# Application of Shortwave Infrared Imaging for Estimation of Soil Hydraulic Properties


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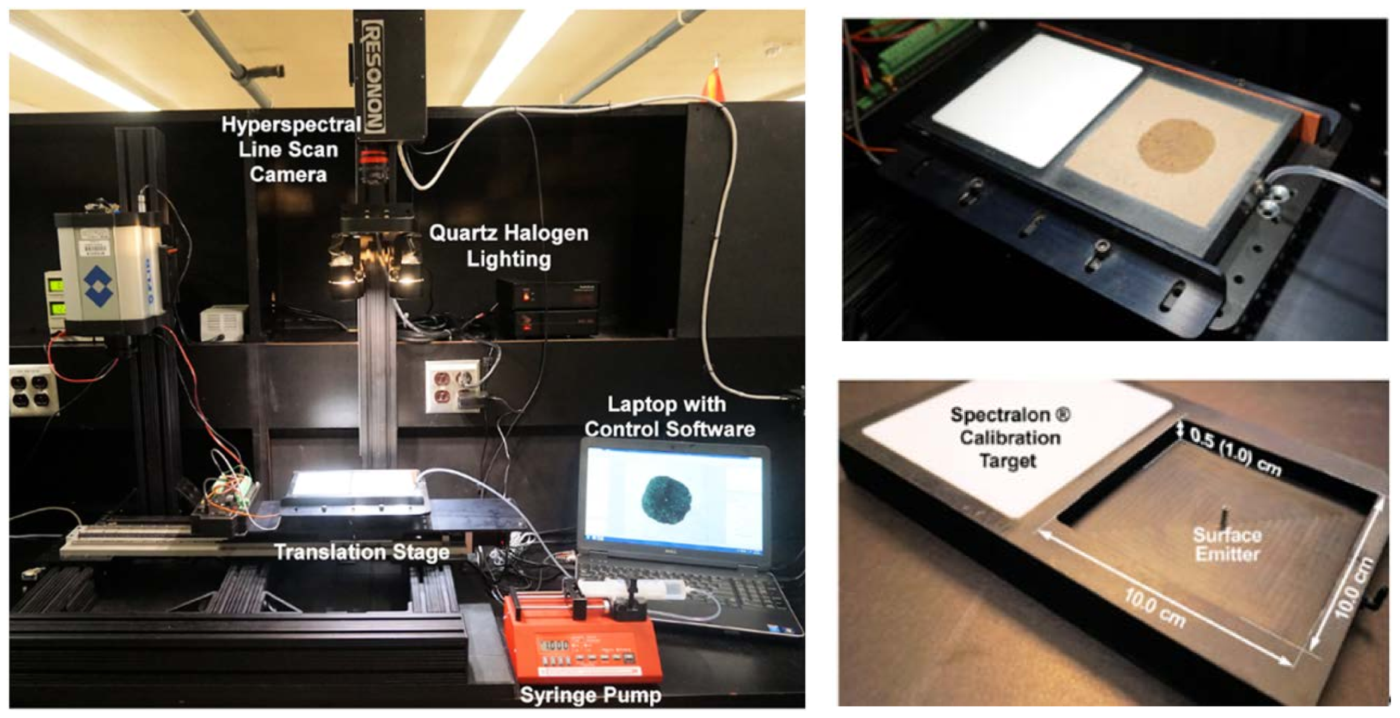
## Introduction

- Soil hydraulic properties (i.e., soil water characteristic and hydraulic conductivity) are key for modeling water flow and transport of solutes, heat and gases in saturated and unsaturated soils.
- Current laboratory and field techniques for hydraulic property measurements are expensive, time-consuming, and impractical for large scale applications.
- We present a rapid laboratory proximal sensing method for estimation of soil hydraulic properties (SHPs).
- The new method infers SHPs from SWIR reflectance imaging of soil moisture during water imbibition into dry soil in conjunction with a physical reflectance model *(Sadeghi et al., 2015)* and inverse numerical modeling of Richards' equation with HYDRUS 2D *(Šimůnek et al., 2008)*.

## Methods

### 1. Experiments

- Water imbibition experiments with a surface emitter with constant discharge rate (0.003 $cm^3\ s^{-1}$) were conducted.
- Soil surface reflectance evolution was imaged with a benchtop SWIR line scan camera.

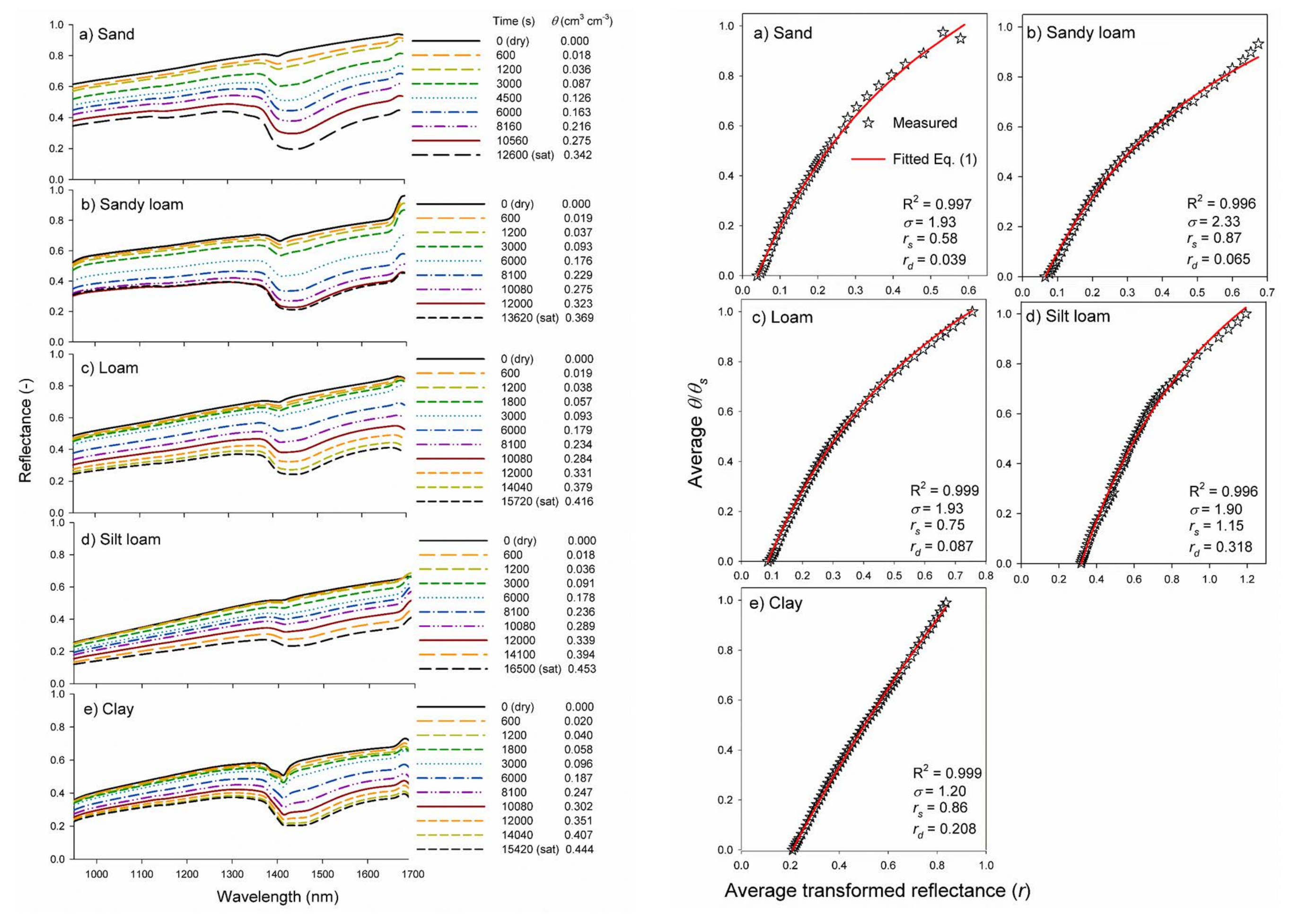



- Reflectance maps were transformed to surface water content maps with a nonlinear model introduced in *Sadeghi et al. (2015)*:

$$\frac{\theta}{\theta_s}=\frac{\sigma(r-r_d)}{r_s-r+\sigma(r-r_d)},\quad r=\frac{(1-R)^2}{2R}$$

**$\theta$**: volumetric water content ($cm^3\ cm^{-3}$)
**$\theta_s$** : saturated volumetric water content ($cm^3\ cm^{-3}$)
**$R$**: average reflectance (-)
**$r$**: transformed reflectance (-)
**$r_d$ and $r_s$**: transformed reflectance at dry and saturation (-)
**$\sigma$**: shape parameter (-)

- Soil reflectance decreases with the advancing wetted region and increasing water content providing an opportunity to monitor surface water content dynamics and thereby retrieving soil hydraulic properties.
- The nonlinear function was fitted to $\theta/\theta_s$ values determined from water mass balance and corresponding $r$ values to optimize $r_d$ *and* $r_s$ parameters.



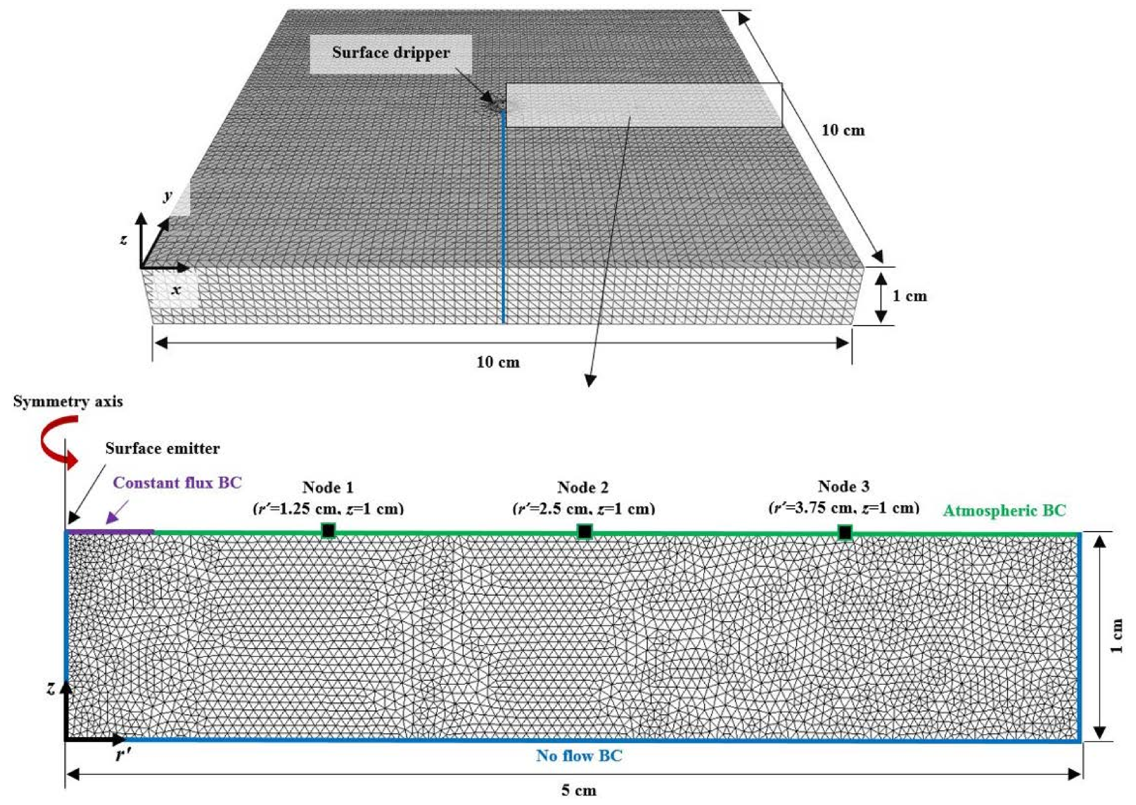

### 2. HYRUS 2D Numerical Modeling and Parameter Optimization

- Water imbibition was described based on *Richards'* equation considering van Genuchten-Mualem hydraulic functions *(van Genuchten, 1980)*:

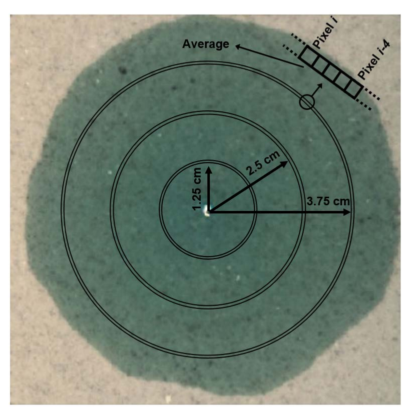
$$\frac{\partial\theta(h)}{\partial t}=\frac{1}{r'}\frac{\partial}{\partial r'}\left[r'K(h)\frac{\partial h}{\partial r'}\right]+\frac{\partial}{\partial z}\left[K(h)\frac{\partial h}{\partial z}+K(h)\right]-S(h)$$

With: $S_e=\dfrac{\theta-\theta_r}{\theta_s-\theta_r}=\left[1+|\alpha h|^n\right]^{-m}$ and $K(h)=K_sS_e^l\left[1-\left(1-S_e^{1/m}\right)^m\right]^2$

- HYDRUS 2D was utilized for water flow modeling (*Šimůnek et al., 2008*). The flow domain was defined as axisymmetrical with three observation nodes located at $r'$ = 1.25, 2.5, and 3.75 cm:




- All SWIR image-derived soil water contents for pixels with Euclidian distances of 1.25, 2.5 and 3.75 cm from the emitter were averaged and considered as the observed soil water contents at the 3 nodes and used in the objective function.



- HYDRUS 2D was coupled with a global optimization method (Simulated Annealing) in MATLAB to optimize hydraulic parameters $\alpha$, $n$, $\theta_r$ and $K_s$ through minimizing the objective function ($\varphi$):

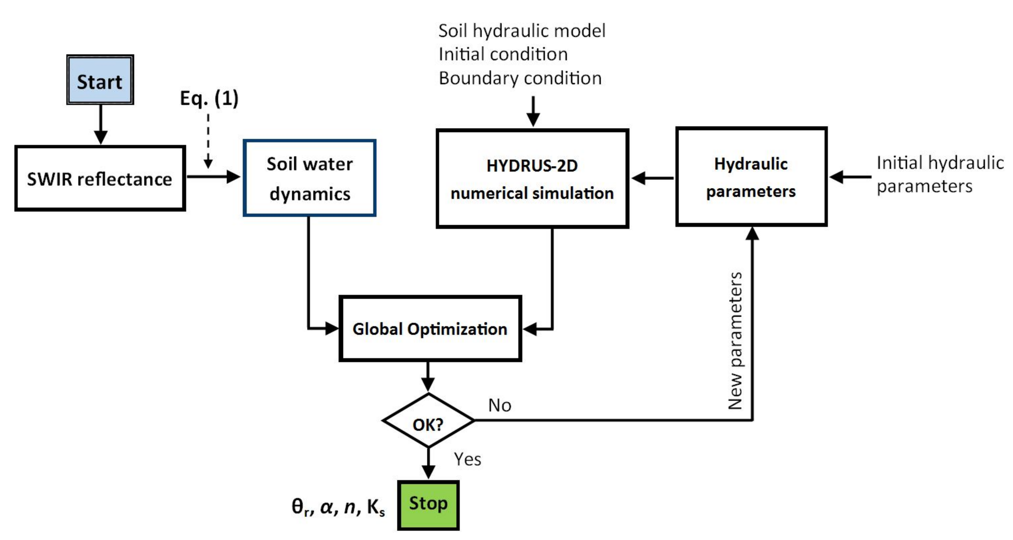
$$\varphi(b)=\sum_{j=1}^{N}\sum_{i=1}^{M}\left[O(r'_j,t_i)-S(r'_j,t_i,b)\right]^2$$

*b* : vector of the optimized parameters
*N and M* : the number of estimations and observations in a particular estimation set
$O(r'_j, t_i)$ : observed water content at time *i* for the $j^{th}$ measurement set at location $r'$
$S(r'_j, t_i, b)$ : corresponding simulated water content for the vector *b*

- Search space and initial values for the *van Genuchten (1980)* hydraulic parameters in the global optimization algorithm.

| Parameter | Search space | | Initial values (NRCS Soil Survey database ) | | | | |
|---|---|---|---|---|---|---|---|
| | Min. | Max. | Sand | Sandy loam | Loam | Silt loam | Clay |
| **$\alpha$ ($cm^{-1}$)** | 0.005 | 0.150 | 0.145 | 0.075 | 0.036 | 0.020 | 0.008 |
| **$n$ (-)** | 1.001 | 4.00 | 2.68 | 1.89 | 1.56 | 1.41 | 1.09 |
| **$\theta_r$ ($cm^3\ cm^{-3}$)** | 0.01 | 0.10 | 0.045 | 0.065 | 0.078 | 0.067 | 0.068 |
| **$K_s$ ($cm\ s^{-1}$)** | 1e-10 | 0.012 | 0.00825 | 0.00123 | 0.00029 | 0.00012 | 0.00005 |

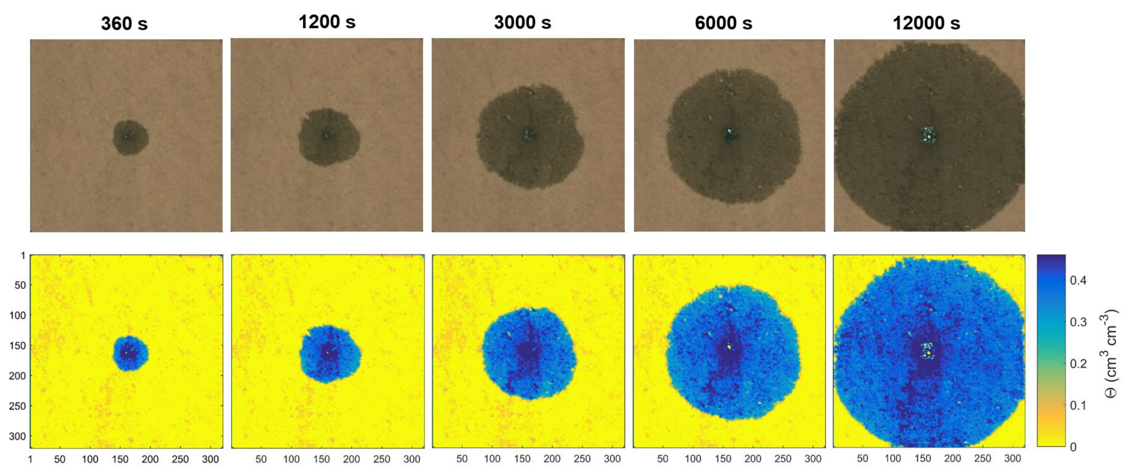
- The simple hysteresis model of *Kool and Parker (1987)* was applied to evaluate estimated wetting parameters against independently measured soil water characteristic data.
- The flowchart illustrates the SHP estimation framework.




## Results

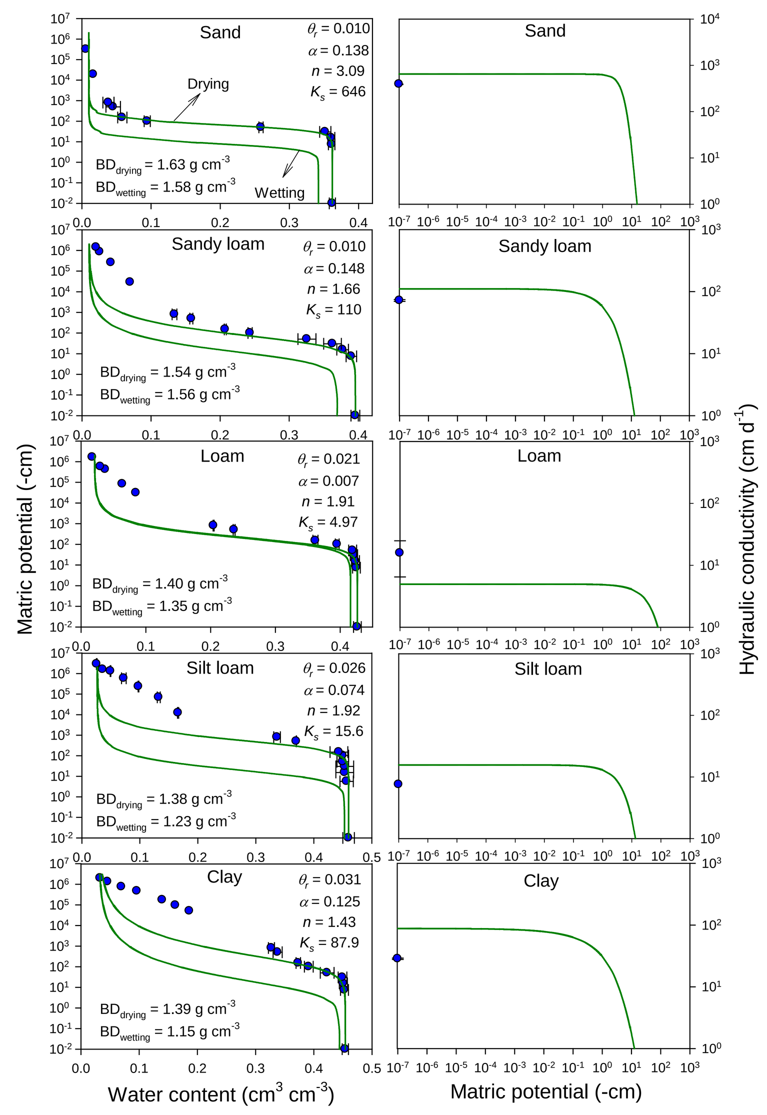
### SWIR imaging-based surface soil water dynamics

- SWIR imaging provides high resolution maps of soil water content during water imbibition.
- With the advancing wetting front, three zones including saturated zone, unsaturated (transition) zone, and dry zone were observed.



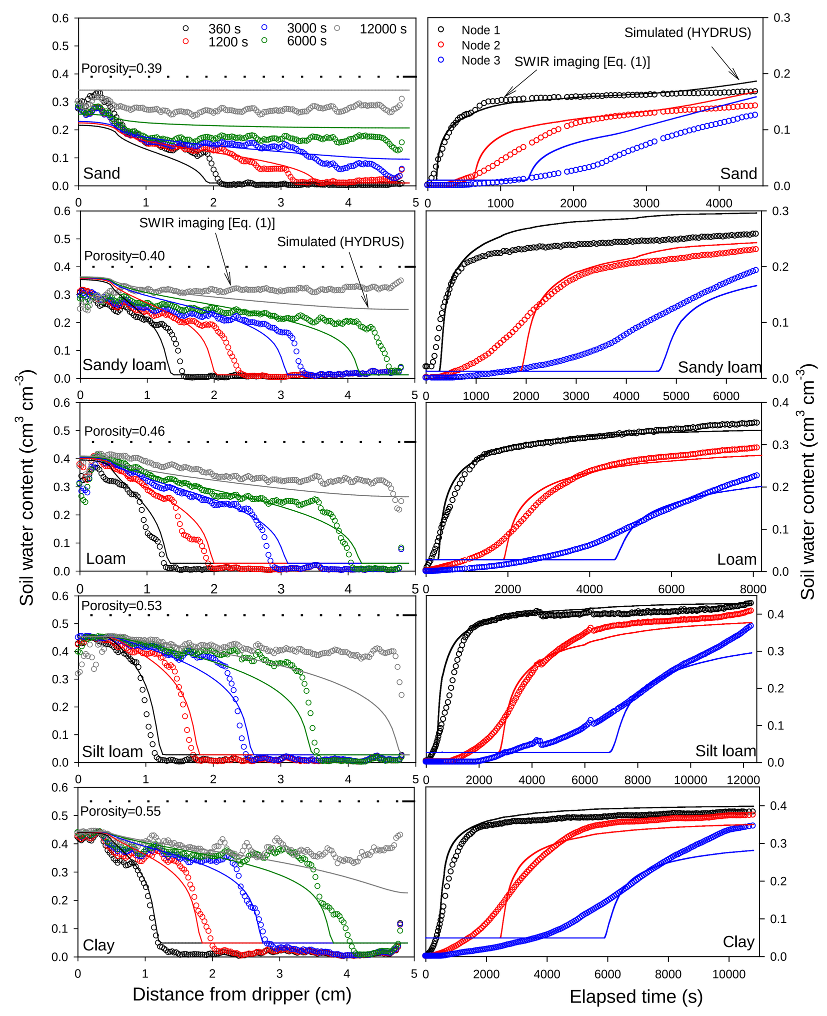

### Estimation of $\theta(h)$ and $K(h)$

- The estimated (converted) drying $\theta(h)$ and wetting $K(h)$ (i.e., $K_s$) showed reasonable agreement with lab-measured $\theta(h)$ and $K_s$. However, there exist some discrepancies at the dry-end ($\theta$ < 0.2), particularly for finer textured soils, which can be potentially attributed to inaccuracy of the used retention model at the dry-end (*Tuller et al., 1999*).




### Soil Water Content Simulations

- A reasonable agreement is observed between the imaging-based estimated and HYDRUS-simulated water contents with respect to distance from the emitter, particular for fine-textured soils where RMSE ranges between 0.025 and 0.067 for sand, and between 0.008 and 0.018 $cm^3\ cm^{-3}$ for clay.
- A reasonable agreement is also observed between imaging-derived and HYDRUS-based simulated water contents with respect to time, especially for the first two nodes, indicating reasonable performance of the optimization method to minimize the objective function.




## Conclusions

- The method allows the determination of the soil water characteristic and hydraulic conductivity function within only a couple of days, which is an advantage when compared to time consuming standard laboratory methods.
- Obtained results for soils spanning a wide textural range are in reasonable agreement with independently measured (i.e., Tempe cells and WP4-T Dewpoint Potentiameter) soil water characteristics.

## References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