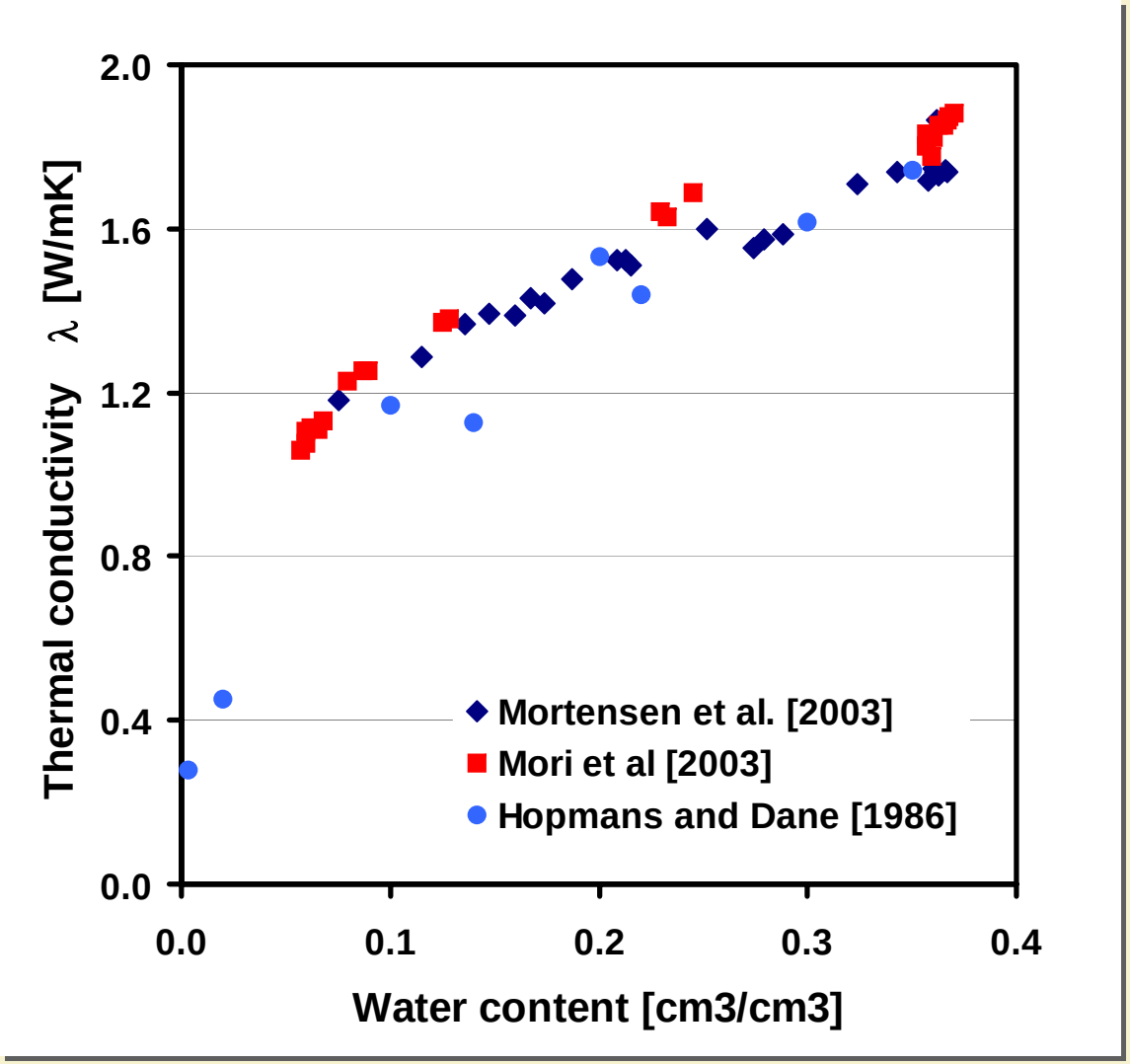
I.Unsaturated hydraulic functions





- Inverse Modeling of Multi-step Outflow

I and II. Estimation of thermal conductivity, λ (heat conduction only)



Thermal conductivity

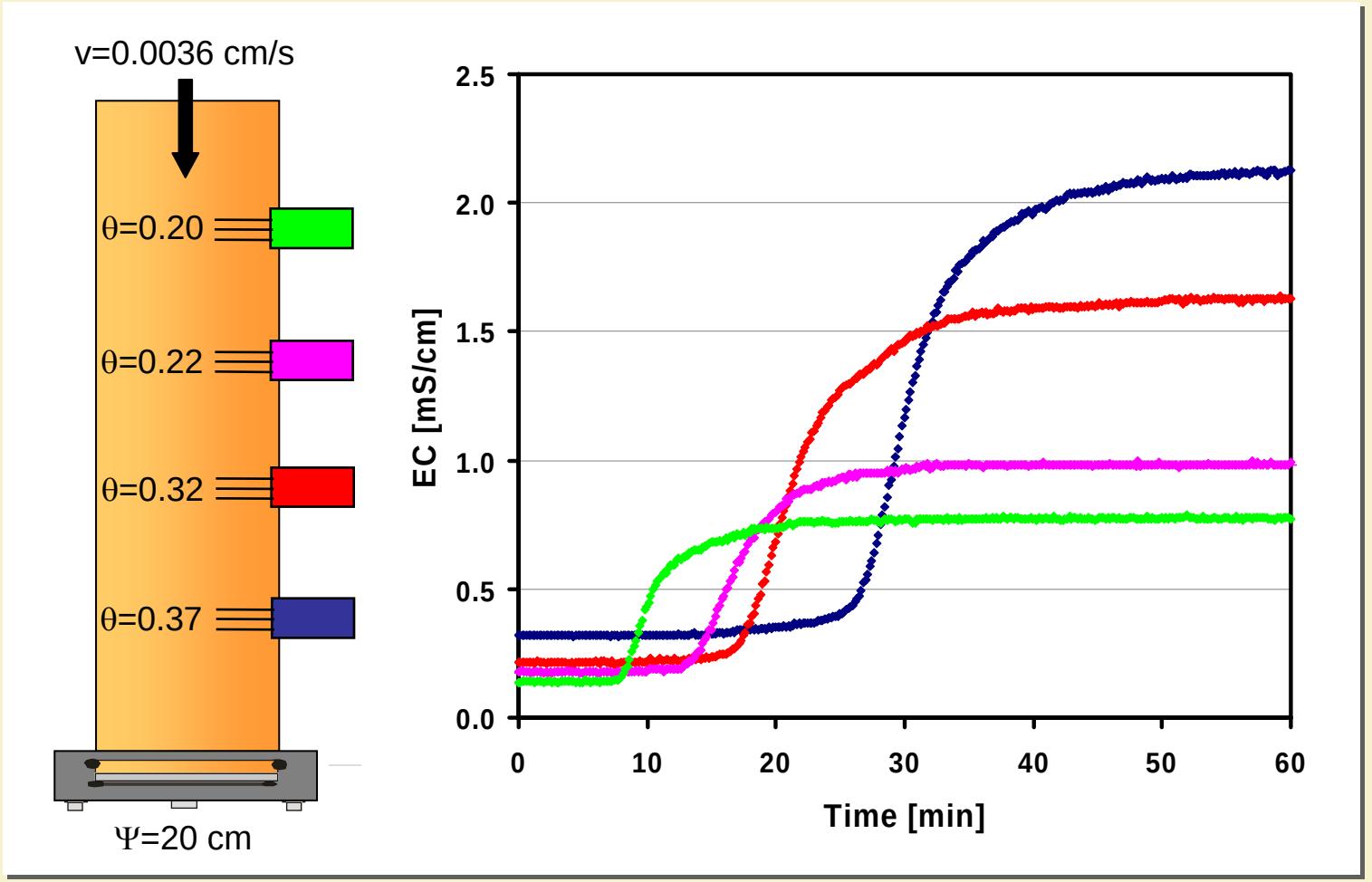
$$\lambda_0 = b_0 + b_1\theta + b_2\theta^{0.5}$$

Thermal diffusivity

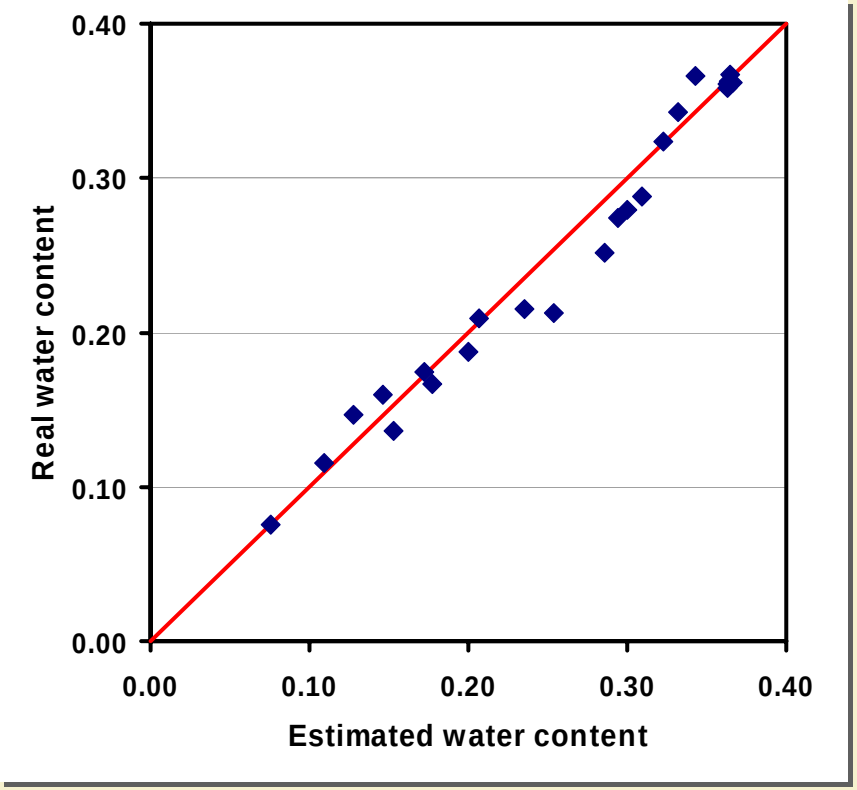
$$\kappa = \lambda_0 / C_{bulk}$$

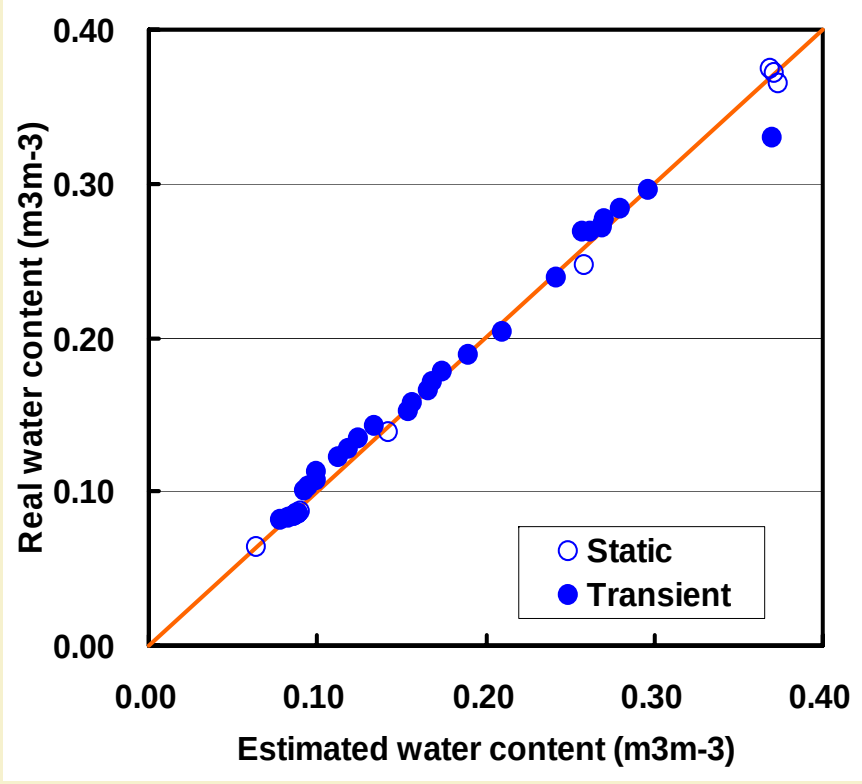
II. Solute transport

- Electrical conductivity $EC_{bulk} = \theta\tau(\theta)EC_{water} + EC_{solid}$

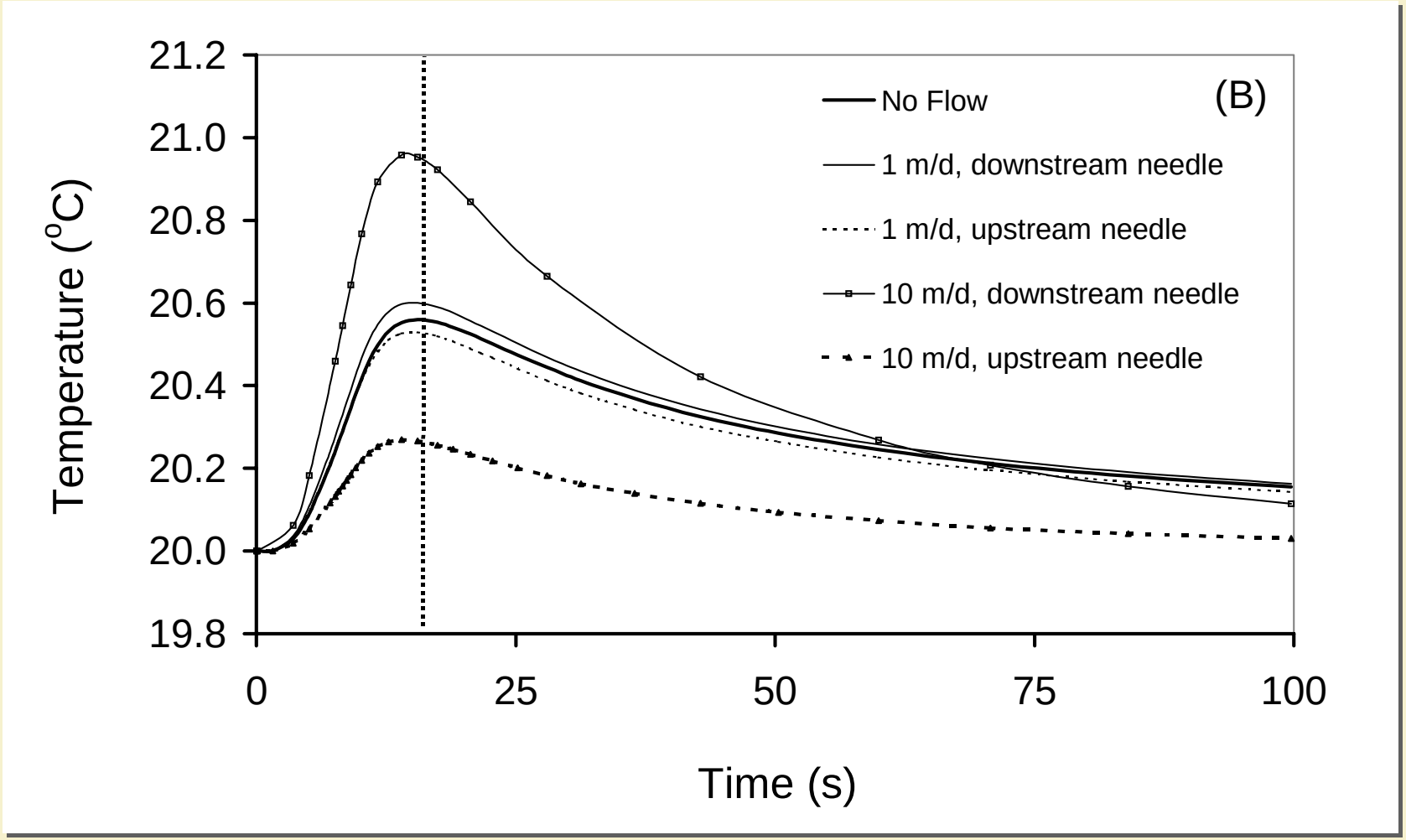


I and II: Estimation of water content, θ (Heat conduction only)



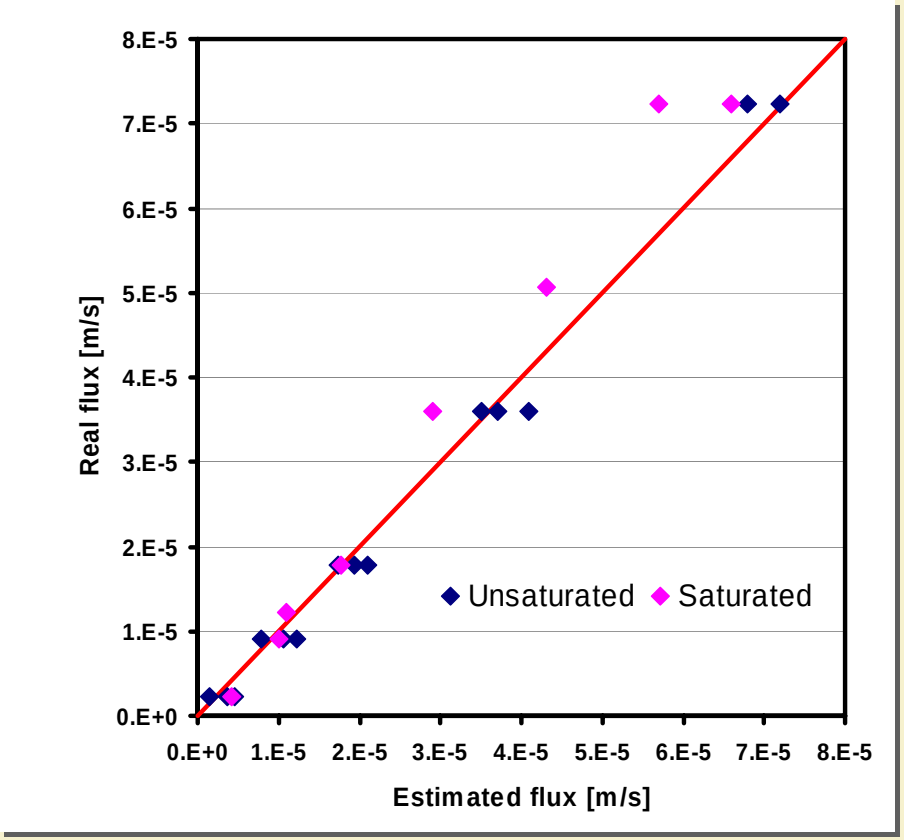


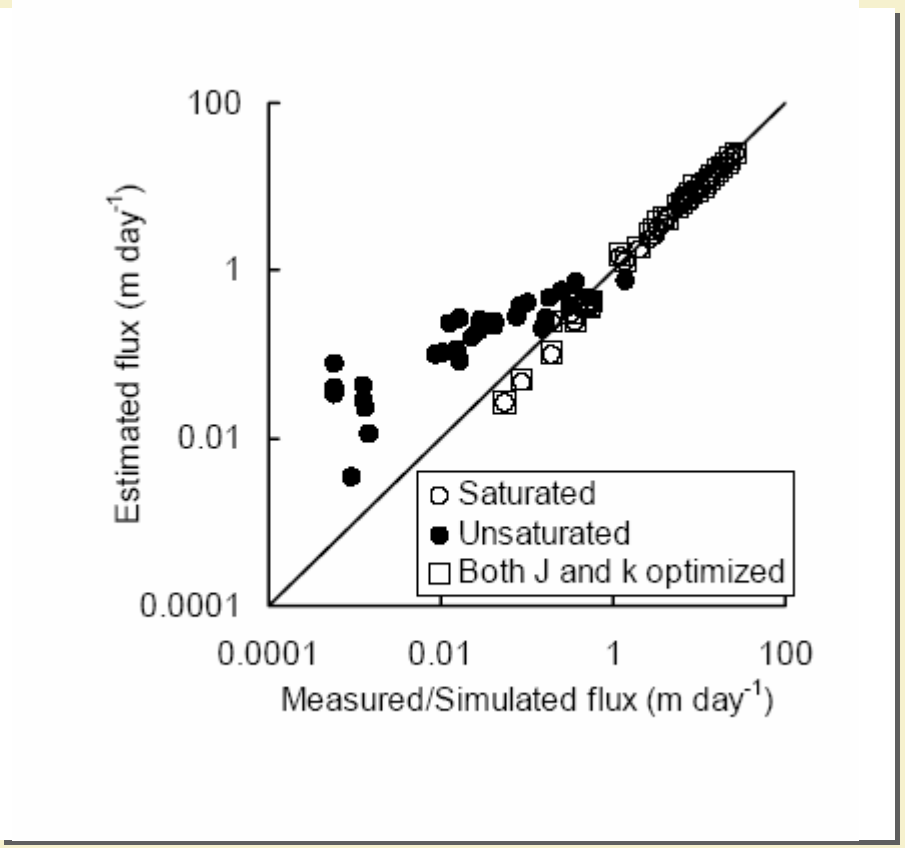
Water flux effect on temperature signature



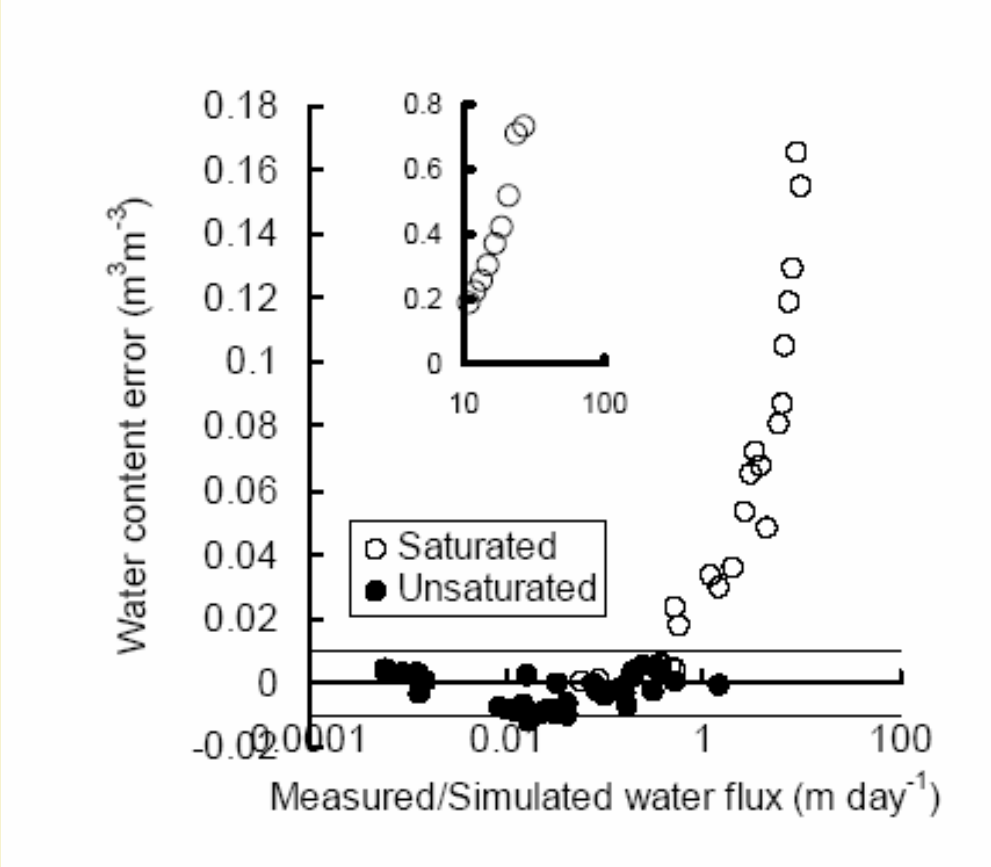
I and II: Estimation of water flux, q_w (heat conduction and convection)

- Accurate range: 0.0001 to 0.01 cm/s or 10 to 1000 cm/day



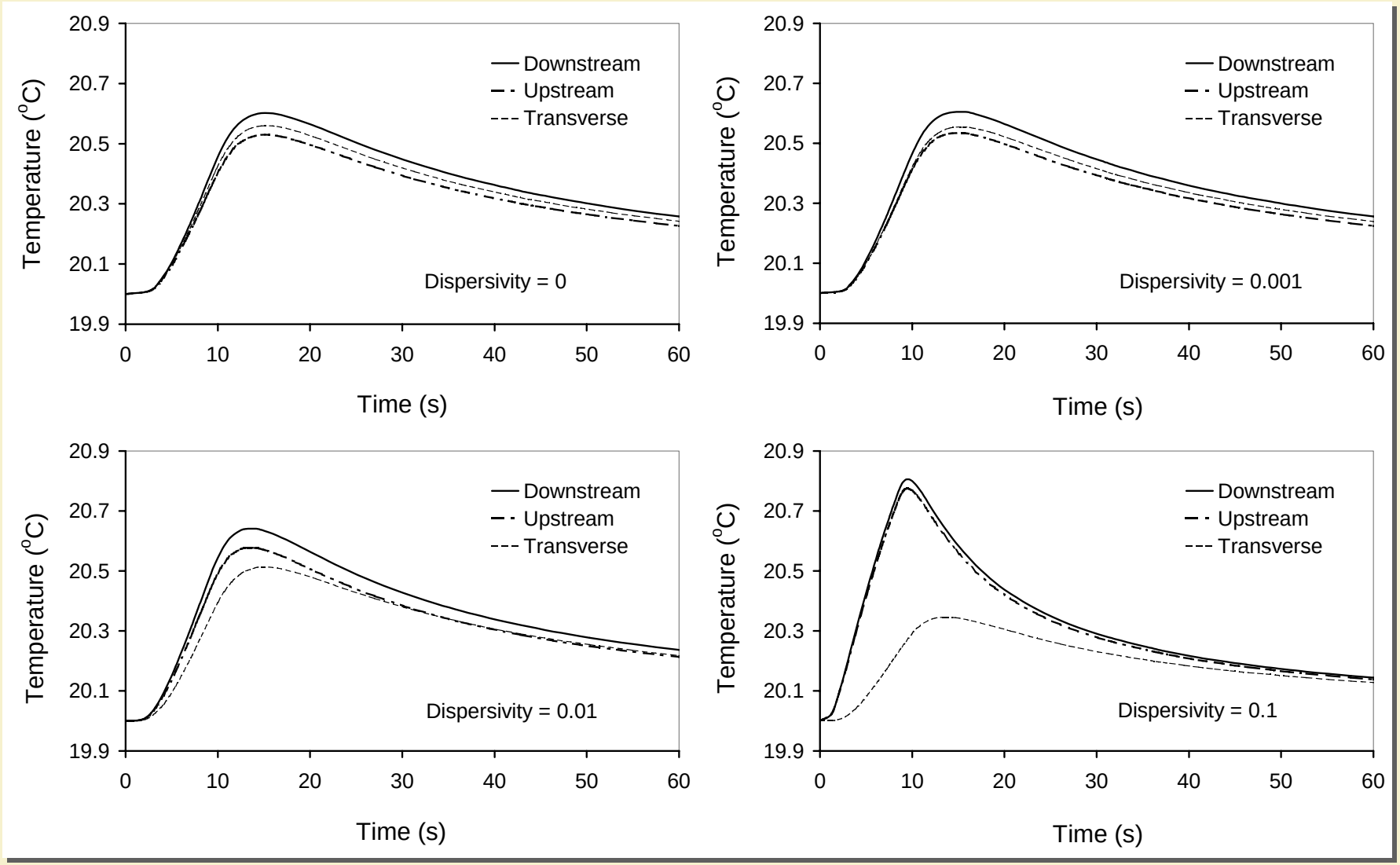


Water content error for high water fluxes



However, these high water fluxes only occur under saturated conditions

Thermal dispersion effect on temperature signature (q_w = 1 m d^{-1})



Conclusions

- Advantages
  - Simultaneous measurement of water flow, solute and heat transport properties within the same sample volume
- Limitations
  - In situ calibration of probe
  - Sensibility to needle spacing
  - Accurate water flux range is limited to 10 - 1000 cm/day
- Future work
  - Compare heat and solute dispersivities
  - Improve for water flux density < 10 cm/day
  - Field applications

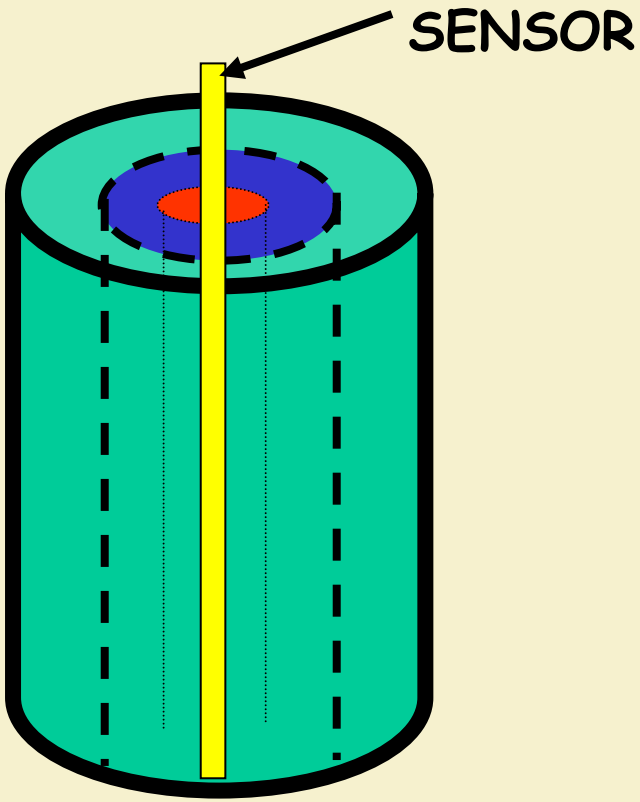
Multi-Functional Sensors:

- Are being developed, that
- Measure approximately same volumes,

BUT

- Issues of probe-soil contact
- Measurement interferences
- What is real measurement volume, contributing to the measurement???

REV (Bear) or Relativist Concept (Baveye and Sposito, 1984) ????



Spatial weighting function, ω:

$$\int_V \omega(x,y,z)\,dV = 1$$

$$\theta_{mac}(x,y,z) = \int_V \omega(x,y,z)\,\theta_{mic}(x,y,z)\,dV$$