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Integration of Heat-Pulse and Sensible Heat Balance Methods to Estimate Evaporation From Bare Soils

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ABSTRACT

A critical component of the water cycle at local, regional, and global scales is evaporation from soil. Because it is difficult to measure soil evaporation and soil moisture in the field, with the exception of using a lysimeter for local measurements, numerous model based estimation methods have been proposed. Numerical approaches that attempt to estimate evaporation rates within the top several centimeters of soil often rely on empirical and semi-empirical methods. Another less well known method to determine evaporation relies on heat-pulse sensors to measure soil temperature and thermal properties. This approach does not rely on knowledge of soil hydraulic properties, effectively removing the need of several common empirical methods employed to define the soil surface boundary condition. The objective of this study was to test the combined heat-pulse and sensible heat balance methods in a numerical code in addition to incorporating and using the sensible heat balance method in a more traditional non-isothermal multiphase flow model developed by *Smits et al.* [2011] to define the boundary conditions at the land/atmosphere interface, ultimately yielding evaporation and cumulative water loss. The numerical code and model was tested using precision experimental data (heat-pulse, temperature, relative humidity) collected under laboratory conditions.

Experimental data was generated in a two-dimensional soil tank containing an array of sensors that allowed soil temperature, soil moisture content, and relative humidity to be collected continuously and autonomously. The soil tank was placed within a wind tunnel test facility to insure that atmospheric conditions were carefully controlled and monitored throughout the duration of the experiment. The results of the numerical approaches were compared with experimental weight measurements which in turn demonstrated the applicability of incorporating the heat-pulse and sensible heat balance methods in numerical approaches. The numerical approaches show great ability to accurately predict soil-water evaporation rates and total cumulative water loss at fine spatial and temporal scale.

1. AIMS AND SCOPE

Modeling:

- ✓ Test the sensible heat balance and heat-pulse methods in a numerical code using accurate experimental data collected in the laboratory
- ✓ Incorporate sensible heat balance into a traditional multiphase flow model developed by *Smits et al.* [2011]
- ✓ Demonstrate the applicability of methods by comparing numerical code and COMSOL simulations to experimental data

Experimental:

- ✓ Development of soil tank apparatus equipped with an array of sensors for continuous and autonomous monitoring of soil moisture, relative humidity, and temperature
- ✓ Generation of precision data under well-controlled atmospheric boundary conditions

2. MATHEMATICAL THEORY

Sensible Heat Balance Vertical soil temperature gradients measured using heat-pulse sensors and calculated soil thermal properties calculated using the heat-pulse method are applied to the sensible heat balance [*Sakai et al.*, 2011] in the numerical code and COMSOL model:

$$LE = \left[\left(-\lambda_{i+\frac{1}{2}}\frac{T_i-T_{i+1}}{z_i-z_{i+1}}\right)-\left(-\lambda_{i-\frac{1}{2}}\frac{T_{i-1}-T_i}{z_{i-1}-z_i}\right)\right]-\Delta S$$

E (m s^{-1}) is the evaporation rate, *L* (J m^{-3}) is the volumetric latent heat of vaporization, λ (W m^{-1} °C^{-1}) is the soil thermal conductivity, T (°C) is the soil temperature, z (m) is depth (z = 0 is the soil surface), and ΔS (W m^{-2}) is the change in soil sensible heat storage.

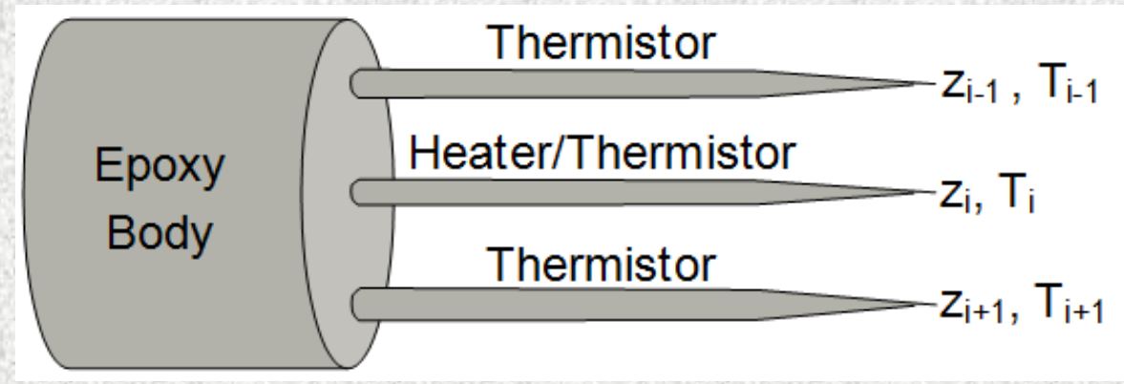


Figure adapted from Sakai et al., 2011

2. MATHEMATICAL THEORY (con't)

Latent Heat of Vaporization (*L*) [*Forsythe*, 1964]:

$$L = 2.49463x10^9 - 2.247x10^6 T_{mean}$$

T_{mean} (°C) is the mean temperature of a soil layer as a function of time

Change in Heat Storage (ΔS) *Ochsner et al.* [2007]

$$\Delta S = \sum_{i=1}^{N} C_{i,j-1}\frac{T_{i,j}-T_{i,j-1}}{t_j-t_{j-1}}(z_i-z_{i-1})$$

j denotes time step and i denotes soil layer

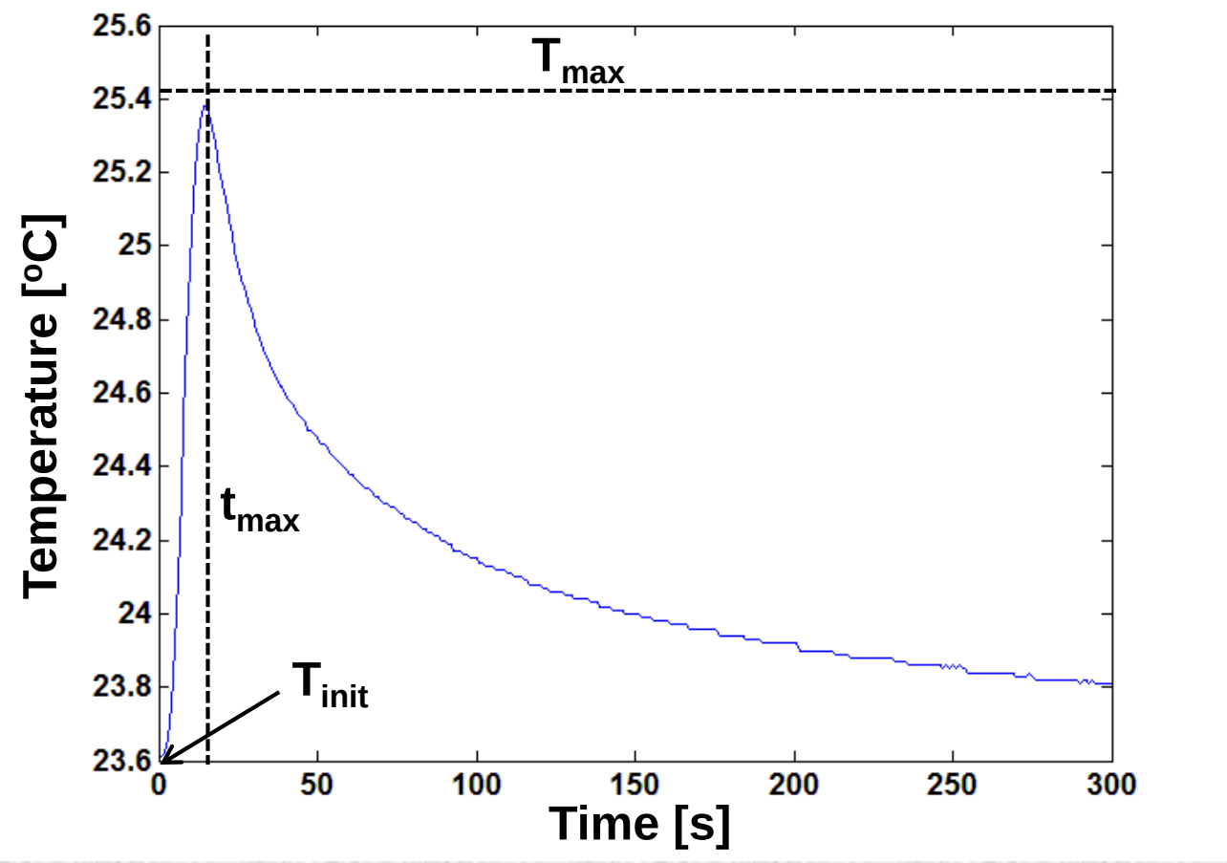
Volumetric Heat Capacity (C) *Kluitenberg et al.* [1993]

$$C = \frac{q'}{4\pi\kappa\Delta T_{max}}\left(Ei\left[-\frac{r^2}{4\kappa(t_{max}-t_0)}\right]-Ei\left[-\frac{r^2}{4\kappa t_{max}}\right]\right)$$

q' (W m^{-1}) is the energy liberated per unit length of heater, and t_0 (s) is the heat-pulse duration, and Ei is the exponential integral

Thermal Diffusivity (κ) [*Bristow et al.*,1994]

$$\kappa = \frac{r^2}{4t_{max}}\left(\frac{t_0}{t_{max}-t_0}\right)\left[\ln\left(\frac{t_{max}}{t_{max}-t_0}\right)\right]^{-1}$$



Thermal Conductivity (λ)

$$\lambda = C\kappa$$

Cumulative Water Loss from tank

$$M_{loss} = A\rho_w dt \sum_{j=1}^{m}\sum_{i=n_{j-1}}^{n_j} E_{j,i}$$

A (m^2) is the cross sectional area perpendicular to flow, ρ_w (kg m^{-2}) is the density of water, d*t* (hr) is the duration of each heating cycle, and $E_{j,i}$ (m hr^{-1}) is the evaporation rate measured from a given soil layer j during heating cycle i

Liquid water mass balance, water vapor mass balance, and energy conservation were coupled together to in a non-equilibrium non-isothermal multiphase COMSOL model to capture the spatial and temporal distributions of soil moisture and thermal properties for use in the sensible heat balance:

Liquid Water Mass Balance [Bear, 1972]

$$\rho_w\frac{\partial\theta_w}{\partial p_c}\frac{\partial p_c}{dt}+\theta_w\frac{\partial\rho_w}{dt}+\nabla\cdot(\theta_w\rho_w\boldsymbol{u}_w) = -R_{gw}$$

Water Vapor Mass Balance [Bear, 1972]

$$\frac{\partial\rho_g w_v\theta_g}{\partial t}+\nabla\cdot\left(\theta_g\rho_g w_v\boldsymbol{u_g}-D_v\nabla(w_v\rho_g)\right) = R_{gw}$$

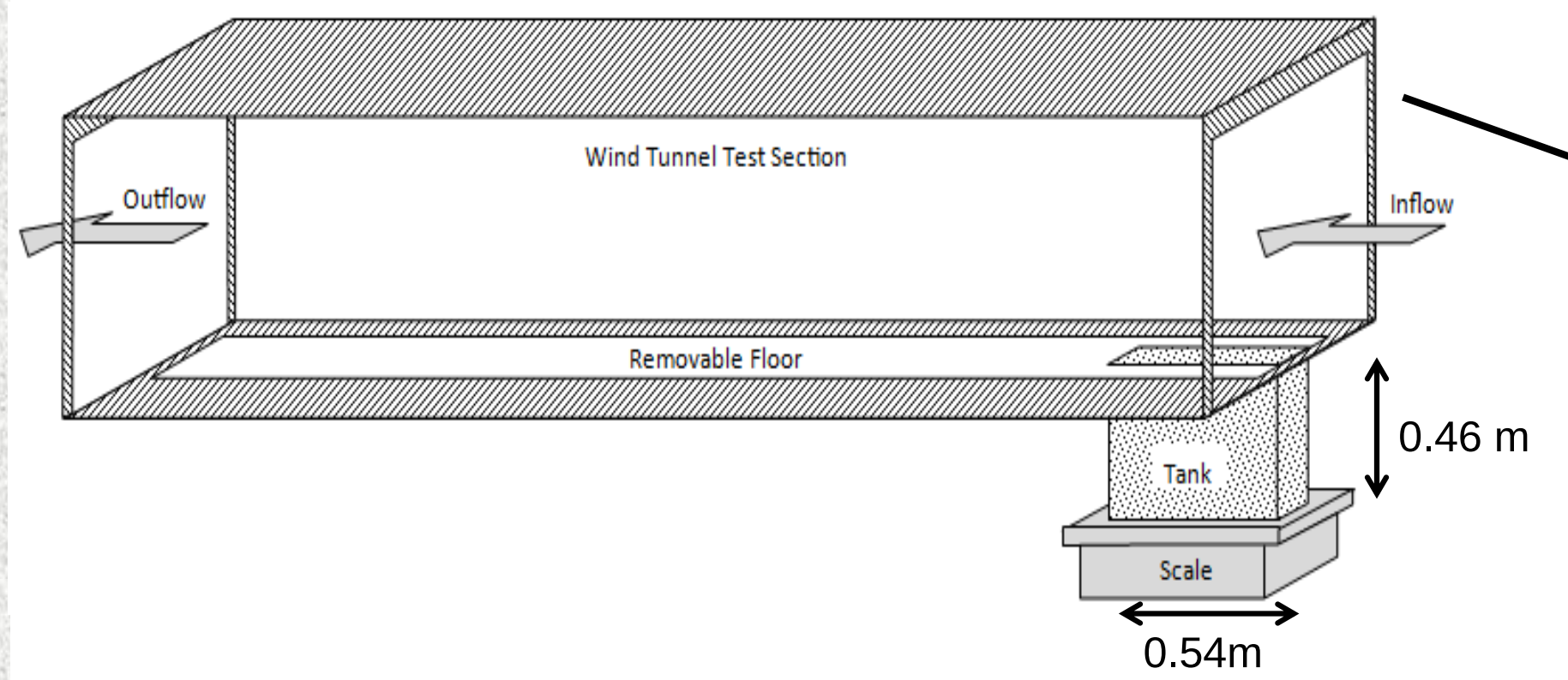
Energy Conservation

$$\nabla\cdot\left(C_g\rho_g T\boldsymbol{u_g}\theta_g+C_w\rho_w T\boldsymbol{u_w}\theta_w-\lambda_T\nabla T\right)+\frac{\partial\rho_b C_b T}{\partial t} = -LR_{gw}-Q_s$$

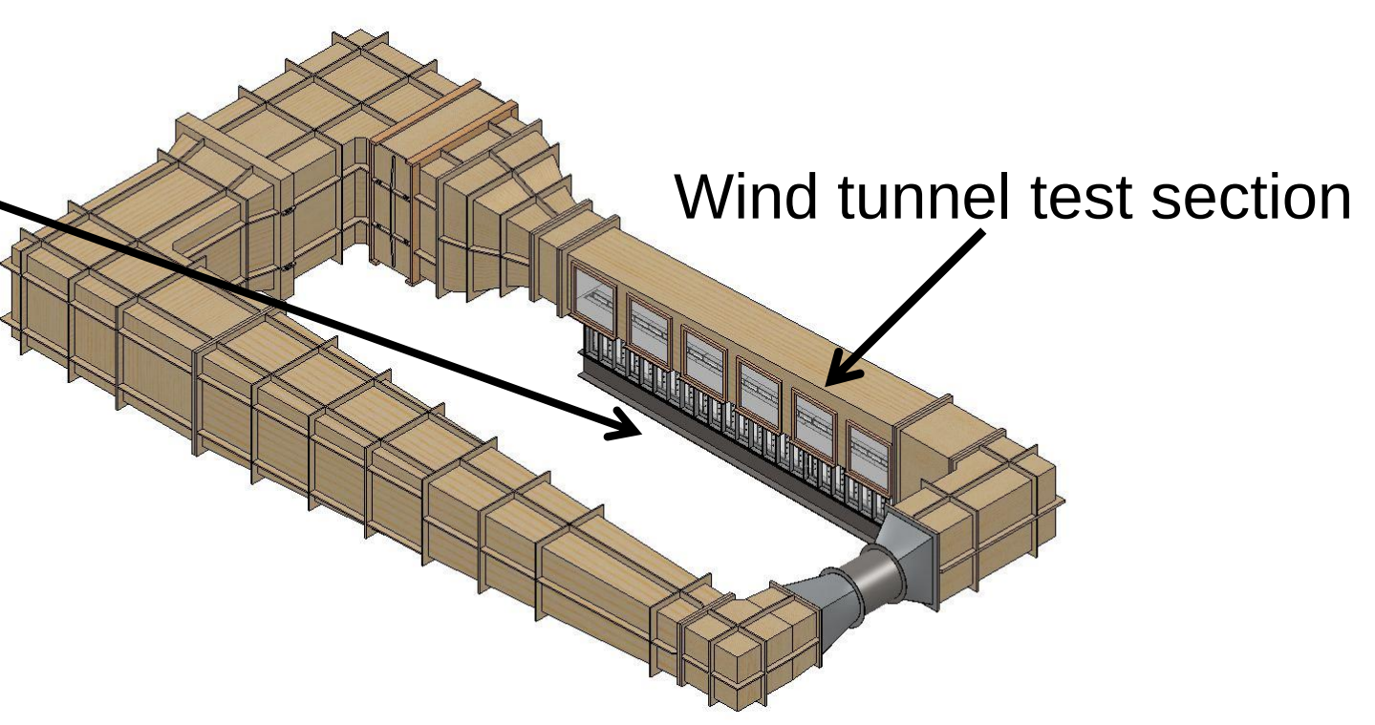
Let *w* and *g* denote the liquid and gaseous phases respectively. *θ* (m^3 m^{-3}) is the volumetric fluid content, p_c (Pa) is the capillary pressure, *ρ* (kg m^{-3}) is the density, *u* (m s^{-1}) is the Darcy velocity, R_{gw} (kg m^{-3} s^{-1}) is the rate of phase change, w_v (kg kg^{-1}) is mass fraction of water vapor in gas phase, D_v (m^2 s^{-1}) is the effective vapor diffusion coefficient, L (J m^{-3}) is the latent heat of vaporization, and Q (J) is heat loss.

3. EXPERIMENTAL METHODS

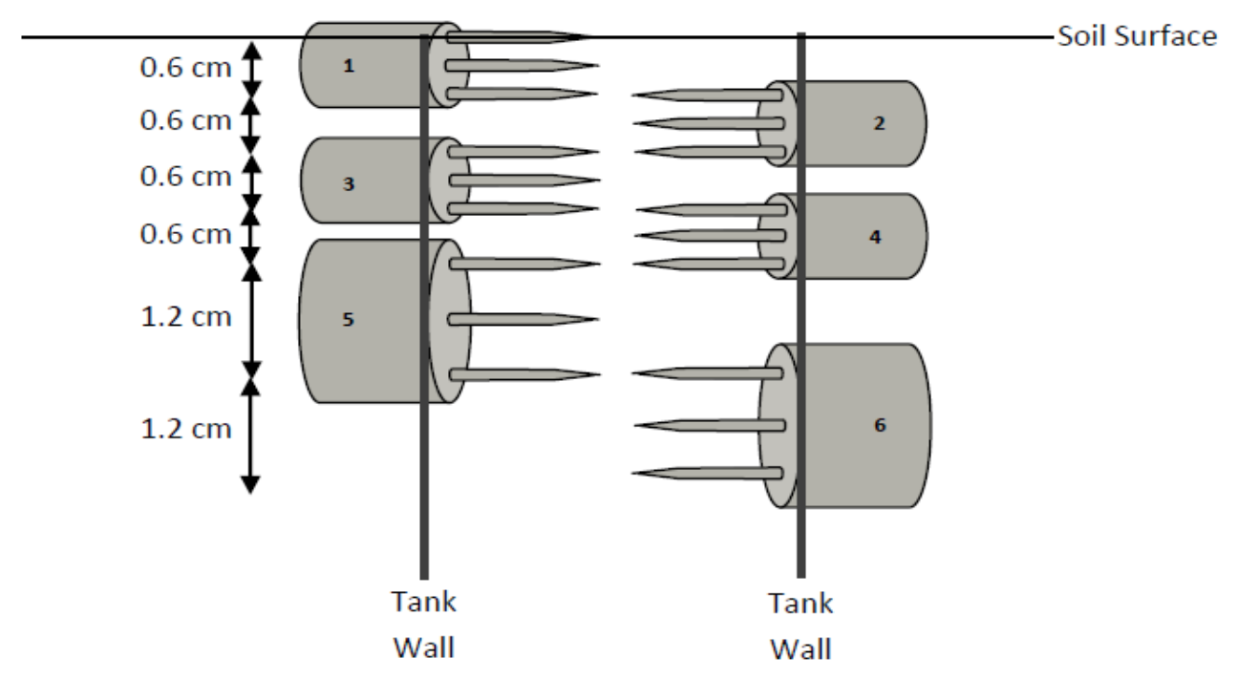
2-D sand tank setup:



Wind tunnel/porous media facility:



Heat pulse sensor arrangement



Wind Tunnel Specifications:

- Maintains wind speeds 0.8 – 10 m s^{-1}
- Humidification and dehumidification system allows relative humidity values to be maintained anywhere within range of 5 – 95%
- Cooling and heating system allows temperature to be maintained anywhere within the range of -4.4 – 35 °C
- Pitot-static tubes for velocity measurement
- LDV system for boundary layer characterization

Procedure:

- ✓ Constant air velocity maintained across upper boundary using CESEPS's low velocity closed circuit wind tunnel designed for porous tank experimentation
- ✓ Water table at initially at soil surface
- ✓ Evaporation induced under strictly drying Conditions
- ✓ No flow bottom boundary
- ✓ Experiment ran for 28 days

Test sand:

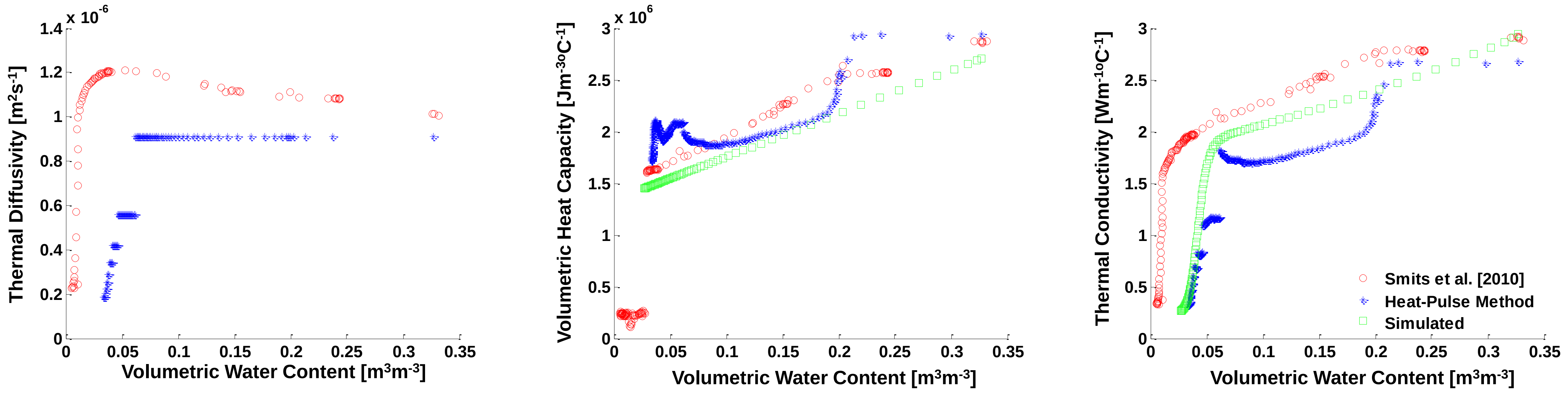
Accusand #30/40

- 99.8% quartz
- d_{50} = 0.53 mm
- Bulk density = 1.783 gcm^{-3}
- Porosity = 0.327
- Ks = 0.104 cm/s

Monitored:

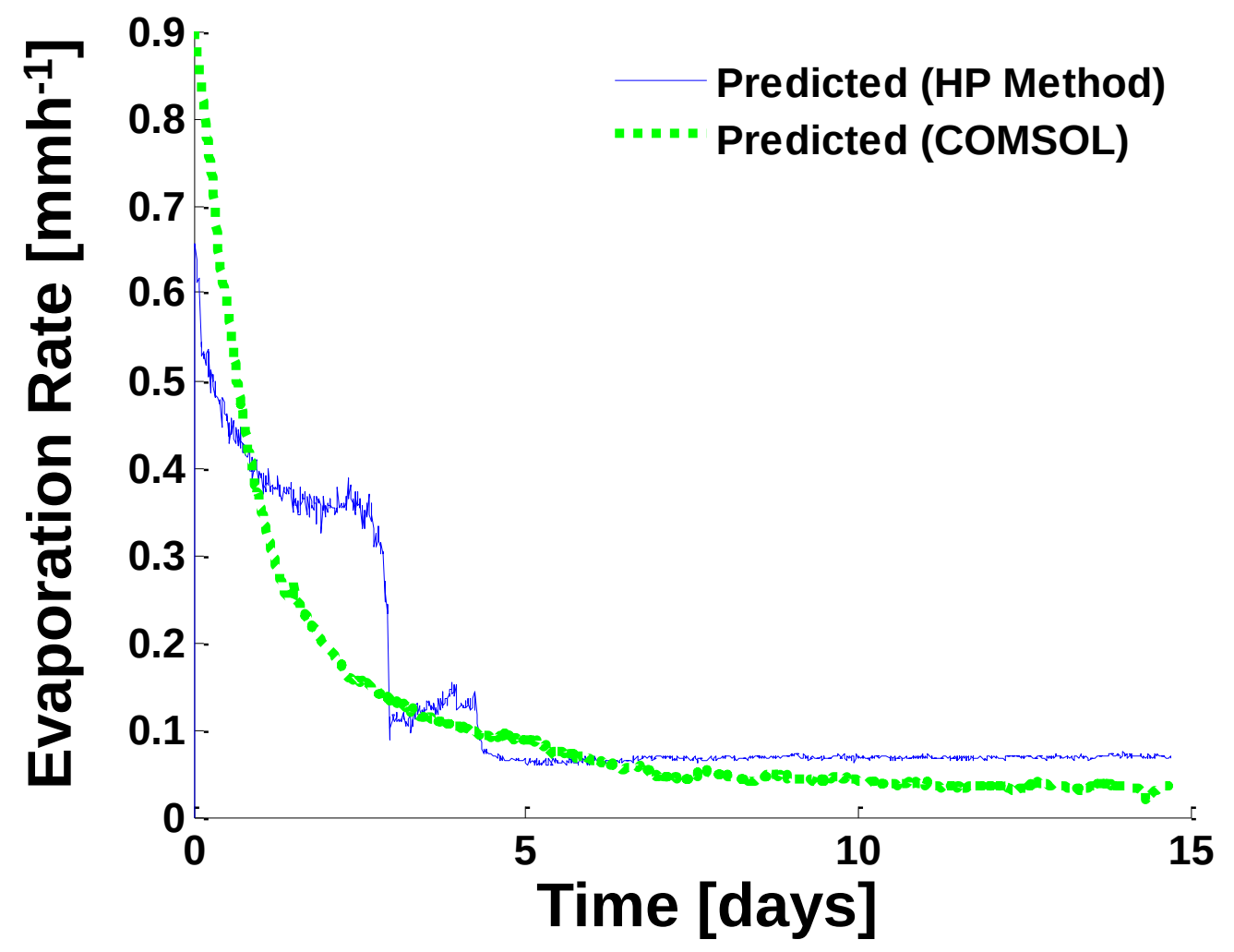
- Soil Moisture
- Relative Humidity
- Temperature
- Column Weight
- Air velocity

4. HEAT-PULSE METHOD TO DETERMINE SOIL THERMAL PROPERTIES

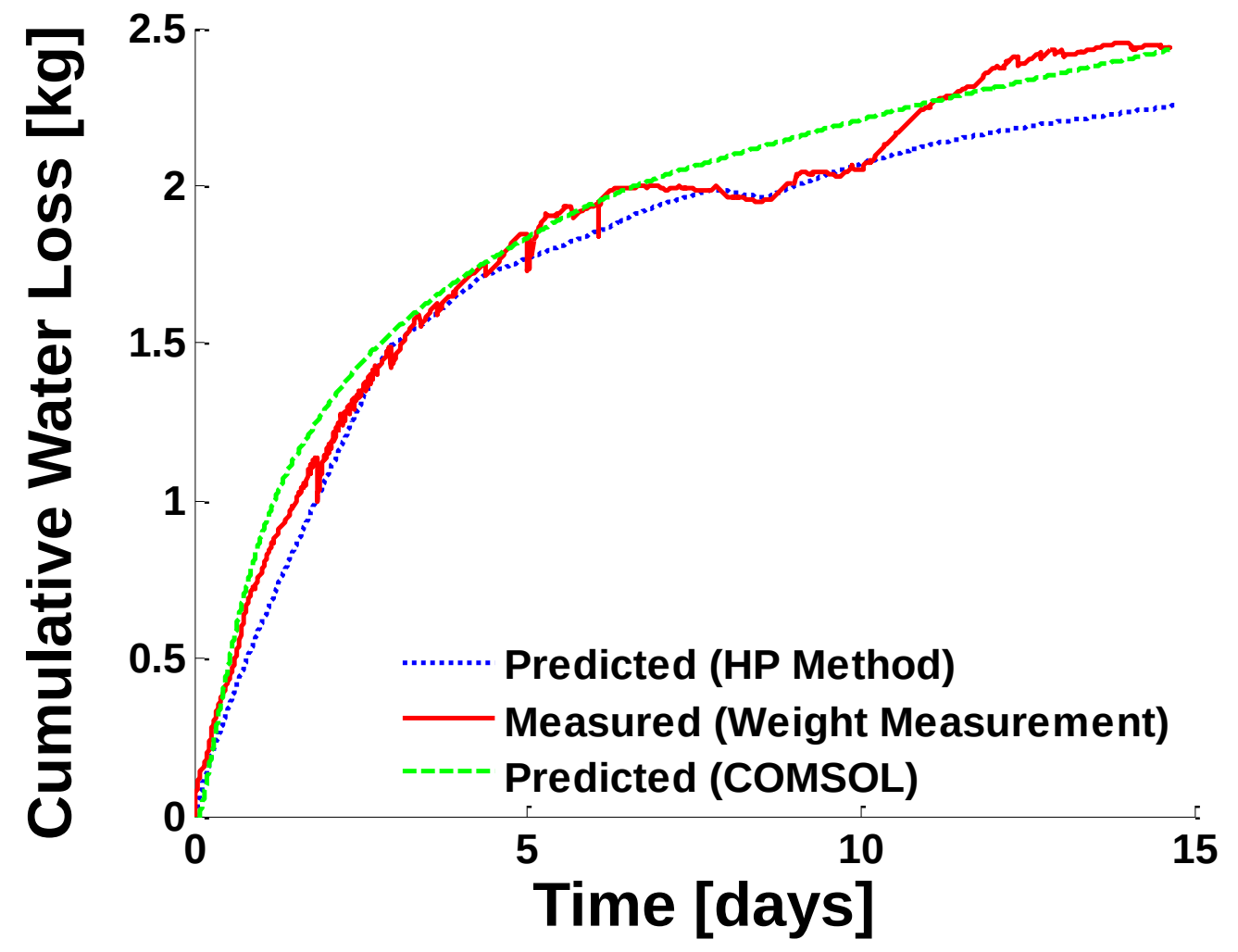


RESULTS: *Obtained good representation of soil thermal properties using heat-pulse method and numerical COMSOL simulation as compared to Smits et al. [2010]*

5. SENSIBLE HEAT BALANCE METHOD TO CALCULATE SUBSURFACE EVAPORATION



Evaporation rates from soil layer 0-0.6 cm bgs



Measured-Calculated
MIA = 97.38%
Measured-Modeled
MIA = 98.22%

RESULTS: Combined heat pulse and sensible heat balance method and numerical model incorporating sensible heat balance method accurately predicts total cumulative water loss. Underestimation of calculated (heat-pulse probe) cumulative water loss expected to presence of "undetectable zones" created by probe structure.

6. CONCLUSIONS

- Good agreement between theoretical predictions using combined heat pulse & sensible heat balance methods and independently measured experimental data
- Good agreement between numerical model that incorporates the sensible heat balance method and independently measured experimental data
- Method accurately captures evaporation rates as well as cumulative water loss
- Underestimation of cumulative water loss using combined heat-pulse and sensible heat balance methods will always occur due probe structure
- Results of this study will be used in future research for larger, more complex atmospheric conditions and soil heterogeneities.

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