Effect of surface layer on evaporation from porous media

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ABSTRACT

Evaporation is a process of mass and heat transfer between the atmosphere and shallow subsurface, and it is critical to many natural and industrial applications. The principles of controlling evaporation have been widely used in agriculture (mulch layer to reduce evaporation). The properties of surface layer have a significant effect on the evaporation process.

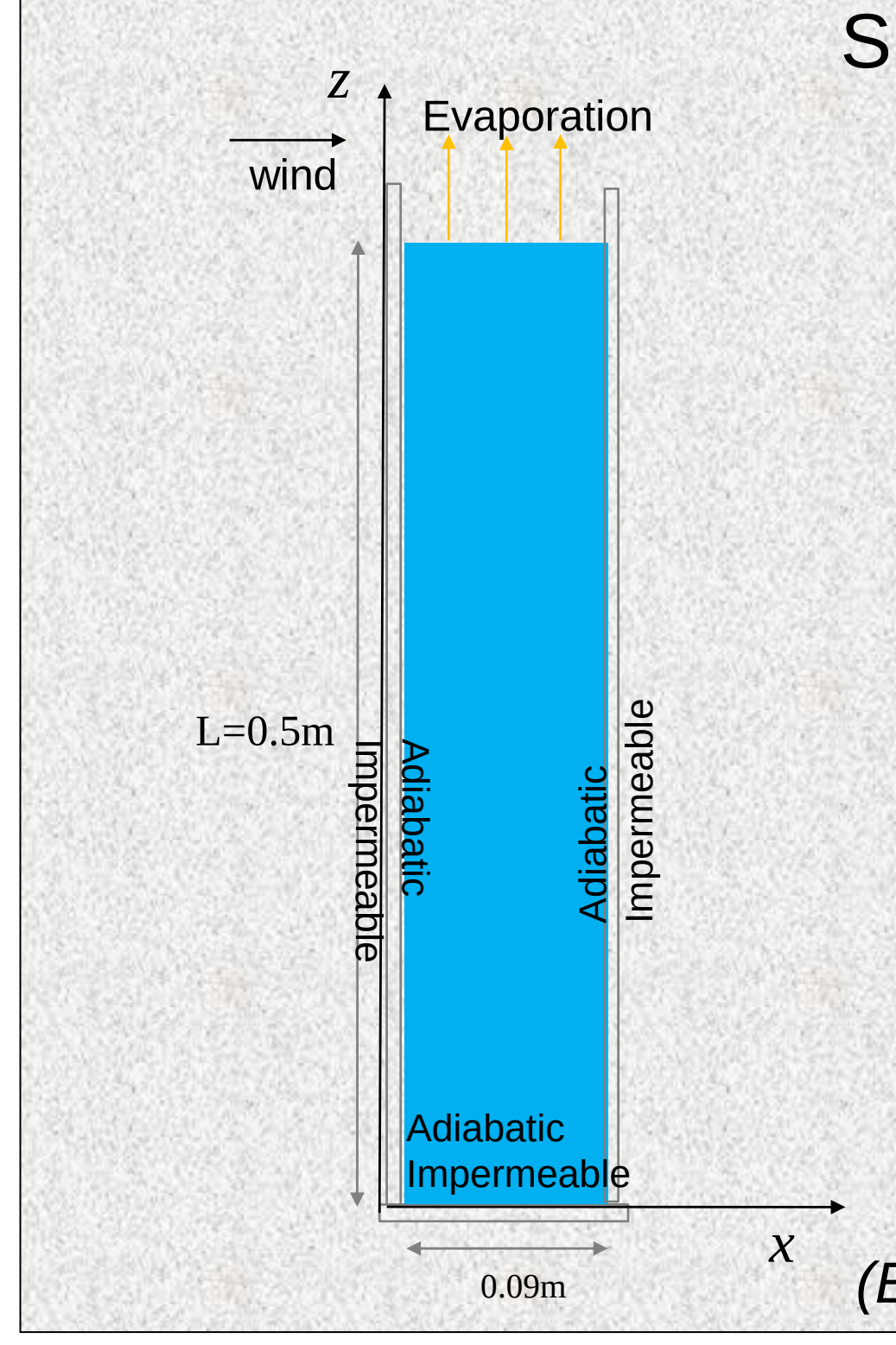
The goal of this work is to investigate the impact of the properties of surface layer on evaporation. A coupled model which consists of liquid water, water vapor and heat transport was developed. Four cases (coarse sand on the surface and sandy loam on the surface with different thickness) were studied, with two homogeneous configurations as controls. The water content distribution and evaporation rates were presented and analyzed.

The results demonstrated the significant role of the surface layer. The properties and the thickness of the surface layer affected the evaporation behavior. The coarse sand on the surface reduced the evaporation and helped conserve water. While the fine layer on the surface layer induced longer stage 1 evaporation so as to increase evaporation. In addition, the results suggested that the air invaded into the coarse layer first no matter the coarse layer is on the surface or not. It should be noted that further experimental work needs to be done to support and strengthen our results.

1. AIMS AND SCOPE

- Develop and implement a coupled numerical model accounting for liquid water, water vapor and heat transport.
- Study impact of the surface layer properties and thickness on the evaporation process.
- Investigate the water content distribution in the layered porous media.

2. APPROACH



Simulation approach

- **Simulation domain:**
  Column: diameter=0.09m, height =0.5m
- **Initial conditions:**
  Liquid water $p_w(x,z)=z$ $S_w(x,z)=1$
  Gas phase $p_g(x,z)=0$ $S_g(x,z)=0$
  Water vapor $c_v(x,z)=0$
  Temperature $T(x,z) = 293\text{K}$
- **Boundary conditions:**
  Liquid water $q_w(t,L) = 0$ (top)
  Water vapor $c_v(t,L)=\rho_{vs}RH(t)$ (top)
  Temperature $T(t,L)=296\text{K}$ (top)

(Experimental work needs to be done further)

3. NUMERICAL MODEL FORMULATION

Mass conservation equation

Liquid phase **(Bear, 1972)**

$$\rho_w \frac{\partial \theta_w}{\partial p_c}\frac{\partial p_c}{\partial t} + \theta_w \frac{\partial \rho_w}{\partial t} + \nabla \cdot (\theta_w \rho_w \boldsymbol{u_w}) = -R_{gw}$$

Gas phase **(Bear, 1972)**

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

Vapor in gas phase **(Bear, 1972)**

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

Momentum conservation equations

Liquid phase **(Bear, 1972)** $\boldsymbol{u_w}\theta_w = -\frac{\boldsymbol{k_s} k_{rw}}{\mu_w} \cdot \nabla(p_w + \rho_w g z)$

Gas phase **(Bear, 1972)** $\boldsymbol{u_g}\theta_g = -\frac{\boldsymbol{k_s} k_{rg}}{\mu_g} \cdot \nabla(p_g + \rho_g g z)$

Energy conservation equation **(Whitaker, 1977)**

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

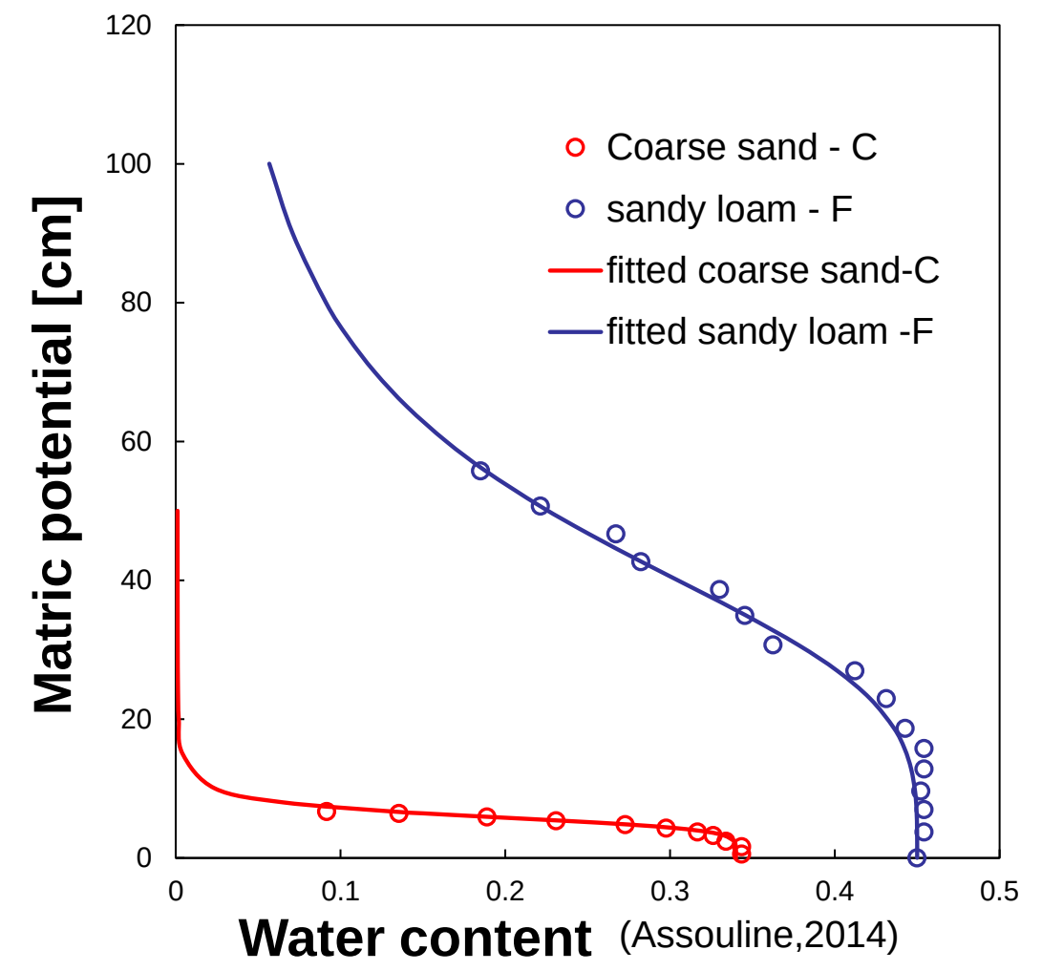
Water-vapor phase change rate(Bixler,1985;Smits,2011)

$$R_{gw} = \frac{b(\theta_w - \theta_{rw})RT}{M_w}(c_{vs}H_{re} - \rho_g w_v)$$

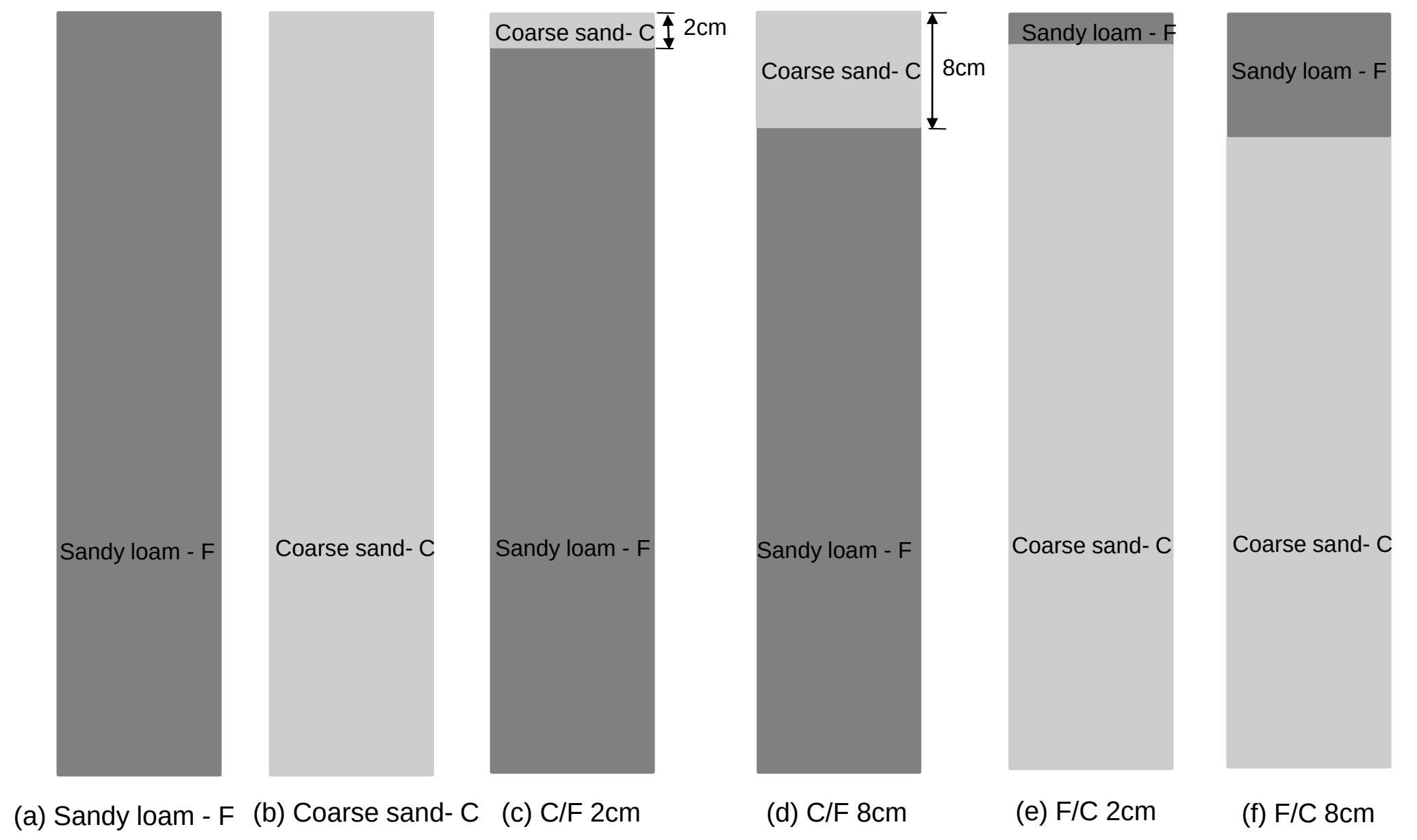
4. SIMULATION SETTING

Soil properties (Assouline,2014)

	θ_s(cm³/cm³)	θ_r(cm³/cm³)	α(cm⁻¹)	*n*	K_s(cm/h)
Coarse sand(C)	0.34	0.001	0.17	6.04	253.8
Sandy loam(F)	0.45	0.01	0.023	3.65	36.3

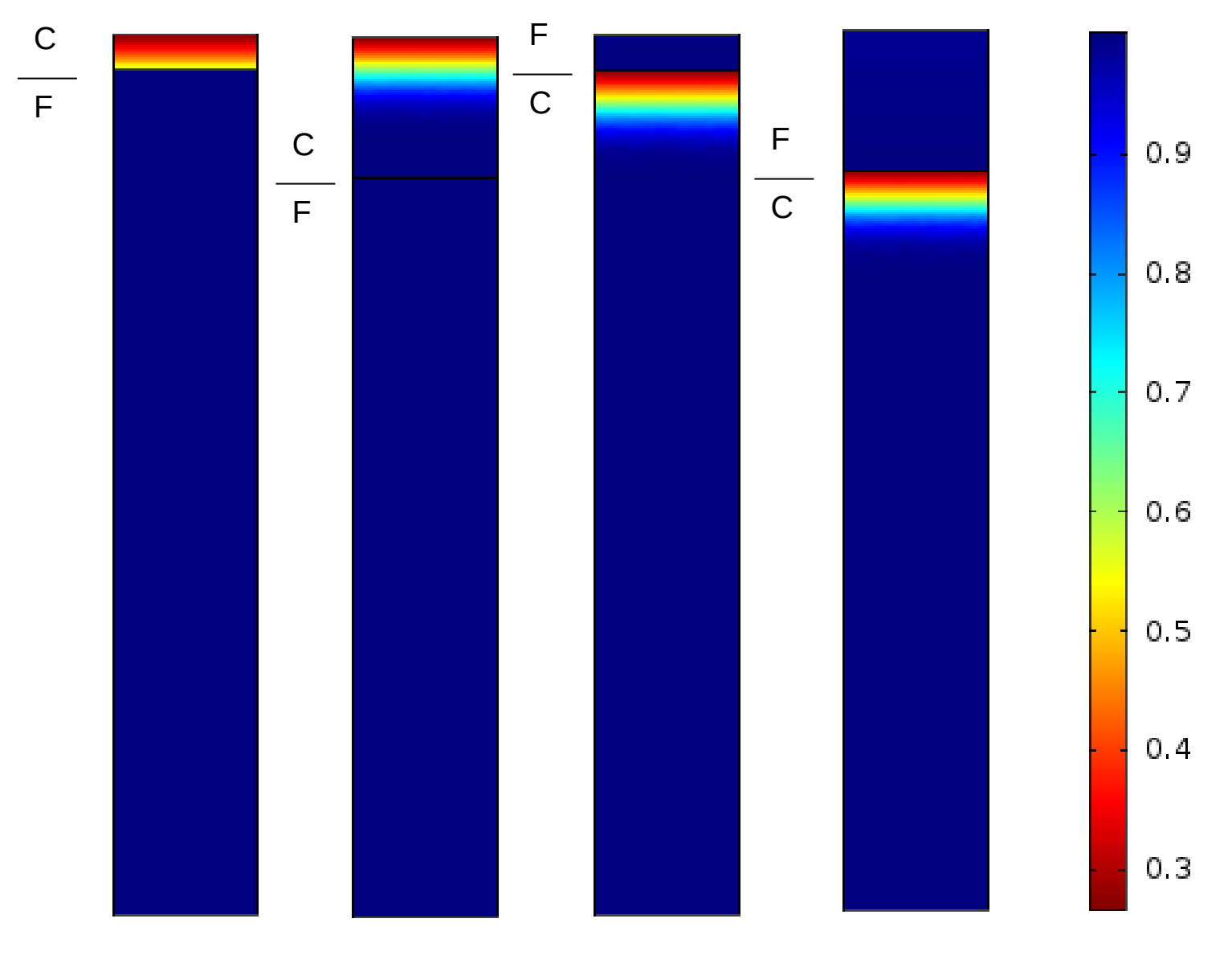


Water content (Assouline,2014)

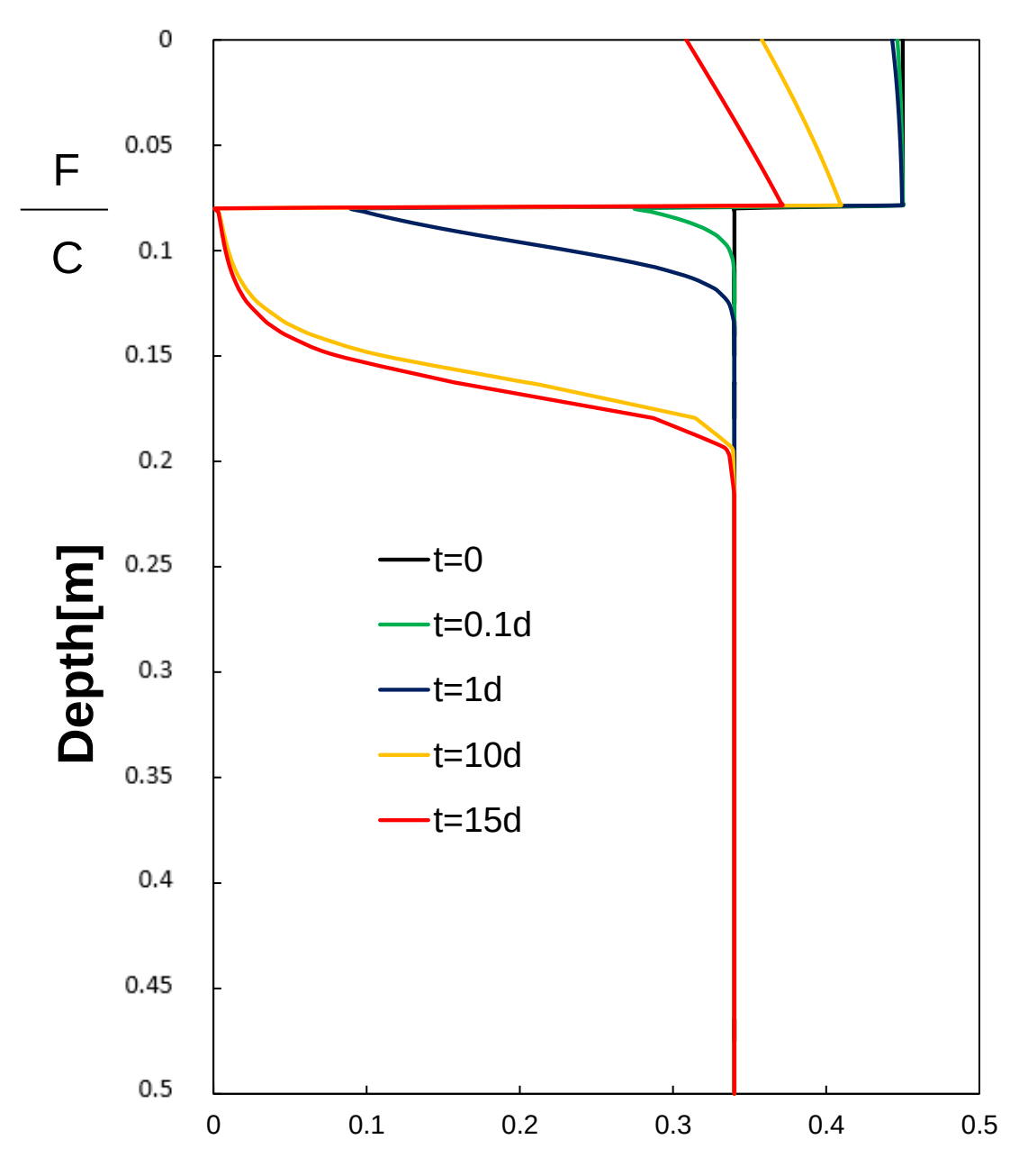


Schematic diagram of simulation configuration

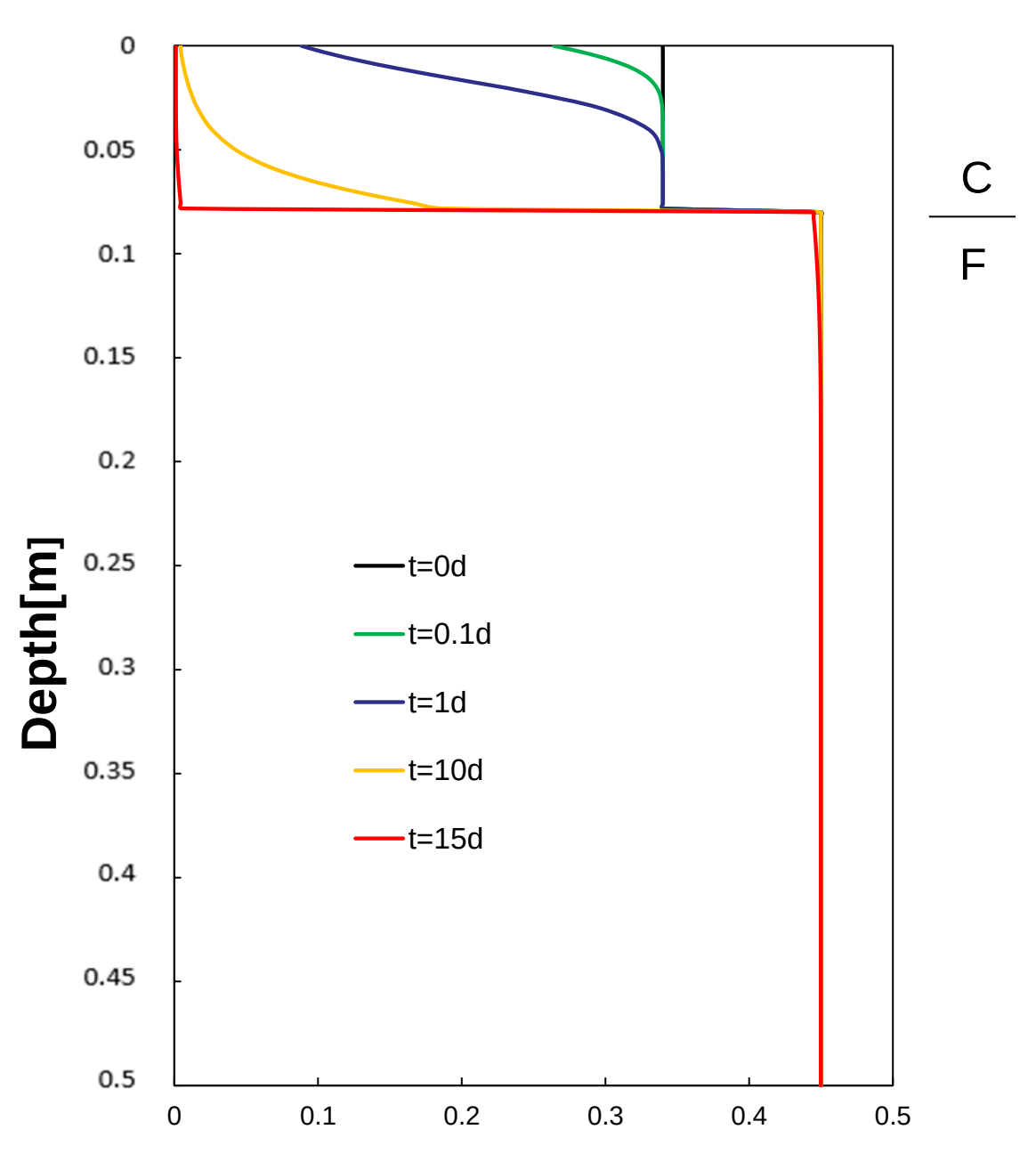
5. SIMULATION RESULTS



Water saturation distribution



Water content

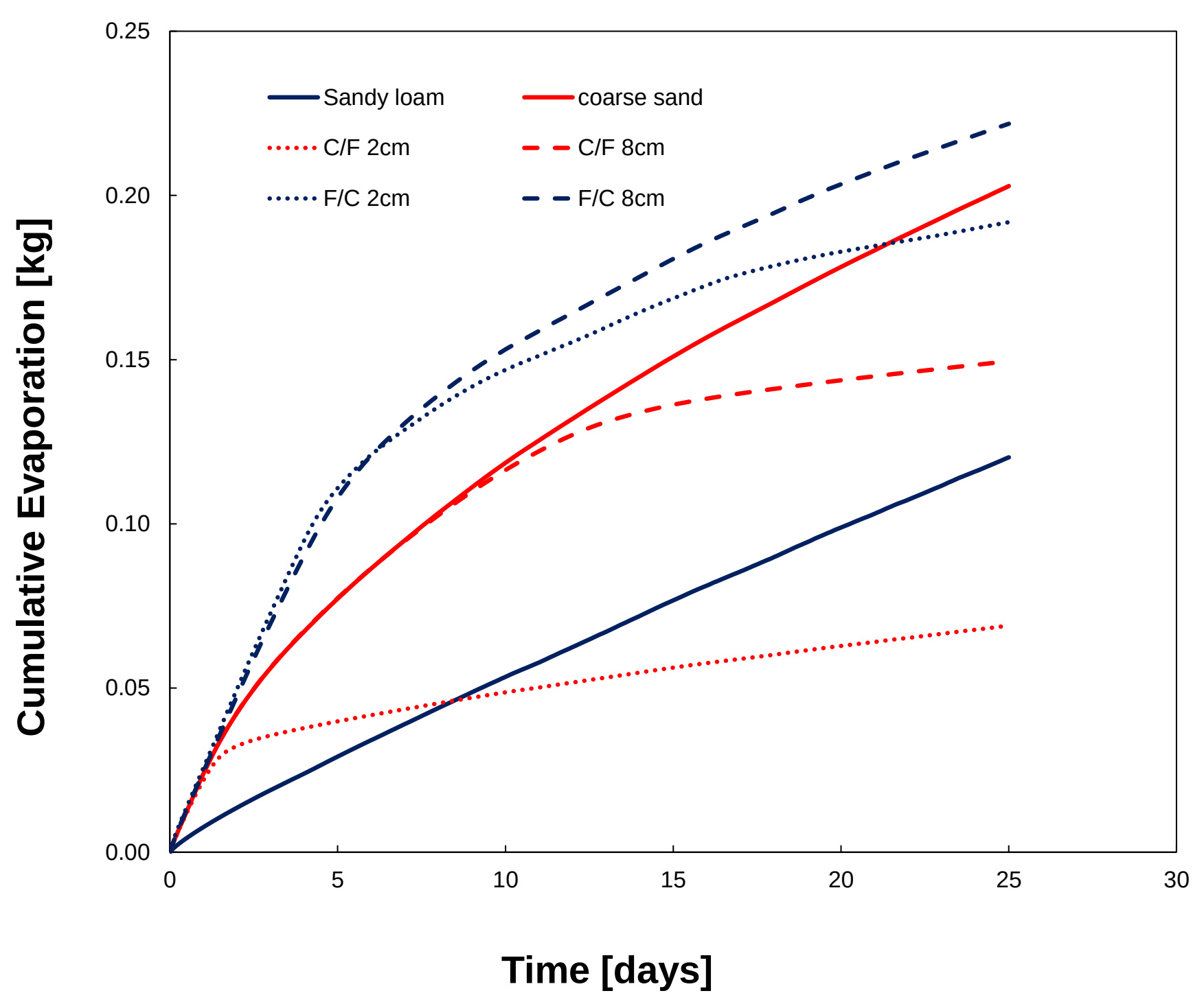


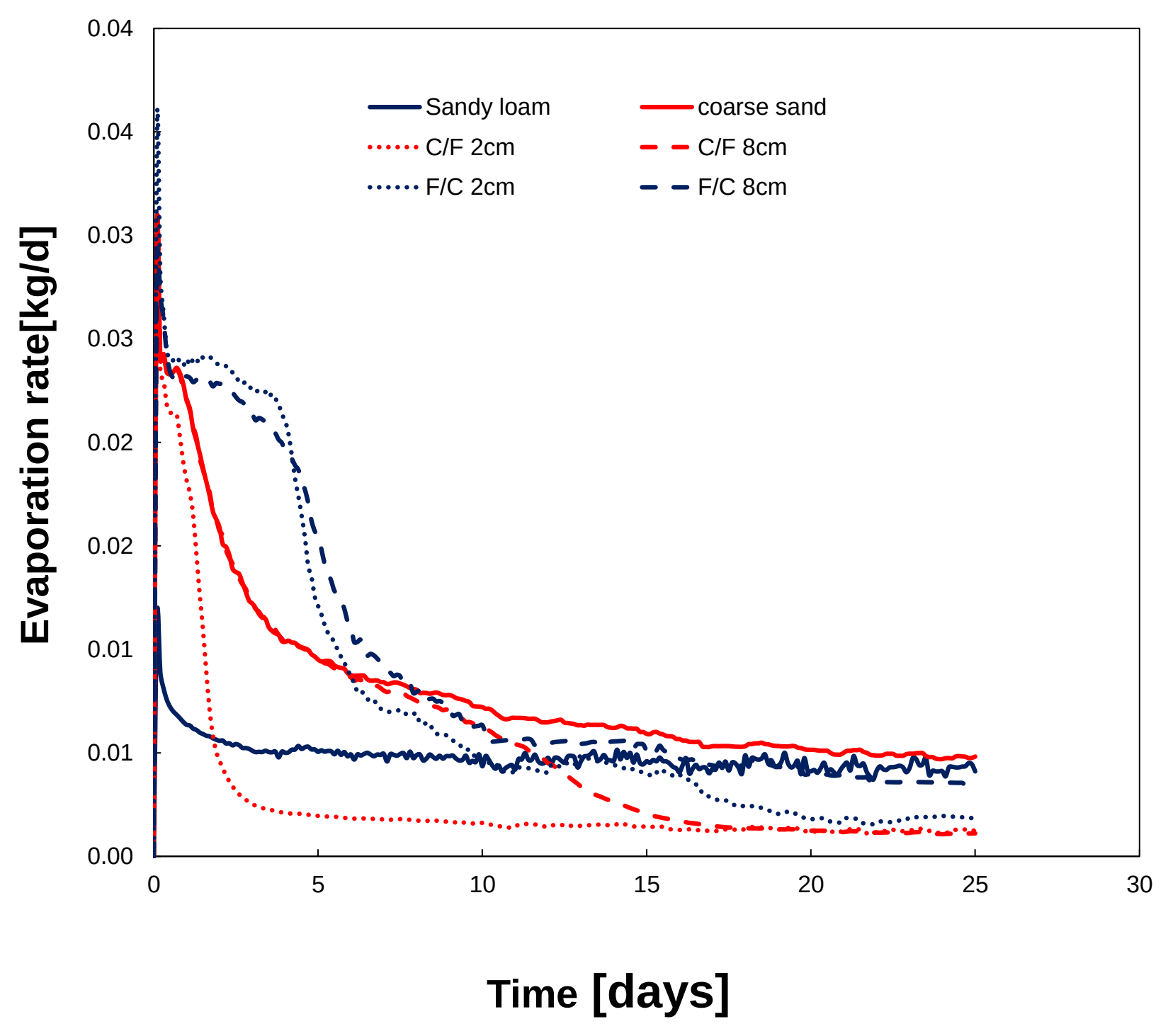
Water content

RESULTS:

- Air invades into the coarse sand first no matter coarse sand is on the top layer or not because of its lower air entry value
- With the coarse sand on the surface, the lower sandy loam soil can keep saturated for a long time.

5. SIMULATION RESULTS





RESULTS:

- The properties of the surface layer has a significant impact on the evaporation.
- The coarse sand on the surface can help reduce evaporation losses because it dries fast and interrupts the hydraulic connections between drying front and atmosphere.

6. CONCLUSIONS

- The properties and thickness of the surface layer have a significant effect on the water content distribution and evaporation behavior.
- The coarse layer on the surface causes evaporation suppression because it cuts the hydraulic connections of the lower soil.
- The evaporation of fine-over-coarse configuration has a longer stage 1 evaporation and higher cumulative evaporation.
- Evaporation occurs at the coarse layer first because of its lower air entry value.
- Additional experimental work needs to be done.

ACKNOWLEDGMENTS

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