Resilience Emerging from Scarcity and Abundance
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A Perfect-Conductor Approach for Estimating Water Flux Density with the Heat-Pulse Method

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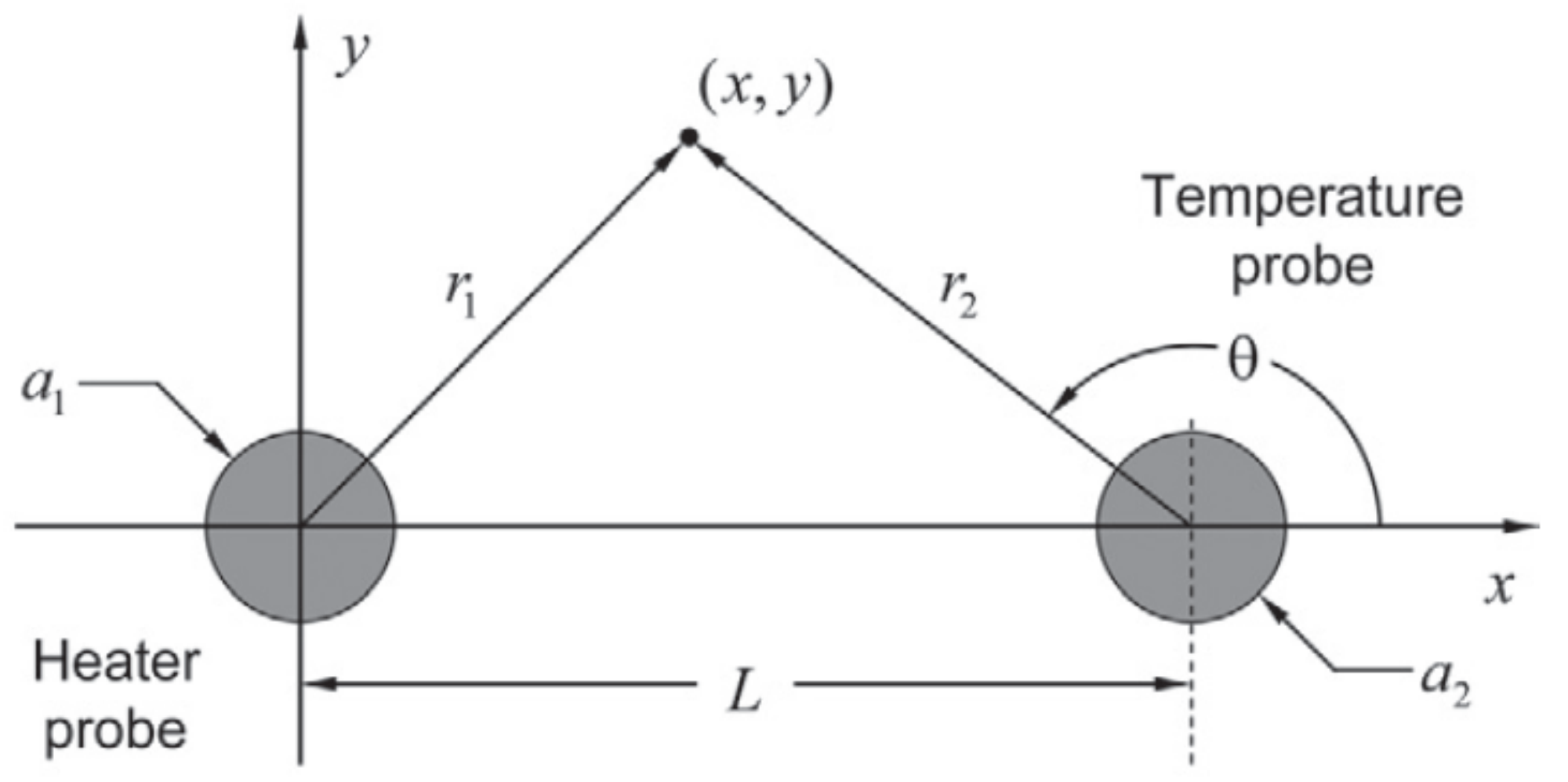
Quantifying and understanding root-water uptake and related processes requires high-resolution (spatial and temporal) and accurate data of soil water content and flux. In this presentation, we report on progress made in development of heat-pulse sensors with rigid probes using a perfect conductor approach for modeling. Through combined advancements in sensor design and heat-transfer modeling we present sensors with improved accuracy and durability.

What

- To improve measurement accuracy, development of the heat-pulse method is conducted in parallel, both by advancement in sensor design and heat-transfer modeling.
- The need for larger probes to withstand field conditions.

Why

- The thermal conductivity of the probes is significanly larger than that of the soil, for most soil conditions.
- The heat capacity of the probes is a significant part of the heat capacity measured with the sensor, especially with larger probes.
- The perfect-conductor approach accounts for the finite radius and heat capacity of the probes, and assumes them to have infinite thermal conductivity.



Method Development and Testing

The heat-pulse velocity (U) is related to water flux dendity (θU_w) by the ratio of volumetric heat capacities of the water and the bulk soil.

$$U = \theta U_w \frac{C_w}{C}$$

The Identical Cylindrical Perfect Conductors (ICPC) Model

- Accounts for the finite heat capacity and radius of the probes
- Assumes a one-dimensional flow in the direction aligned with the probes.
- Assumes the temperature distribution around the heater probe is unaffected by the presence of the temperature probe.
- Solution in the Laplace domain requires numerical inversion.

$$\hat{T}_C(p) = \frac{q' W_{12}}{4\pi\lambda W^2 p}\exp(bL) \qquad T_P(t) = \begin{cases} T_C(t); & 0 < t < t_0 \\ T_C(t) - T_C(t-t_0); & t > t_0 \end{cases}$$

$$W(p) = \frac{a^2\beta p}{2\kappa} + \sum_{n=0}^{\infty} \frac{(-1)^n \varepsilon_n I_n^2(ba)}{K_n(\mu a)}[\mu a K_{n+1}(\mu a) - n K_n(\mu a)]$$

$$W_{12}(p) = \sum_{m=0}^{\infty}\left\{\sum_{n=0}^{\infty}\frac{(-1)^n \varepsilon_n I_n(ba)[K_{n-m}(\mu L) + K_{n+m}(\mu L)]}{K_n(\mu a)}\right\}\frac{(-1)^m \varepsilon_m I_m(ba)}{K_m(\mu a)}$$

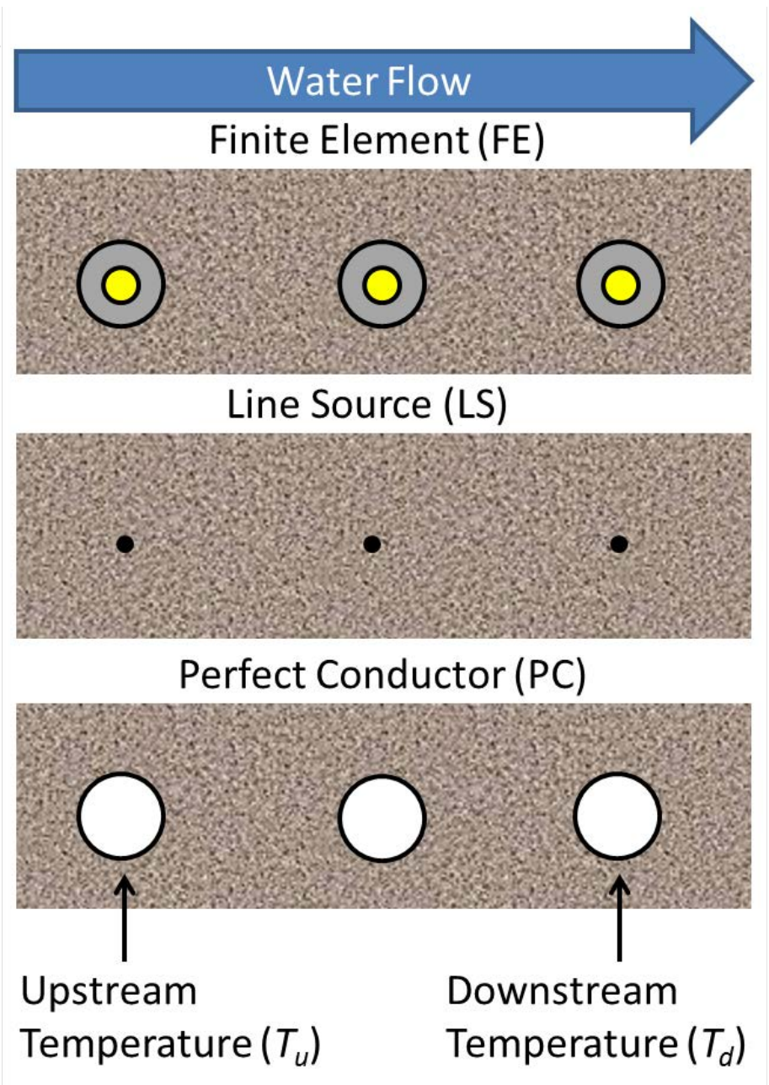
Data Simulation and Analysis

Simulation

- Temperature data are generate using a finite-element model that accounts for the thermal properties of all the materials and the flow around the probes.
- Sensors include:
  - The conventional heat-pulse (HP) sensor with probes of 1.27 mm diameter and 6 mm center-to-center sapcing.
  - The rigid HP (R-HP) sensor with probes of 2.38 mm diameter and 7 mm center-to-center spacing.
- Scenarios include:
  - Four saturation levels: 10, 20, 30, and 37.1% volumetric water content (VWC), with the latter being the saturated case.
  - 8 Water Flux Density magnitudes: 1, 5, 10, 50, 100, 200, 500, and 1000 cm/d (Darcy flux).

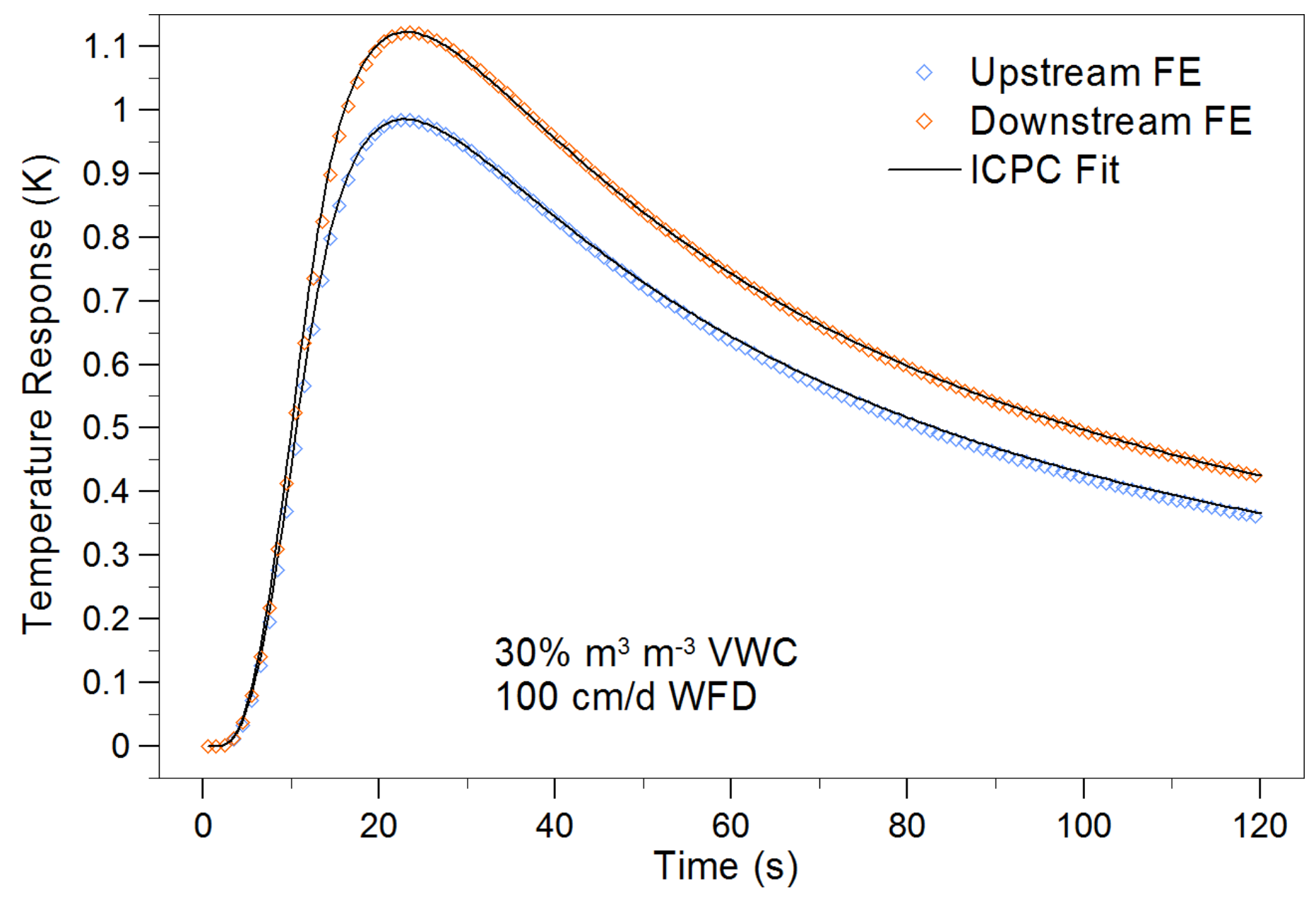
Analysis

- Temperature data are inverted using the:
  - Line source (LS) model.
  - Idendical cylindrical perfect conductors (ICPC) model.
- Assumed known: thermal properties and center-to-center probe spacing.
- Optimized: Water Flux Density!

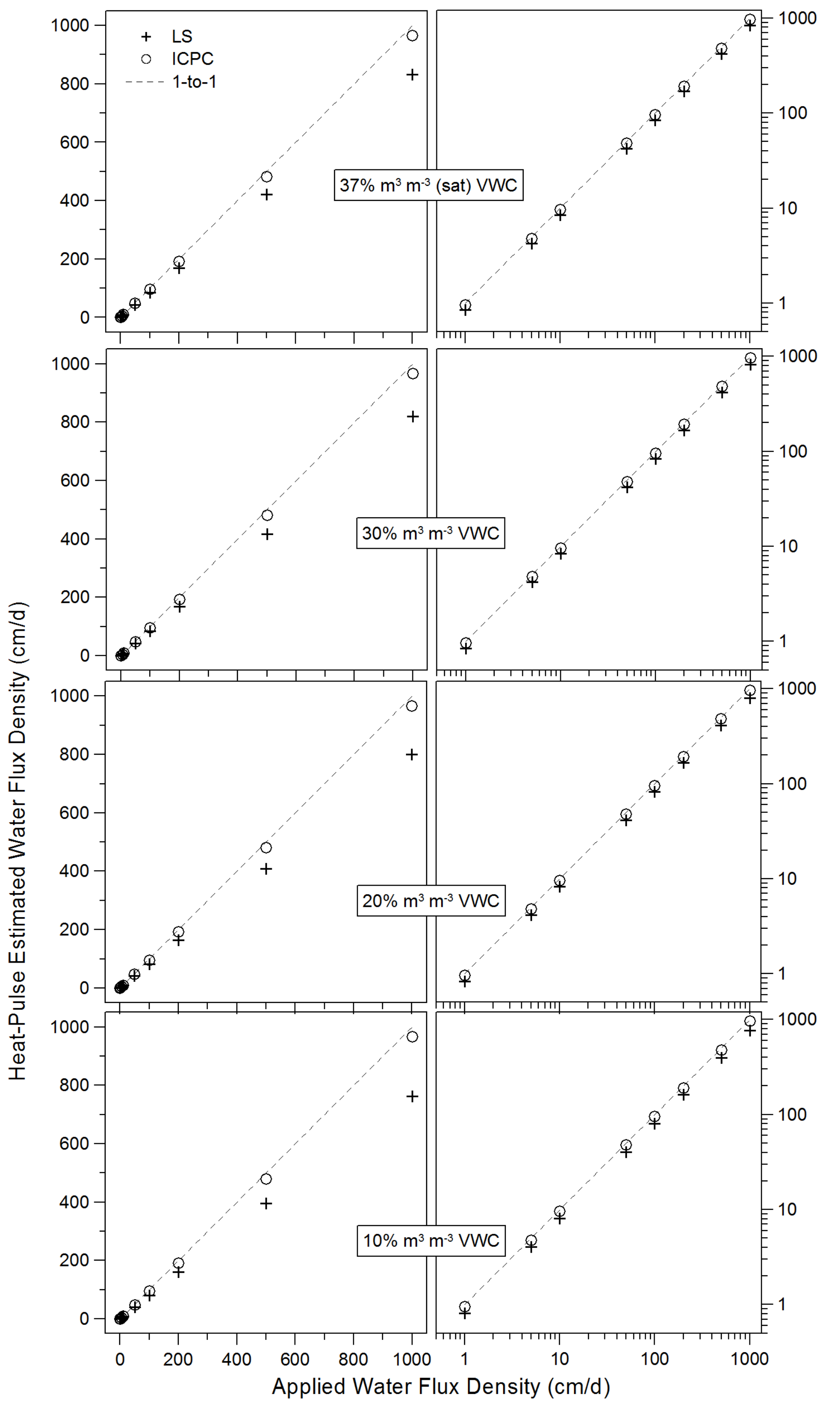


Soil Water Flux Density Results

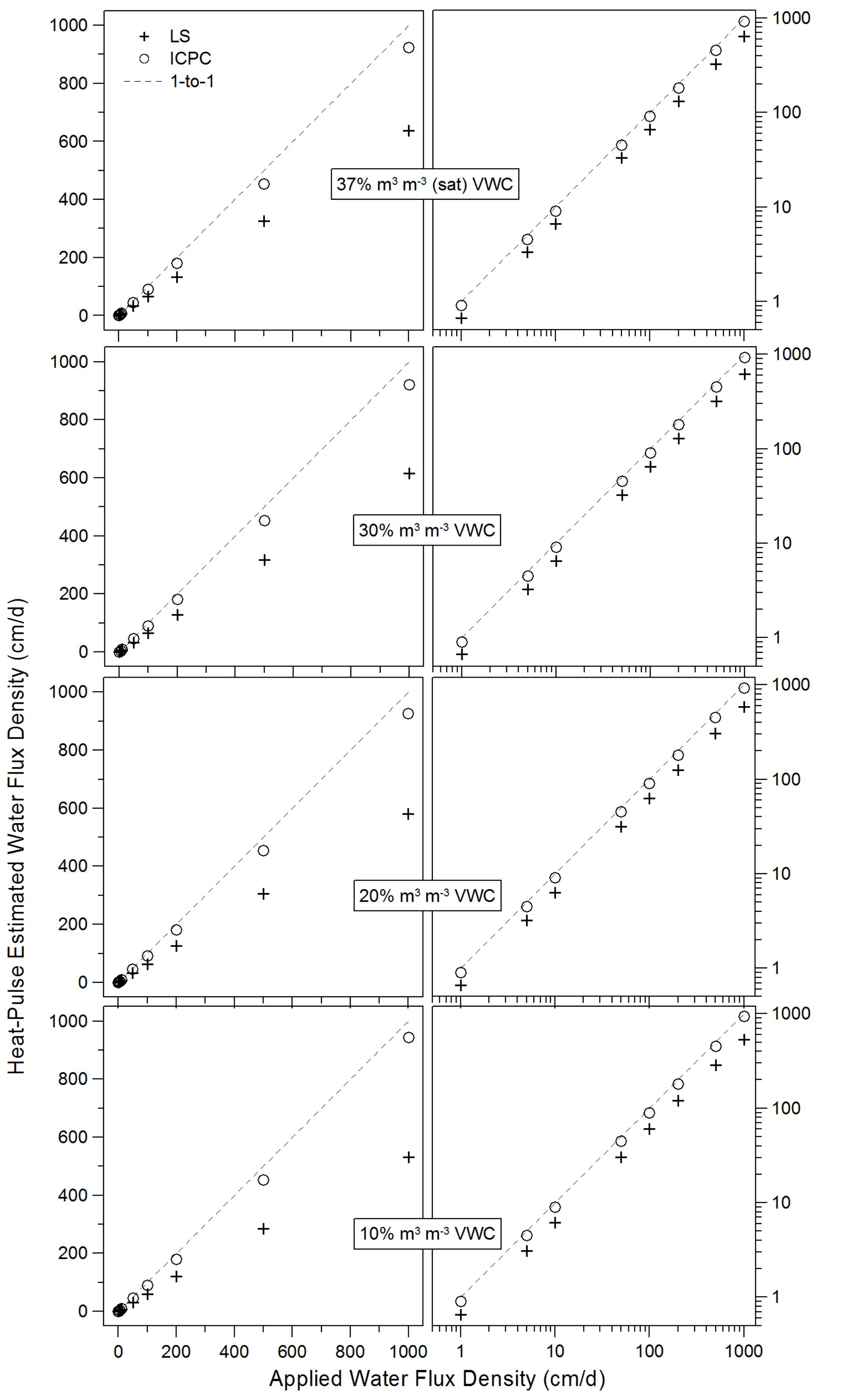
- Estimation of water flux density (WFD) relies on the difference between the temperatures of the downstream and upstream probes.
- Therefore, the ability to predict those temperatures will affect estimation accuracy.
- Assessment of model performance (LS and ICPC) and their capability to estimate flow is presented by comparing their estimated results to the WFD of the finite element model.



Conventional heat-pulse sensor (with small –diameter probes)



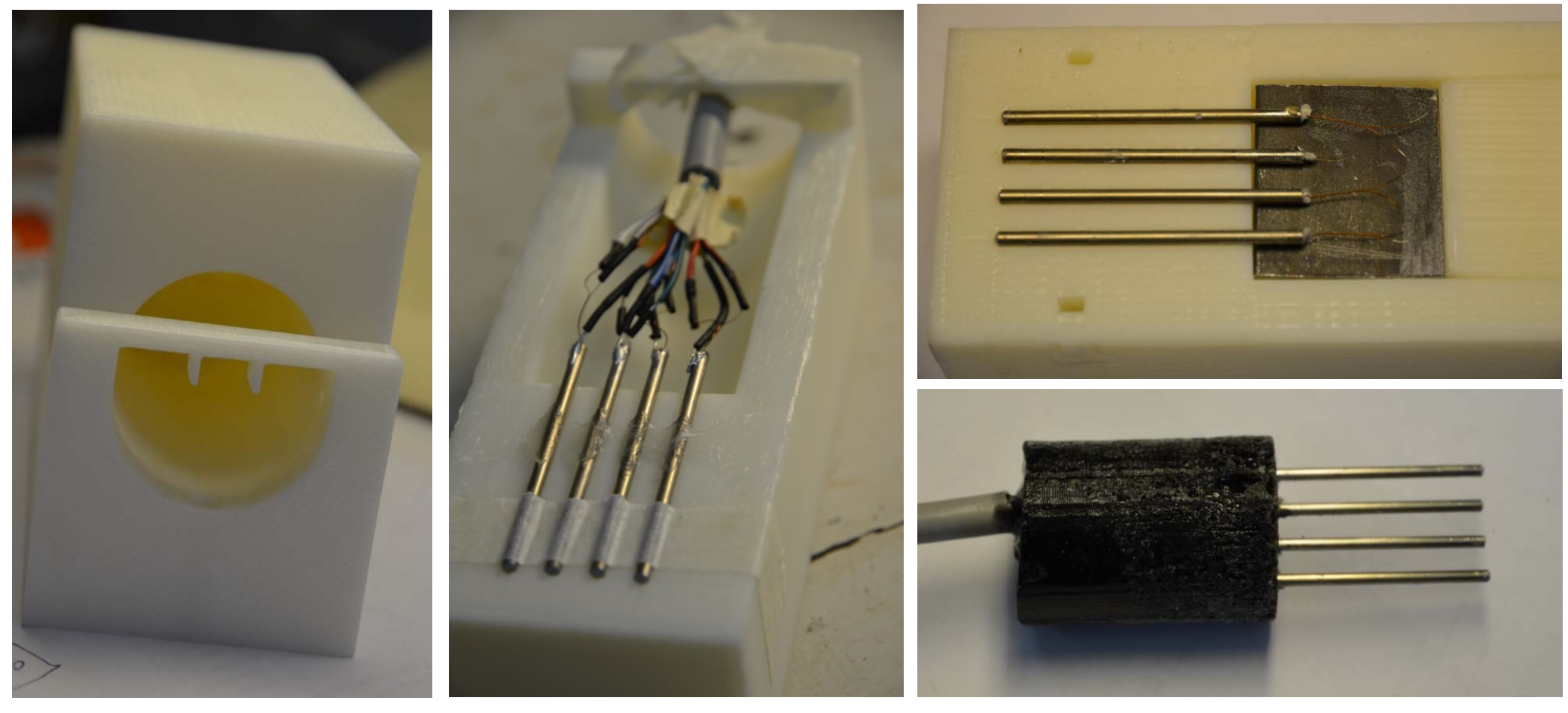
Rigid heat-pulse sensor (with large-diameter probes)



- Estimation of water flux density (WFD) is significanly improved with the ICPC model.
- Both the LS and the ICPC models underestimate WFD.
- As the soil gets drier, errors of LS estimates are larger, but ICPC estimates get better.

Sensor construction of a rigid heat-pulse (R-HP) sensor, with probe dimensions:

- 2.38 mm diameter
- 40 mm long
- 7 mm probe spacing



Construction of a rigid heat-pulse sensor for water content, water flux density, and EC measurements

Preliminary Conclusions and Future Work

- The perfect conductor assumption provides a semianalytical solution for inverse modeling.
- This model perfoms well across a wide range of saturation levels and water fluxes.
- The assumption of the perfect conductor allows it to work well on the dry end too.
- Ongoing work includes experiments and investigation of the underestimations for relating them to the assumptions of perfect conductor and one-dimensional flow.

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