

# 2-D Water Flux using a Penta-Probe Heat-Pulse Sensor: Laboratory Experiment and Numerical Evaluation



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## Introduction

Recent work using heat-pulse measurements to assess water flux in soil have shown promise for determination of infiltration rates. One-dimensional sensors having one heater probe and one pair of upstream and downstream temperature sensing needles may not be suitable for inferring hill-slope percolation rates due to the likelihood of multidimensional water flux

- Objectives:**
- 1) Present a new heat pulse method to estimate 2-D soil water flux
  - 2) Evaluate the method using a numerical model
  - 3) Test the method with lab experiments

## Theoretical considerations

- For porous medium with thermal diffusivity,  $\alpha$ , and uniform water flow at heat velocities,  $V_x$  and  $V_y$  along the  $x$ - and  $y$ - directions, the equation for combined heat conduction and convection is given by:

$$\frac{\partial T}{\partial t} = \alpha \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) - V_x \frac{\partial T}{\partial x} - V_y \frac{\partial T}{\partial y}$$

- The analytical solution

- Estimation of soil water flux from temperature increases measured at two pairs of down- and up-streams probes

$$T(x, y, t) = \begin{cases} \frac{q}{4\pi\lambda} \int_0^t s^{-1} \exp\left[-\frac{(x-V_x s)^2 + (y-V_y s)^2}{4\alpha s}\right] ds & 0 < t < t_0 \\ \frac{q}{4\pi\lambda} \int_{t_0}^t s^{-1} \exp\left[-\frac{(x-V_x s)^2 + (y-V_y s)^2}{4\alpha s}\right] ds & t > t_0 \end{cases}$$

Water flux in  $x$ -direction

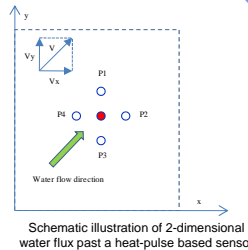
$$J_x = \frac{\rho c}{(\rho c)_s} \frac{2\alpha}{(x_2 + x_1)} \ln \left[ \frac{T_1}{T_2} \right]$$

Water flux in  $y$ -direction

$$J_y = \frac{\rho c}{(\rho c)_s} \frac{2\alpha}{(y_1 + y_2)} \ln \left[ \frac{T_1}{T_2} \right]$$

Water flow direction

$$\phi = \tan^{-1} \left( \frac{J_y}{J_x} \right)$$

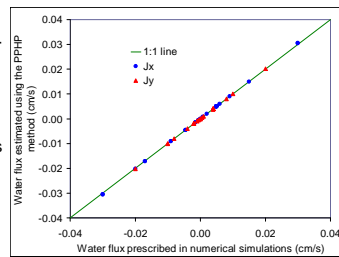


Schematic illustration of 2-dimensional water flux past a heat-pulse based sensor

## Synthetic simulations

Synthetic numerical simulations using CORE<sup>2D</sup> V4 provided estimates of 2-D soil water flux for comparison to measured values

- Simulated domain is 10 cm in width x 10 cm in length
- A probe having two orthogonal pairs of thermistor needles that coincide with the  $x$ - and  $y$ - coordinates is located at the center of the simulated domain
- Temperature rise simulated in CORE<sup>2D</sup> V4 for each opposing pair of thermistors yield water flux estimates  $J_x$  and  $J_y$
- Estimated  $J_x$  and  $J_y$  from temperature increases are compared to those prescribed in numerical simulations



Comparison of soil fluxes estimated using the PPHP method with prescribed flux in numerical simulations

## Conclusions

- A PPHP method is presented in this study to estimate 2-D water flux in soil
- This method was evaluated synthetically, and water fluxes estimated using this method agree with values prescribed in the numerical hydrodynamic simulations
- Lab experiments were carried out to test the PPHP sensor using a cylindrical 2D-flow cell
- Water flux estimates using the new method match well with the water fluxes simulated using CORE<sup>2D</sup> V4
- The PPHP method can be used to estimate 2-D water fluxes in soils

## PPHP

Penta-probe heat-pulse sensor

- Four 1 o.d. mm needles and one 2 o.d. mm needle, all parallel
- Four thermistor needles are half the length of the heater needle with the two pairs orthogonally arranged
- Time duration of heat input is 8 second
- Heater-thermister spacing is around 6 mm
- Automatic time step for data collection is 0.25 to 1 s

Front view



Side view



## Laboratory experiment

Flow cell

- PVC tube and stainless porous media
- Four separate reservoirs surrounded the stainless porous media
- Glass beads filled the inner cylinder
- Two inlets and two outlets were installed in the outer cylinder



Flow cell and the probe

Lab experiment

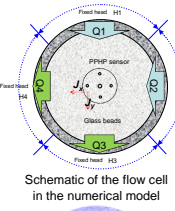
- Water supply from two Marriott bottles
- Pressure heads measured in the four reservoirs
- Outflow rates measured at the two outlets
- PPHP sensor connected to a CSI CR1000 datalogger
- Temperature increase measured in each thermistor for 2 minutes
- Different water velocities in the flow cell generated by adjusting water levels at the outlets



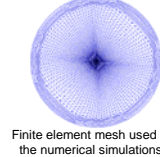
Setup of the lab experiment

## Results

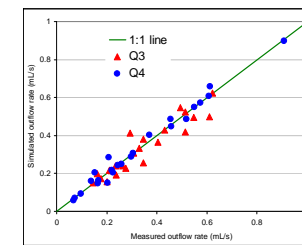
- The numerical model simulates flow in the cell
- Hydraulic conductivities of the stainless porous tube and glass beads were calibrated to fit outflow rates at the two outlets
- Water velocities in the cell were computed using CORE<sup>2D</sup> V4
- Bulk heat capacity of glass beads were estimated from temperature responses under static conditions
- Water velocities were estimated from PPHP sensor measurements



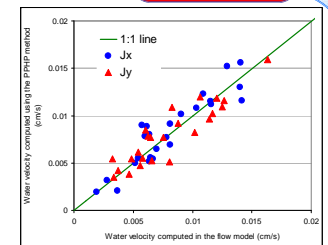
Schematic of the flow cell in the numerical model



Finite element mesh used in the numerical simulations



Comparison of simulated and measured outflow rates for each outlet simulation



Comparison of water velocities computed in numerical models and estimated using PPHP method

- Average relative differences of water velocities estimated using PPHP and simulated using CORE<sup>2D</sup> V4 are 15.3% at  $x$ -direction and 17.1% at  $y$ -direction, respectively.
- Possible explanations (the effect of wall flow, Non-uniform distribution of water velocity in the flow cell Probes of 1 and 3 and 2 and 4 may not align with the  $x$ - &  $y$ - axes in the numerical model)

## References

- Ren, T., G.J. Kluitenberg, and R. Horton. 2000. Determining Soil Water Flux and Pore Water Velocity by a Heat Pulse Technique. *Soil Sci Soc Am J* 64:552-560.
- Wang, Q., T.E. Ochsner, and R. Horton. 2002. Mathematical analysis of heat pulse signals for soil water flux determination. *Water Resour. Res.* 38:1091, doi:10.1029/2001WR001089.
- Mortensen, A.P., Hopmans, J.W., Mori, Y., Simunek, J., 2006. Multi-functional heat pulse probe measurements of coupled vadose zone flow and transport. *Advances in Water Resources*, 29(2), 250-267
- Yang, C., J. Samper, and L. Montenegro. 2007. CORE<sup>2D</sup> V4: A Code for water flow, heat and solute transport, geochemical reactions, and microbial processes. *Physics and Chemistry of the Earth, in review.*
- Yang, C. and S. Jones. 2-D water flux using a Penta-Probe Heat-Pulse sensor: laboratory experiment and numerical evaluation, in preparation for a special issue of *Water Resources Research*.

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