# On wettability and unstable flow in porous media


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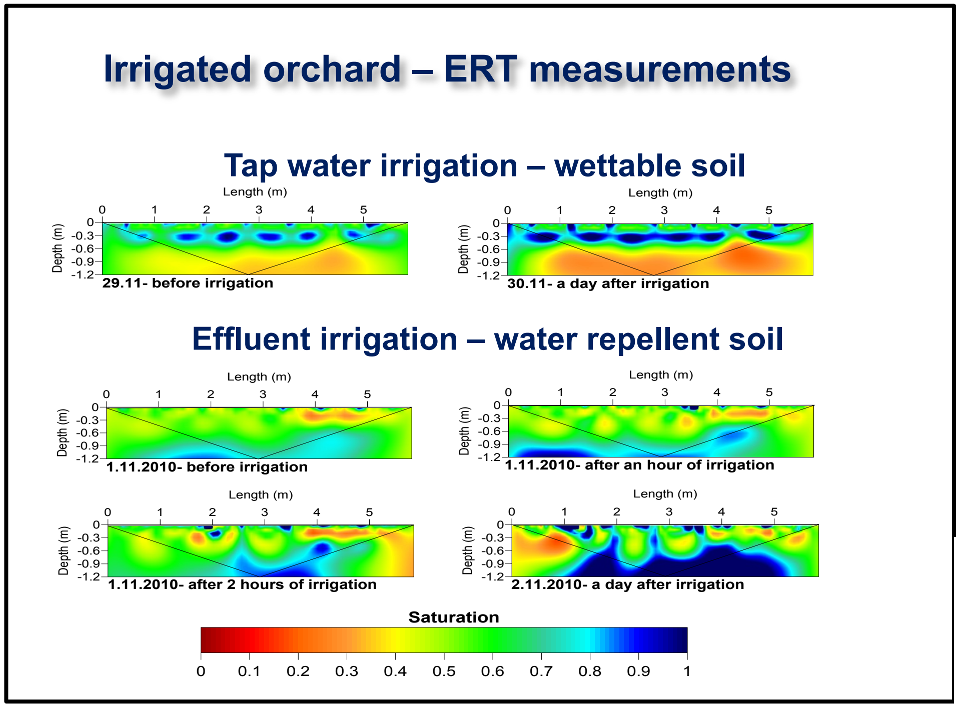
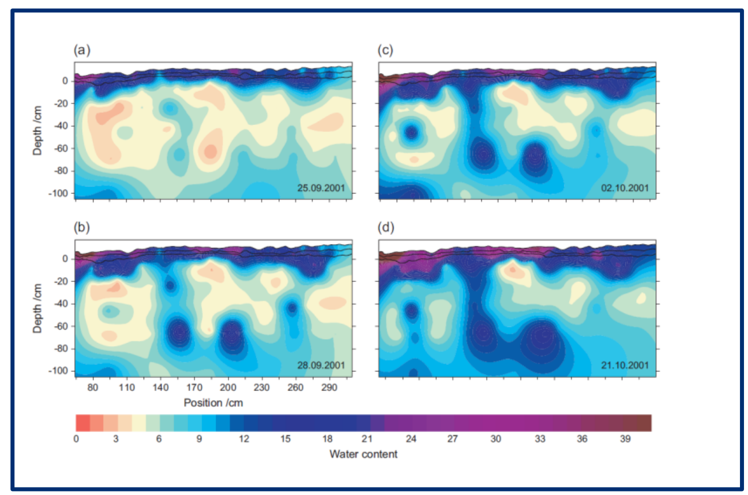
# Preface

- It is well known that flow in water-repellent soils ($\theta \geq 90^0$) takes place in distinct preferential flow pathways.
- Fingering due to unstable flow were also observed in wettable soils.
- The contact angle in wettable soils is normally assumed zero and so do models used to simulate flow in wettable soils.

# Preferential flow in water-repellent soils




Wessolek et al., 2008, EJSS

# Preface

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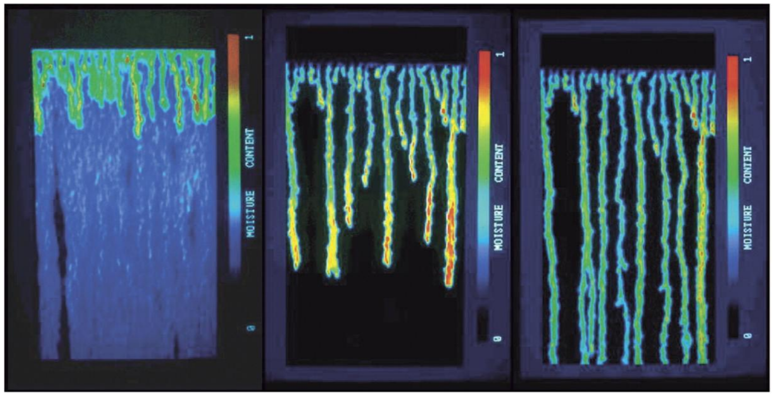
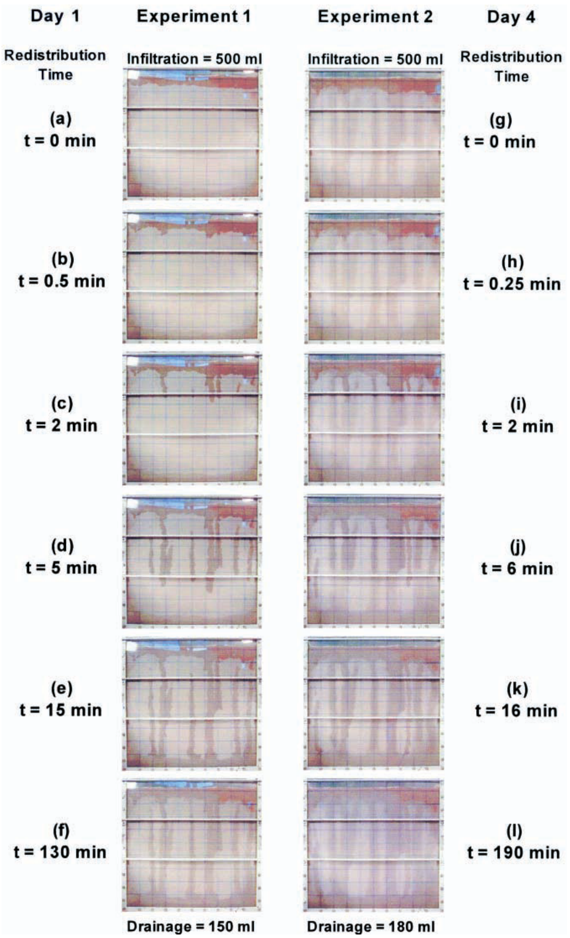


Moisture content visualization of finger formation and persistence in a sand slab (Glass et al., 1989).




Wetting front taken at different times (a–f) during redistribution in dry sand and (g–l) during second cycle of redistribution with fingers in the sand (Wang et al., 2003)

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- Fingering due to unstable flow were also observed in wettable soils.
- Contact angles in wettable soils are normally assumed zero and so do models used to simulate flow in thesee soils.

# Ensuing questions

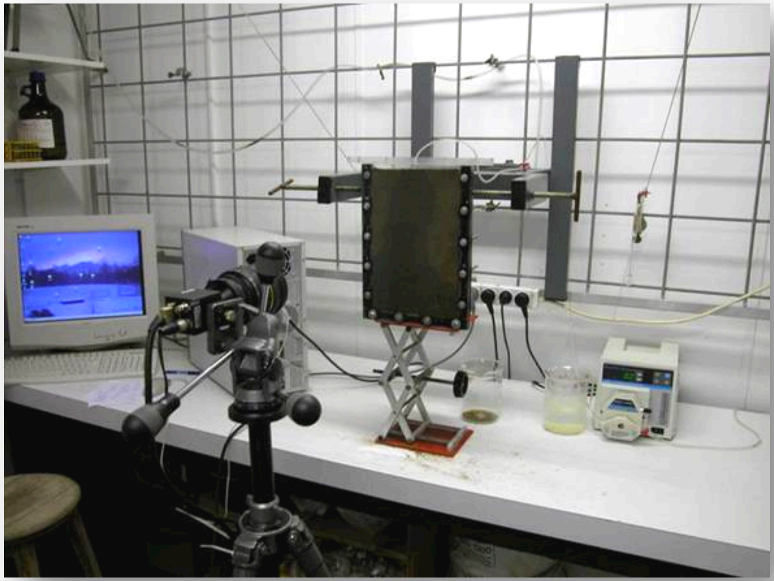
- Does finger generation and persistence controlled by the contact angle $0^o<\theta<90^o$ between the water and soil (sub-critical repellent soils)?
- If yes, how do fingers formed and expand in these media ?

# Experiments setup

## Materials

- Model substrates: modified and un-modified 0.3-0.5 mm quartz dune sand. The modification of the quartz particles was obtained by silylation which induces stable contact angles of varying degrees (S100 – $35^0$, S450 – $48^0$, S1000 – $56^0$, and S1500 – $73^0$).
- Sandy soil from Safariya Citrus Orchard (sieved to <0.5 mm) that rendered water repellent by prolonged irrigation with treated wastewater

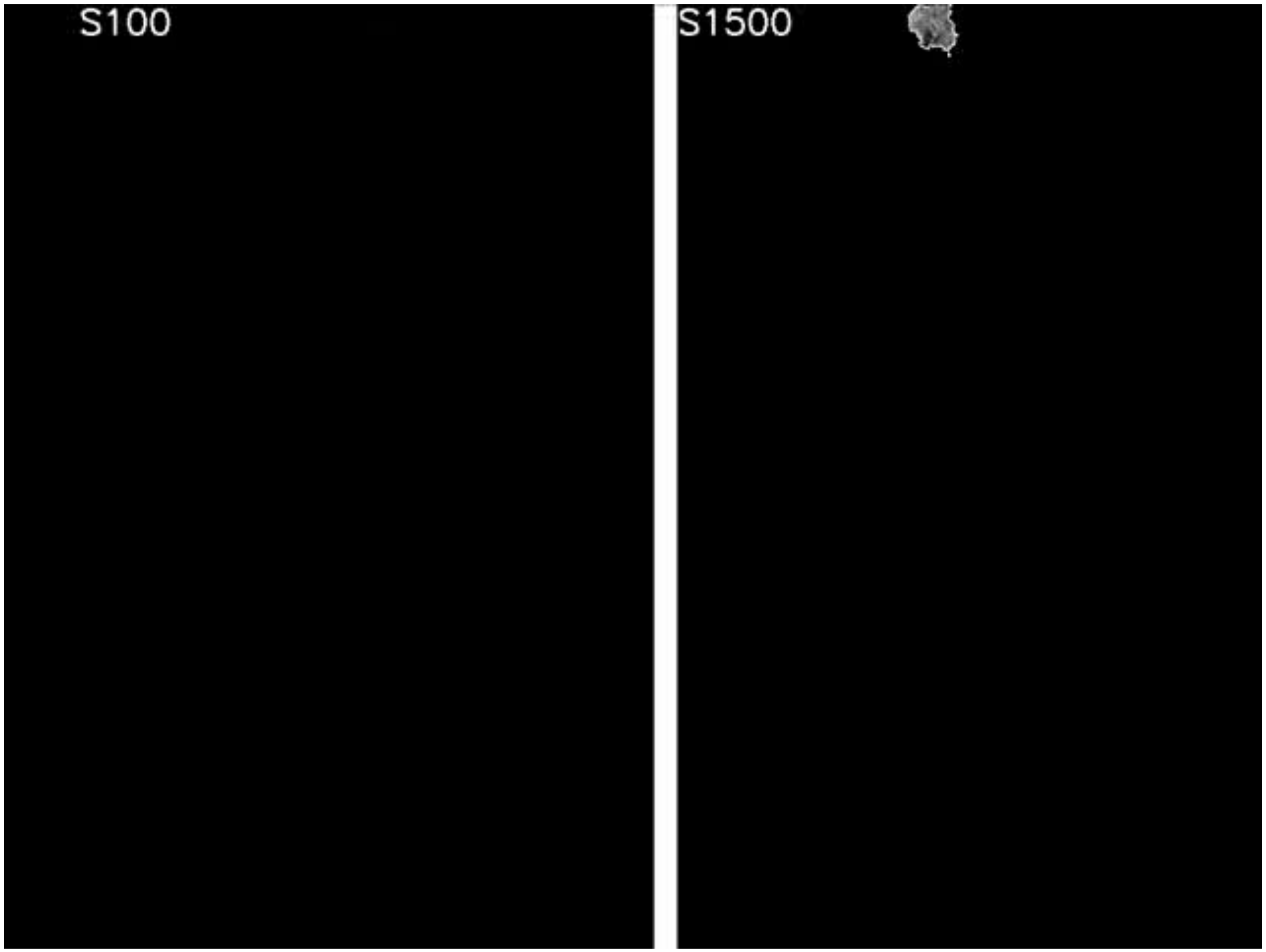
# Flow chamber and a CCD camera



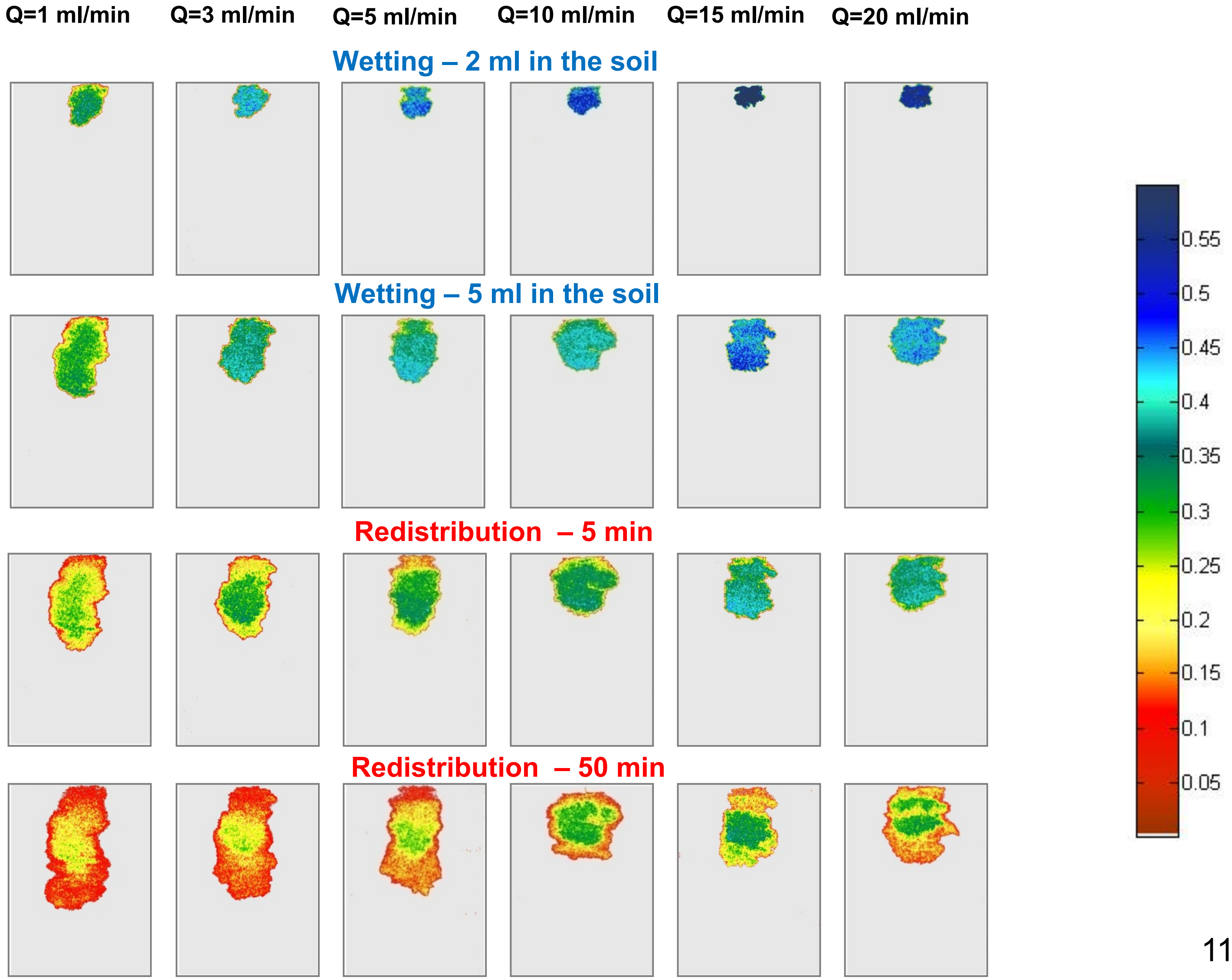
- Transparent flow chamber, 25-cm high, 15-cm wide, and 0.5-cm thick (inner dimensions) for the quartz runs and 32.5-cm high, 30-cm wide, and 0.8-cm thick (inner dimensions) for the repellent soil runs.
- CCD camera (1920 × 1080 pixels, 8 fps).
- Water was applied at different rates to the soil surface as a point source; 5 ml for the quartz and 60 ml for the repellent soil.

# Flow chamber runs

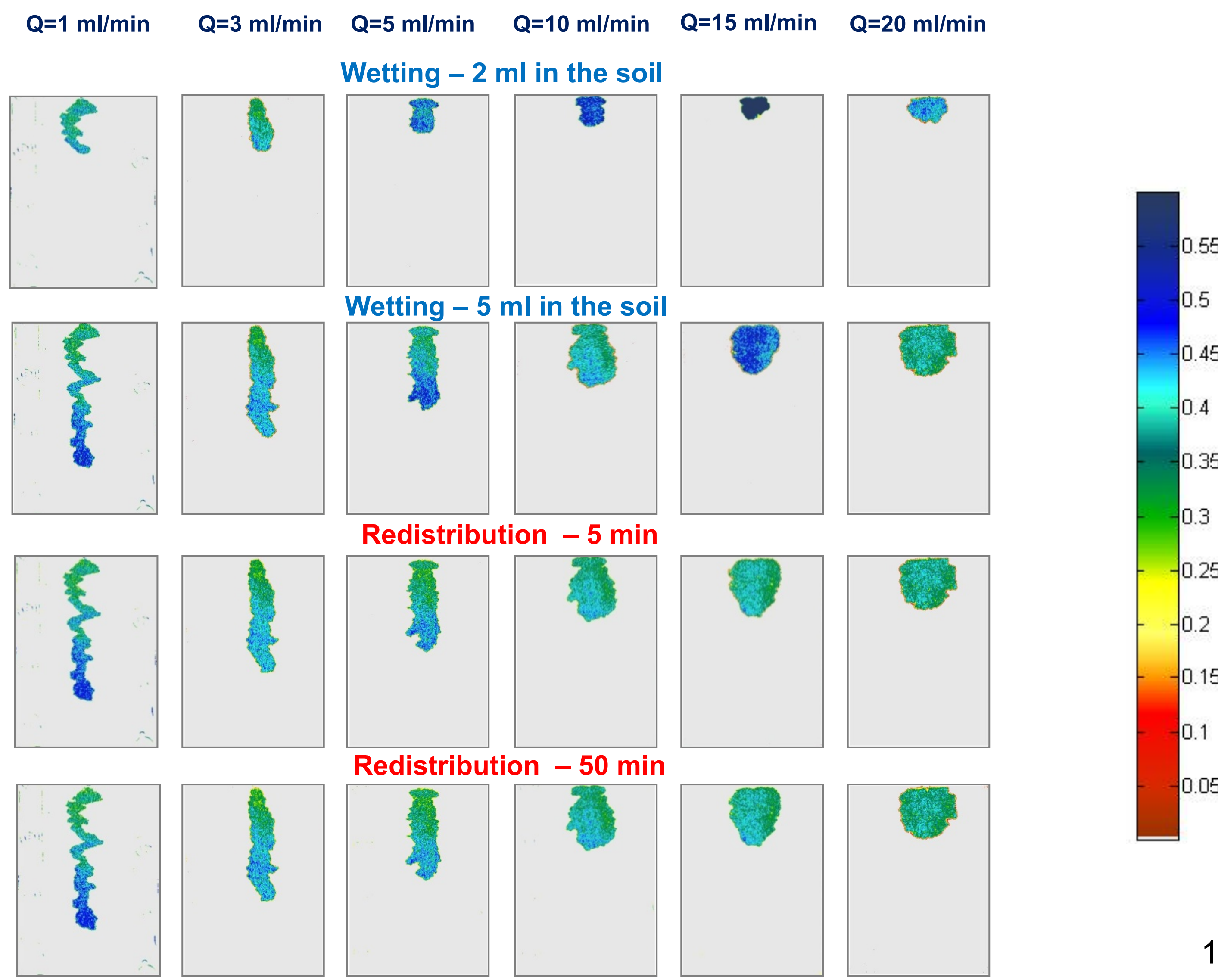
## 1 ml/min



# S-100 ($\theta \approx 33^0$)



# S-1500 ($\theta \approx 75^0$)



# S-100 ($\theta \approx 30^0$) and S-1500 ($\theta \approx 75^0$)

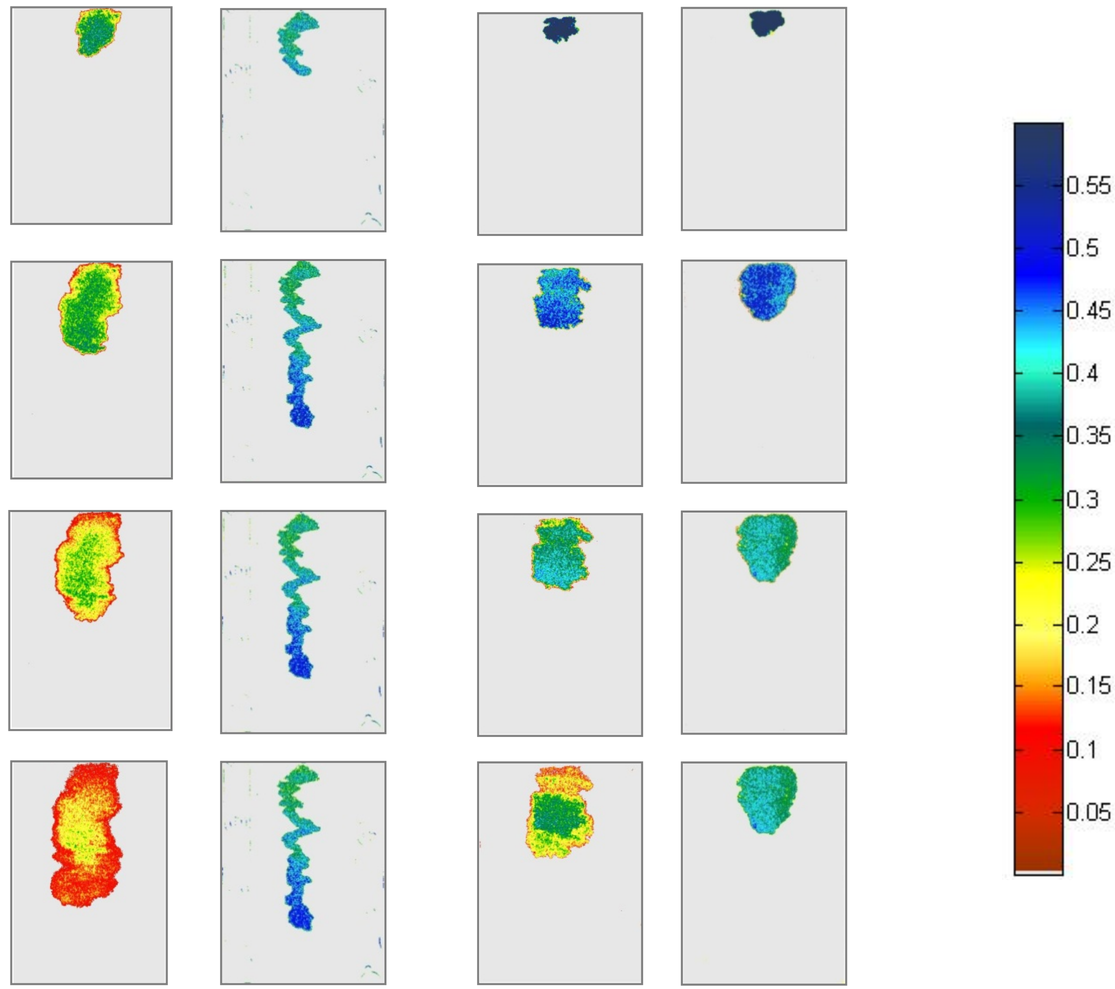
S100 Q=1 ml/min | S1500 Q=1 ml/min | S100 Q=15 ml/min | S1500 Q=15 ml/min

Wetting – 2 ml in the soil

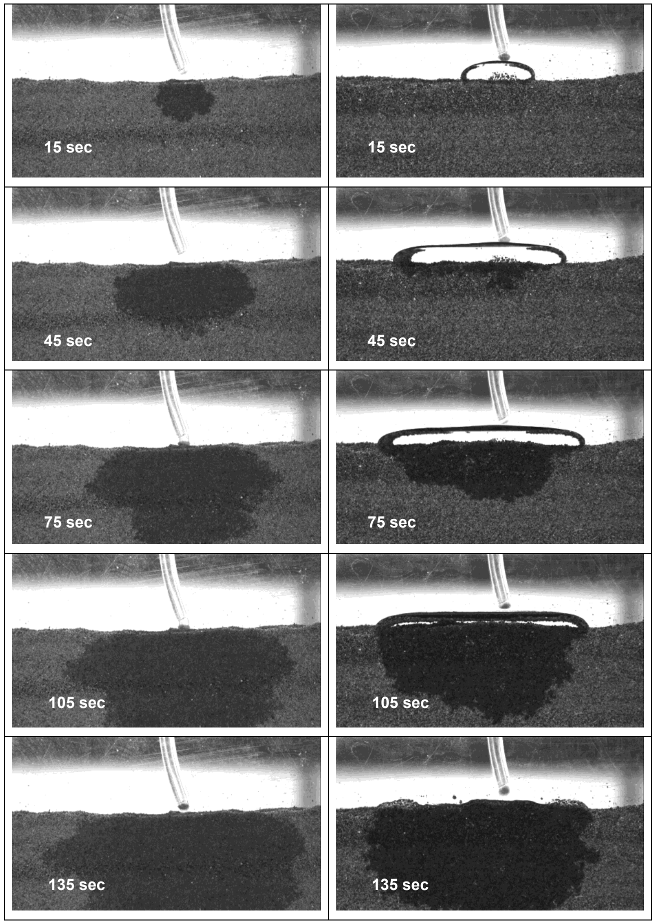
Wetting – 5 ml in the soil

Redistribution – 5 min

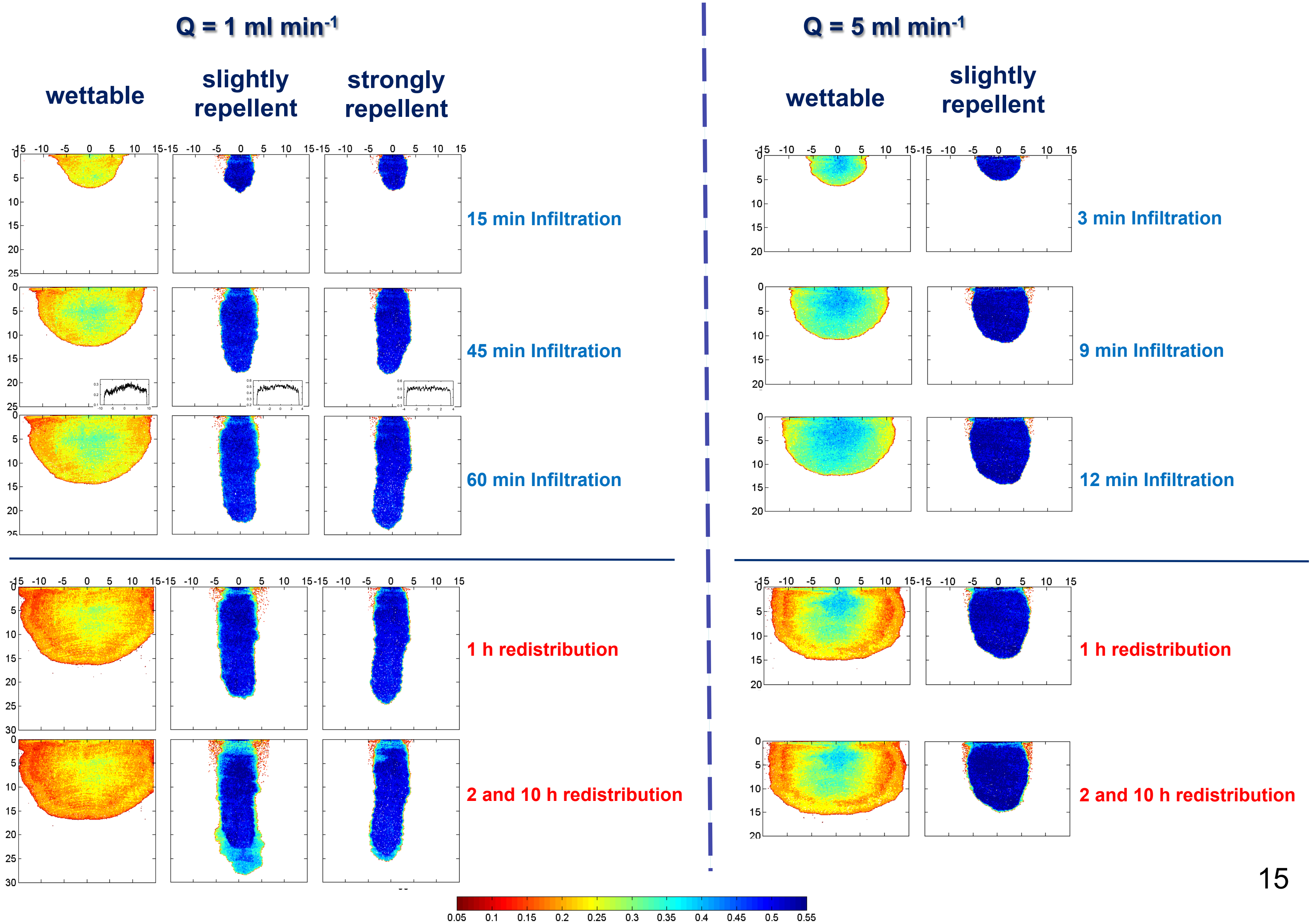
Redistribution – 50 min



# Infiltration to wettable and water repellent soils

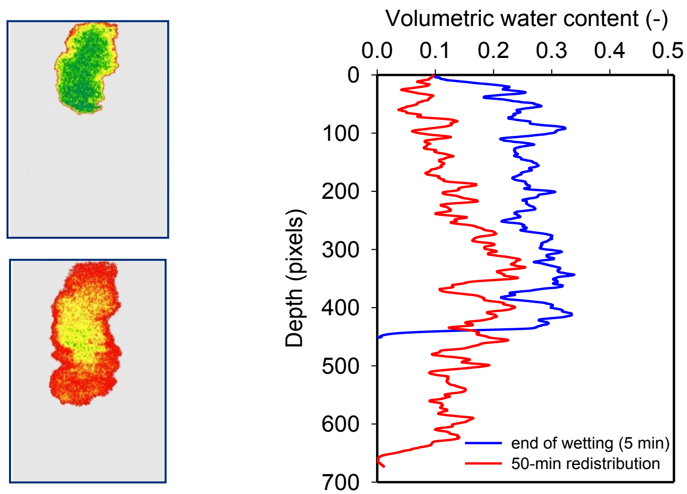


# Flow chamber study for wettable and water repellent soils (Xiong, Furman, Wallach, 2012)



# Vertical cross-section along the plumes' center

**S100 1ml/min**

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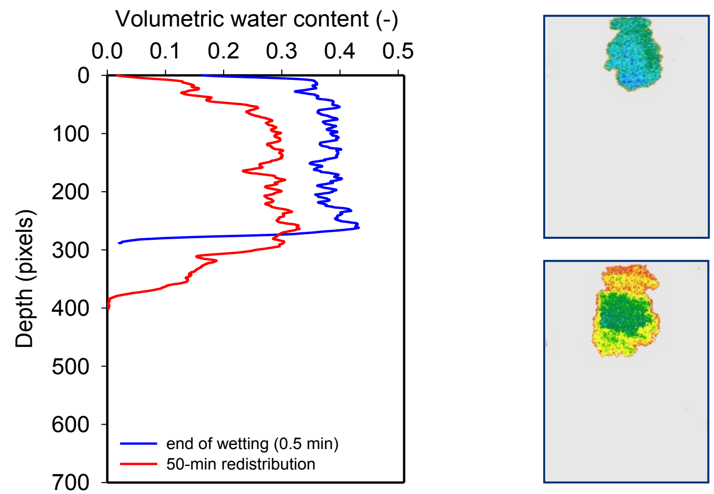
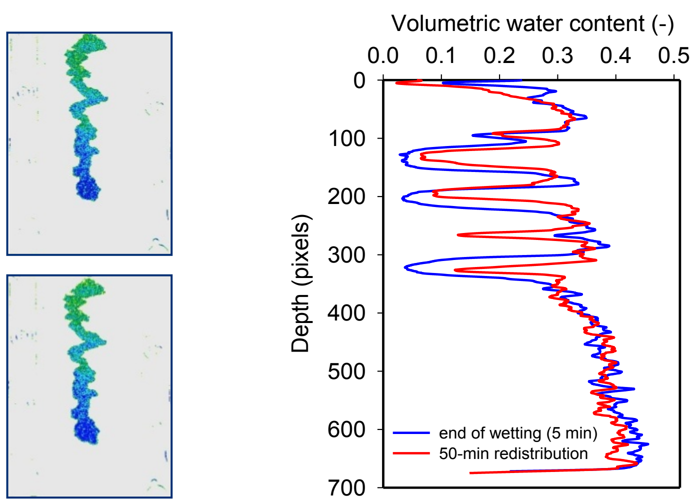
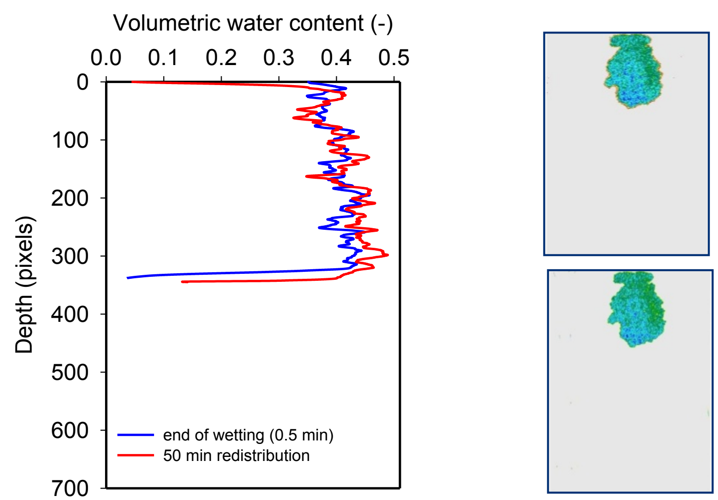



**S1500 1ml/min**




**S1500 10 ml/min**



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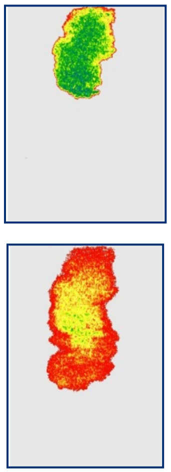

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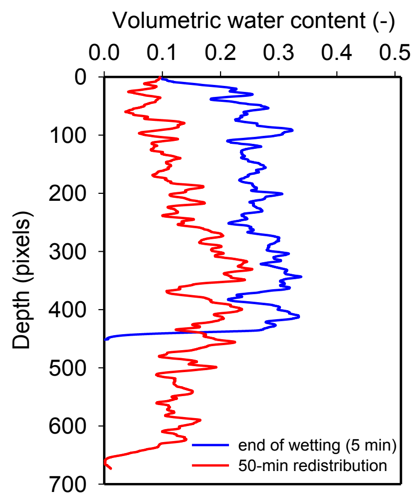


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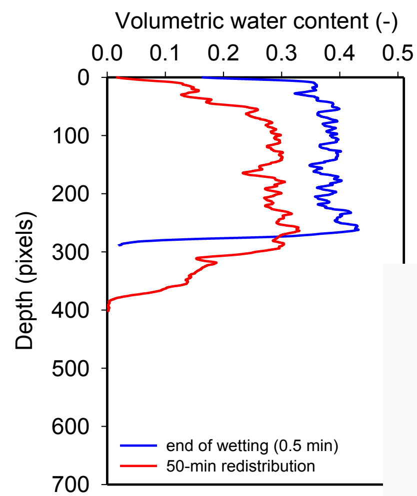
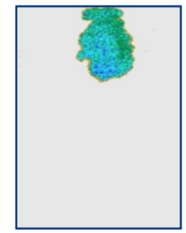
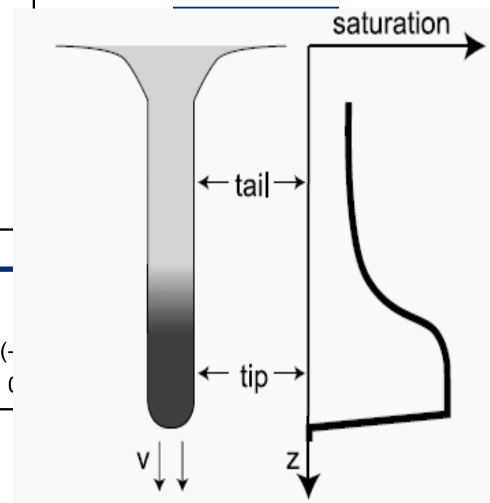
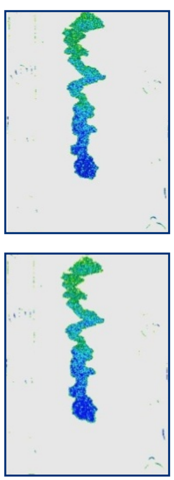





Cartoon of a preferential flow path and the associated saturation within the flow path. Saturation overshoot occurs when the tip saturation is greater than the tail saturation.



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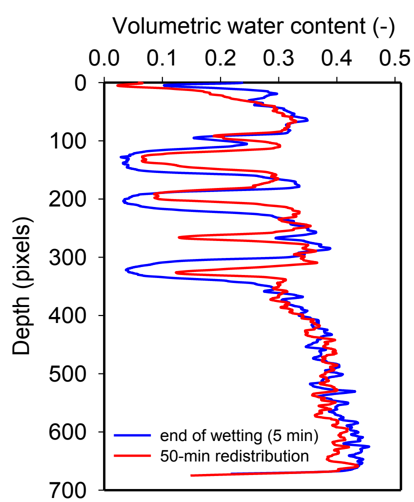


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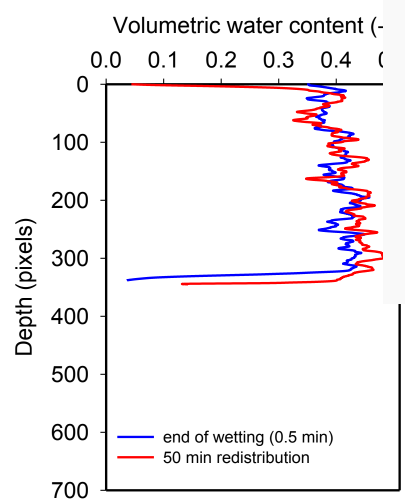


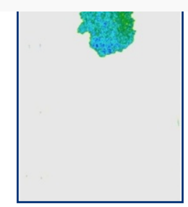

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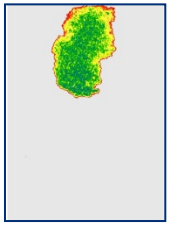
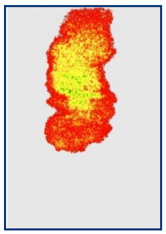
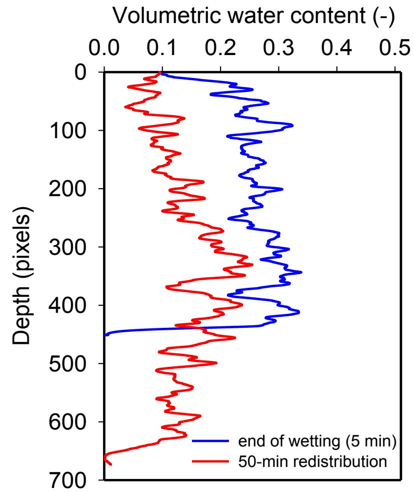
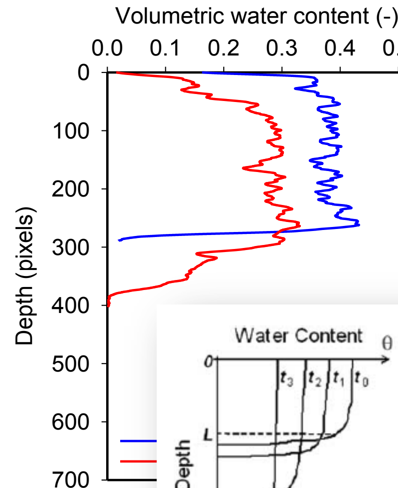
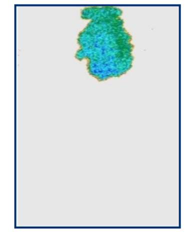
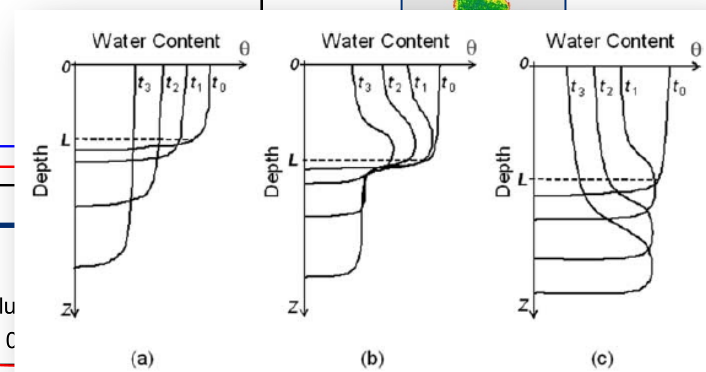
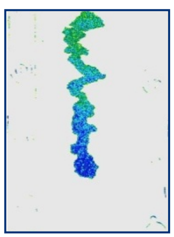
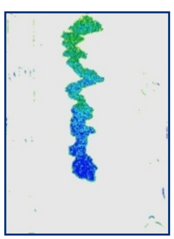
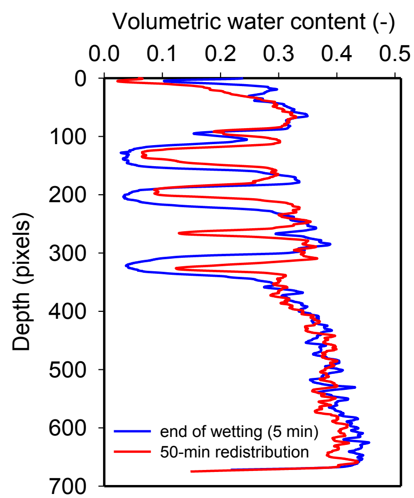
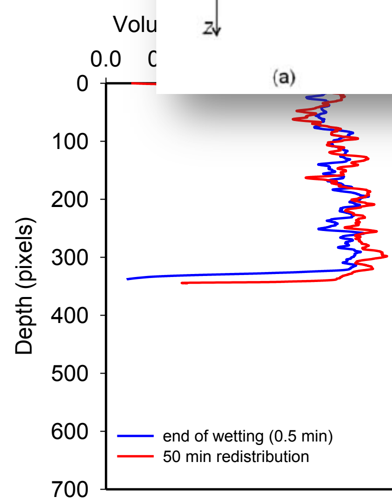




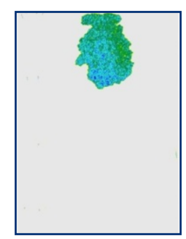




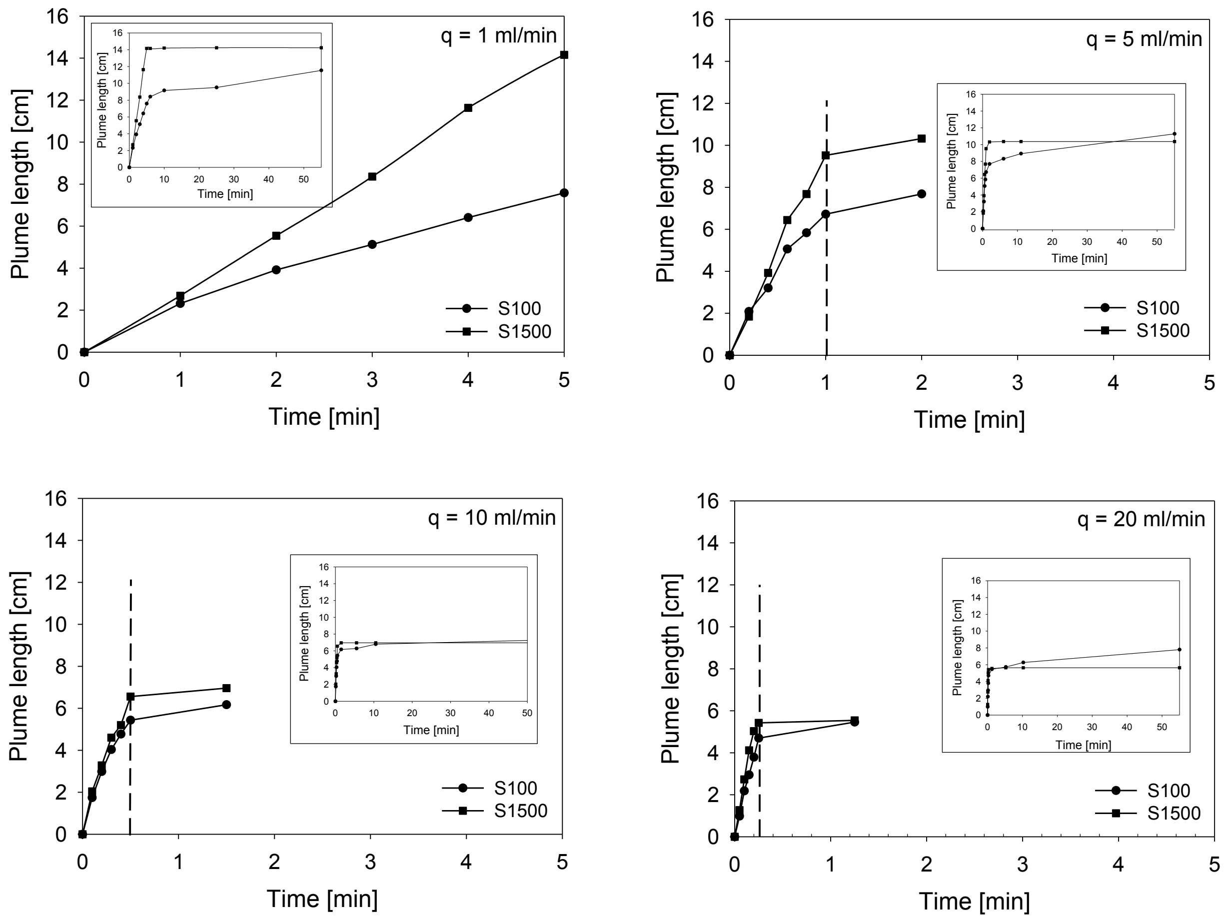


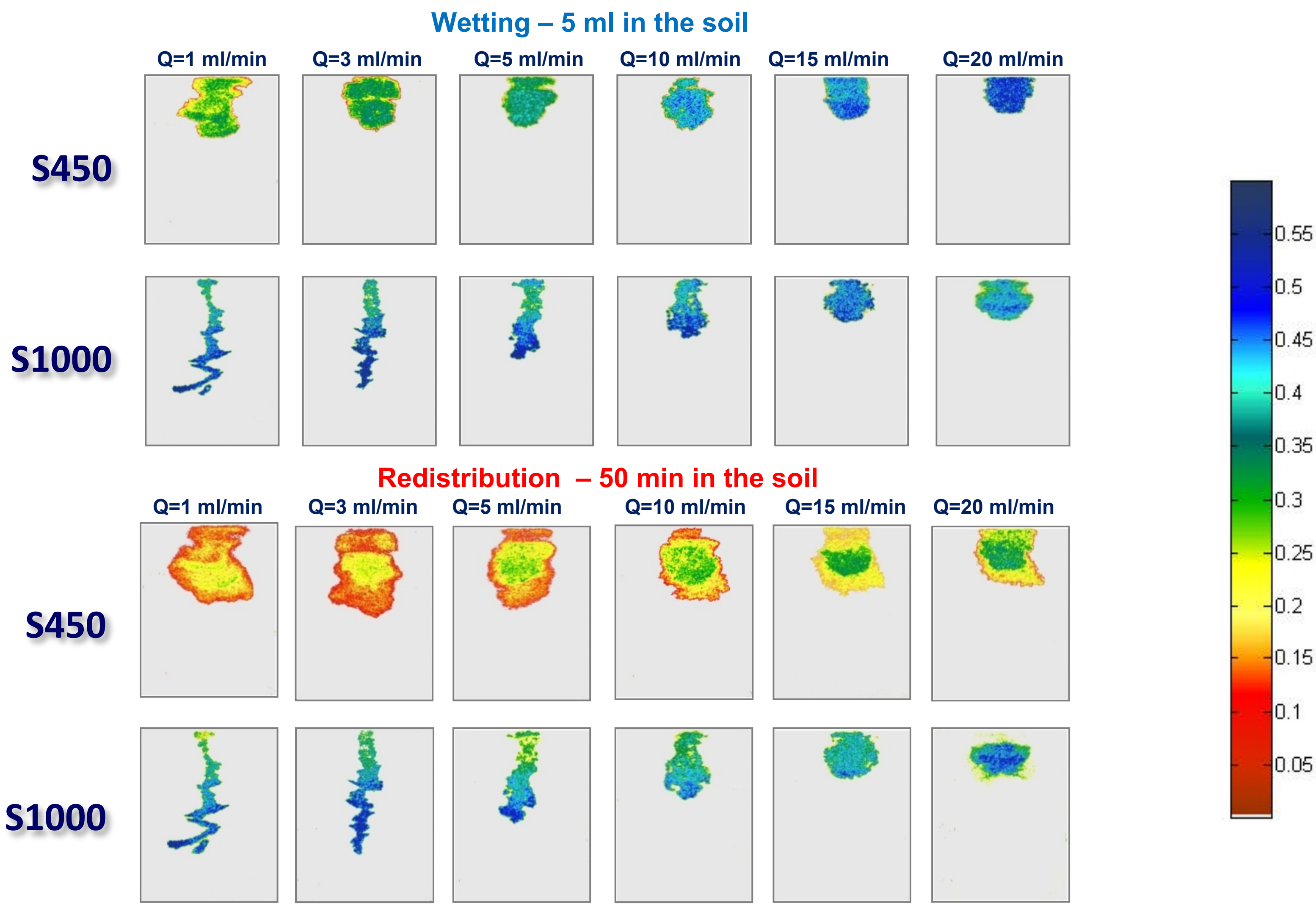


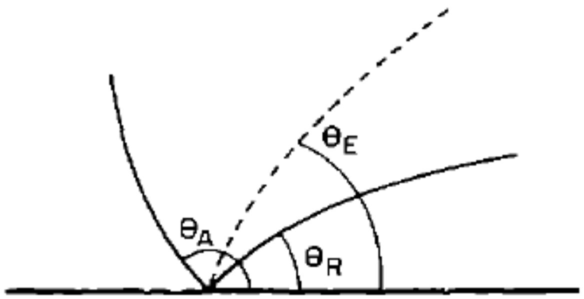


# Plumes elongation during wetting and redistribution



# S-450 ($\theta \approx 48^0$) and S-1000; $\theta \approx 56^0$





(b) Contact angle hysteresis at a rough surface

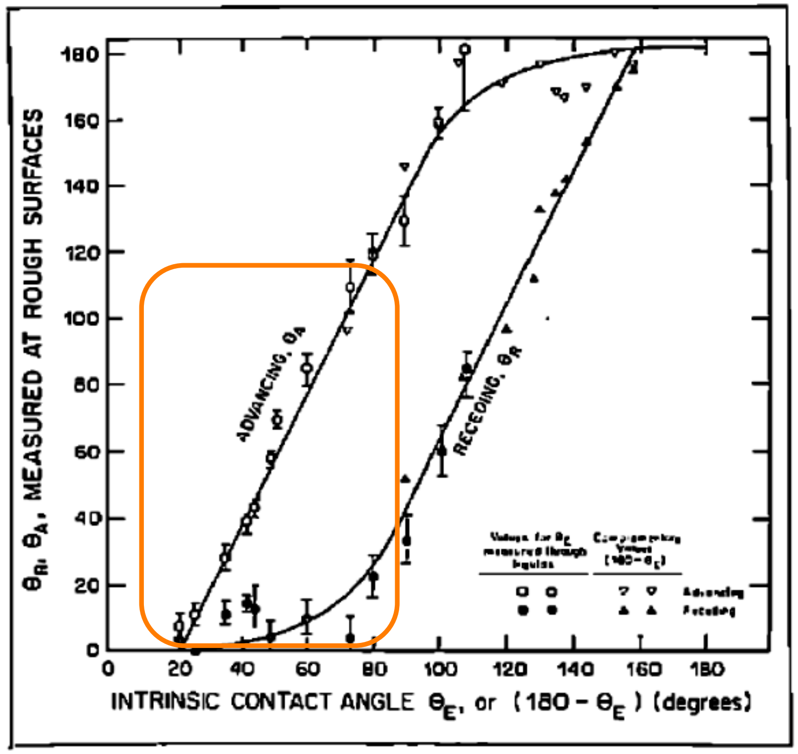
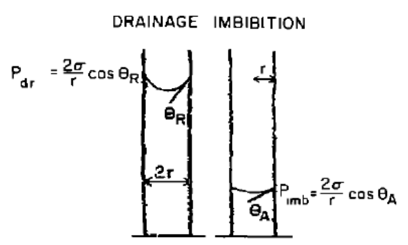
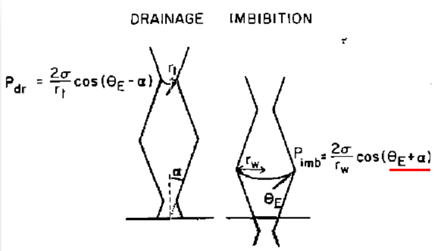



FIGURE 3 — Values of advancing ($\theta_A$) and receding ($\theta_R$) contact angles observed at rough surfaces[5], versus intrinsic contact angle, $\theta_E$.

From: Morrow, 1976




*(c) Hysteresis in capillary rise due to contact angle hysteresis.*




*(e) Hysteresis in capillary rise with interaction of contact angle and pore geometry in absence of contact angle hysteresis.*

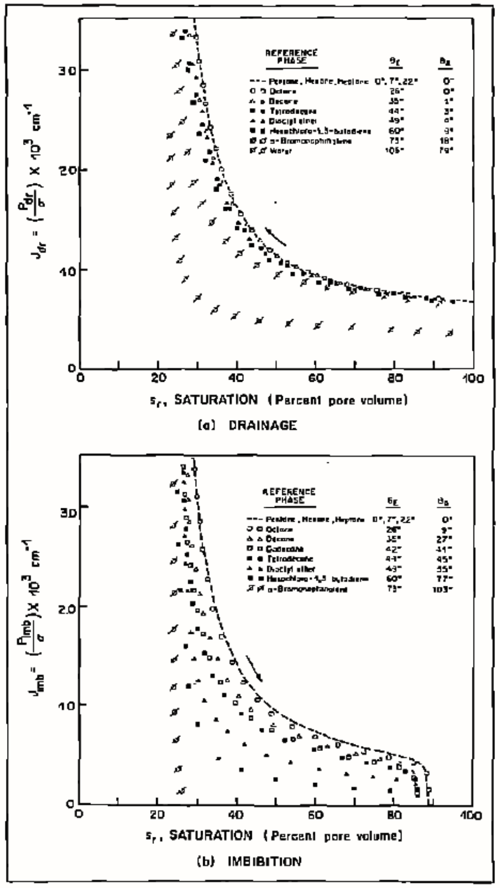



FIGURE 4 — Effect of contact angle on capillary pressure, core No. 1.

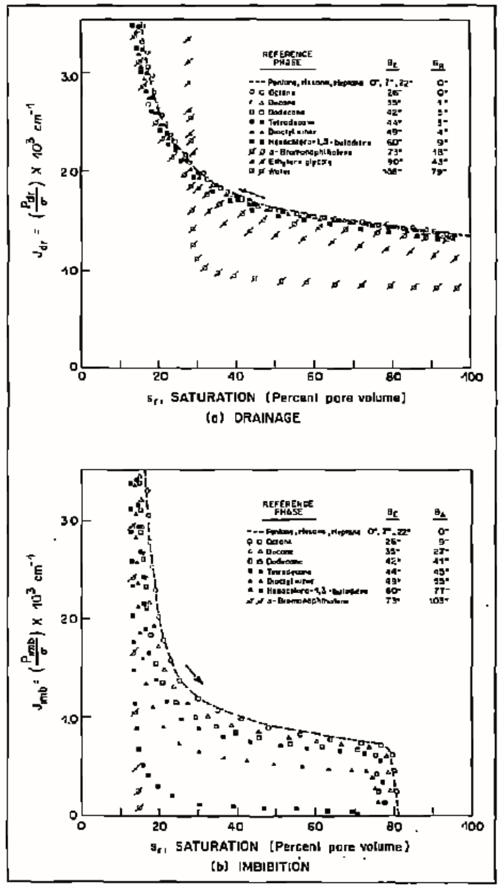



FIGURE 5 — Effect of contact angle on capillary pressure, core No. 2.

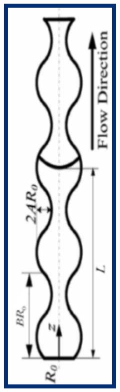
Morrow, 1976

$u$)

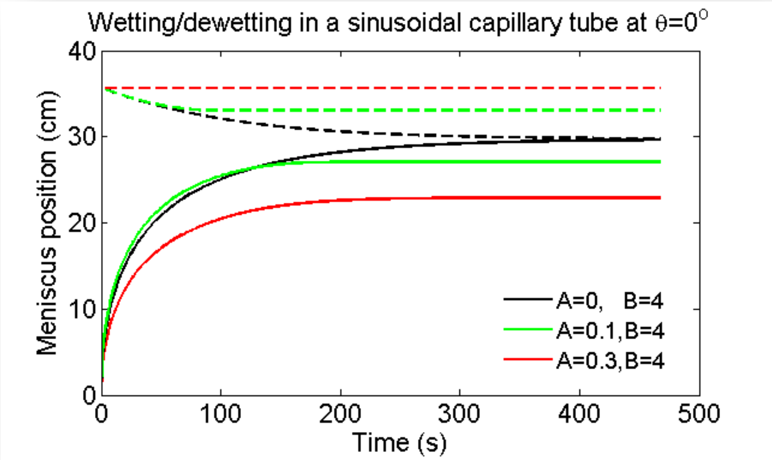
# The "bundle of capillaries" model

*Editor's note: Equations removed at request of author.*

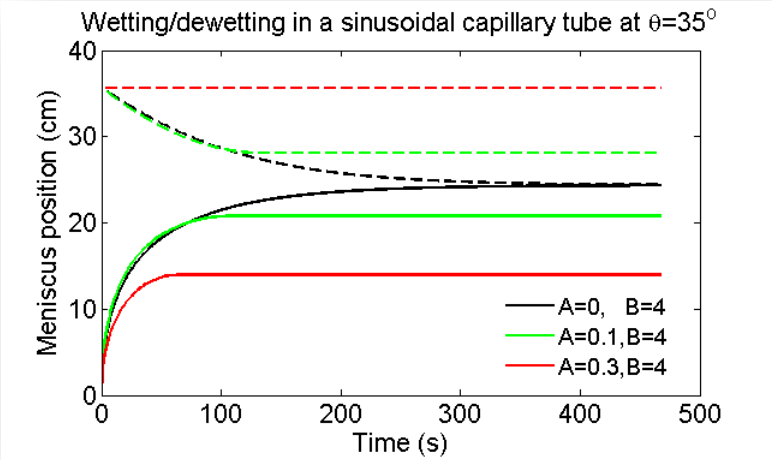
# Hysteresis due to capillary wetting and dewetting - geometry and CA effects




$\theta = 0^0$

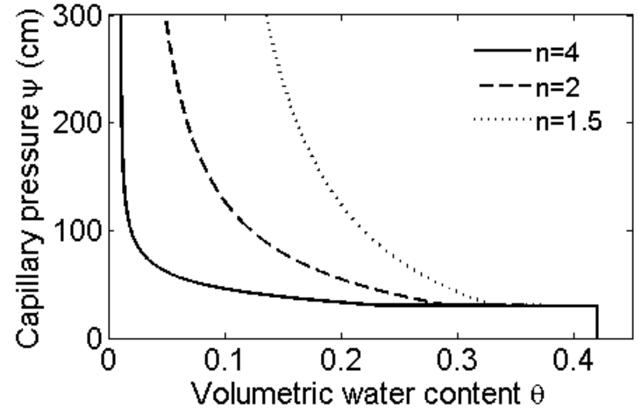


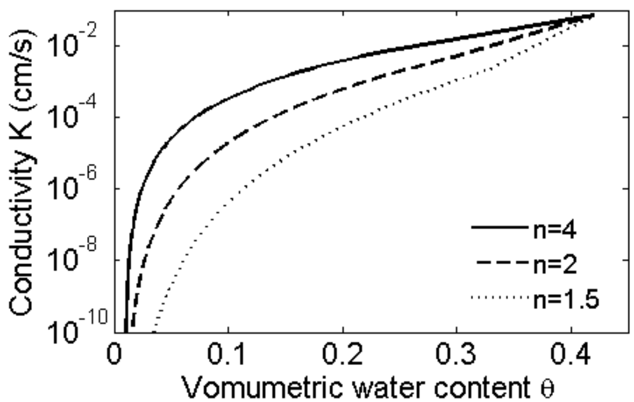

$\theta = 35^0$

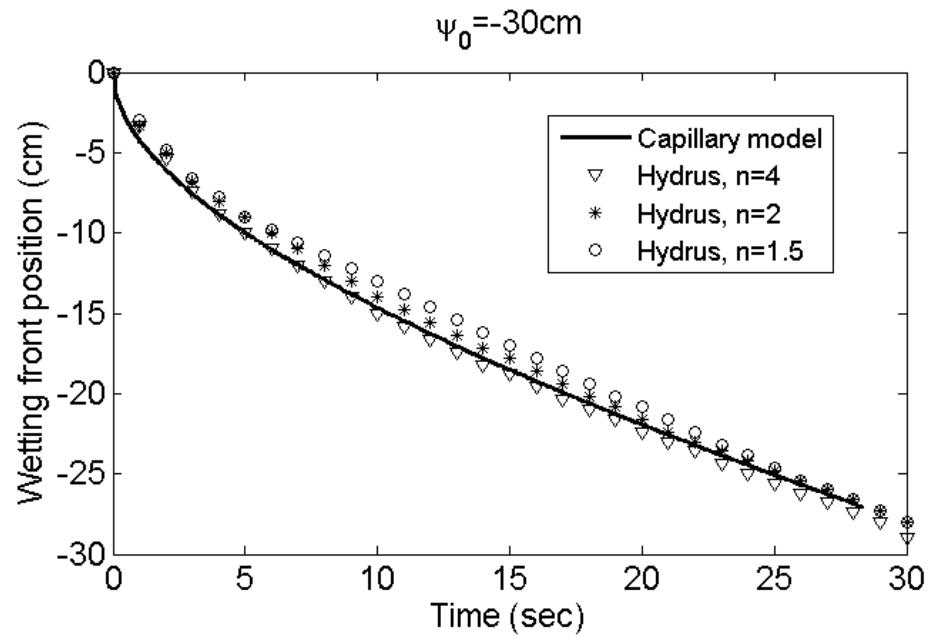



$$R(z) = R_0\left[1 + A\sin(2\pi z / BR_0)\right]$$

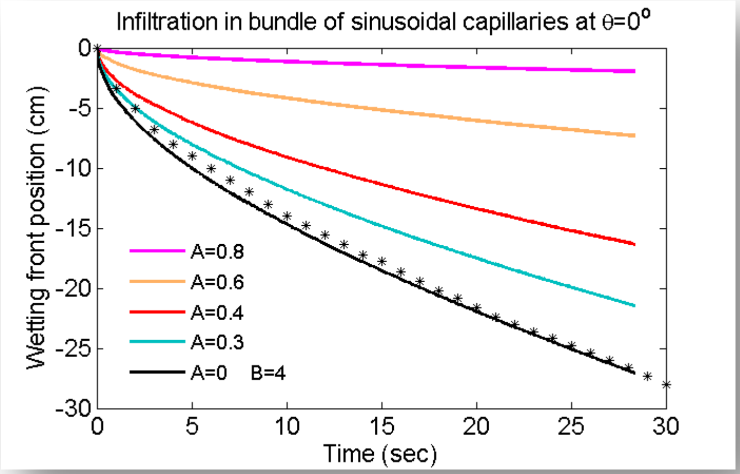
# The use of the capillary-bundle model for water flow in soil



# Pore geometry and contact angle effects on the wetting front deceleration



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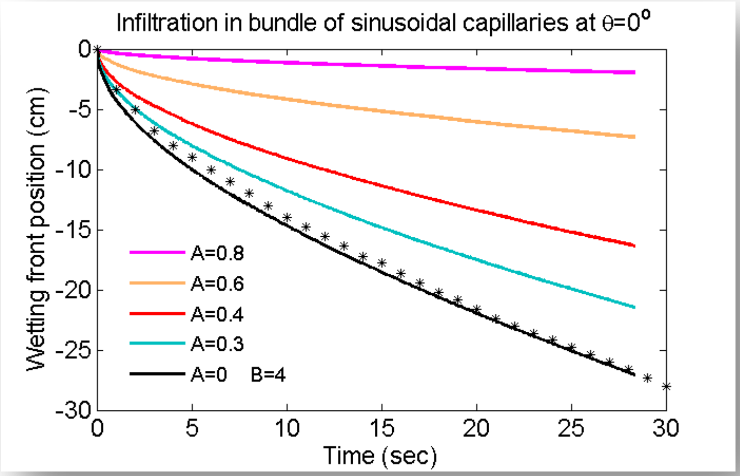


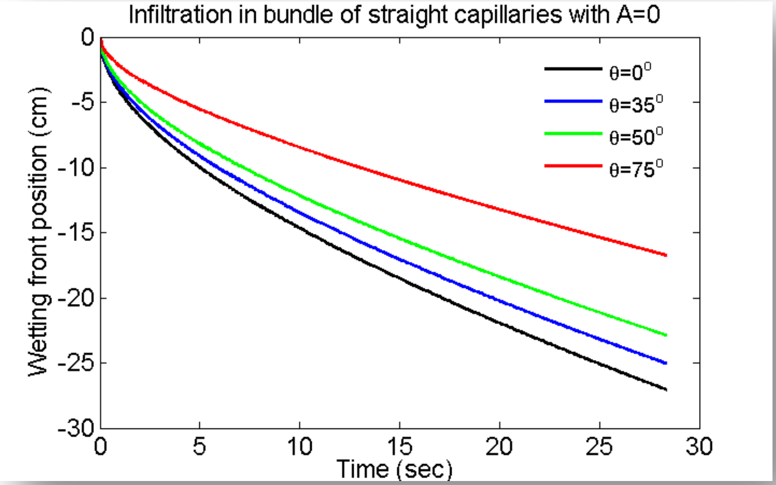

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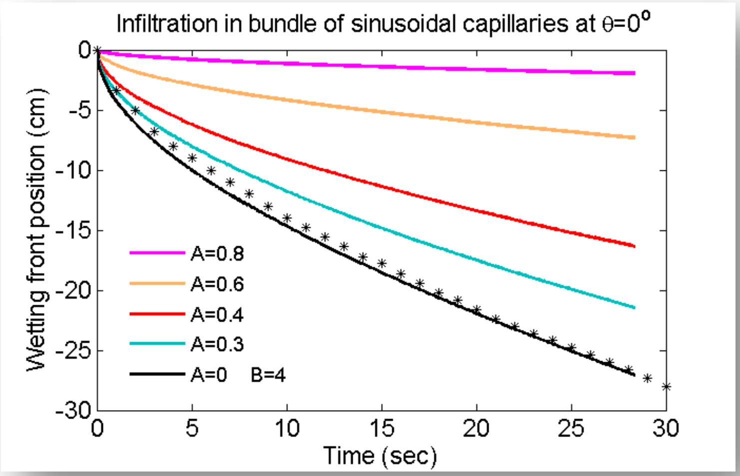


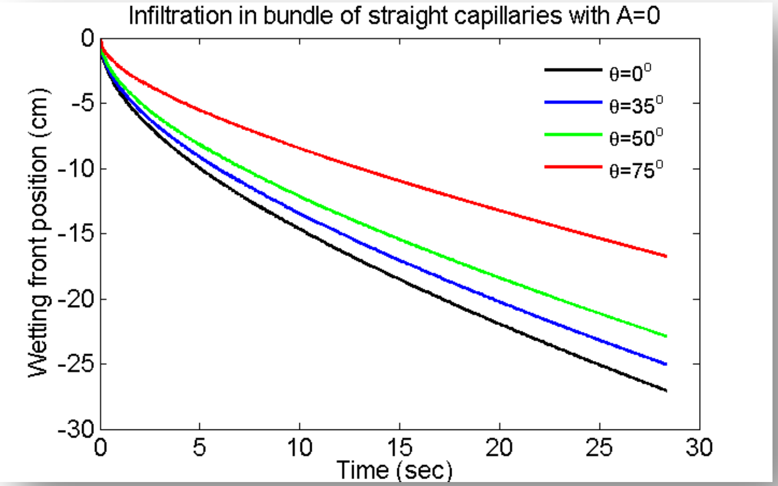


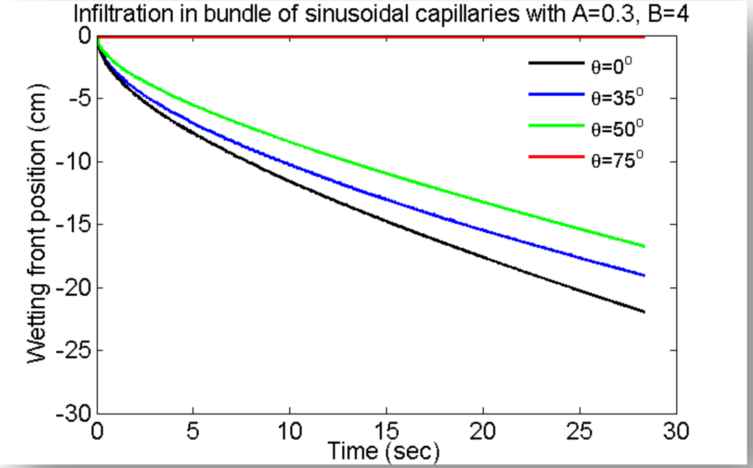

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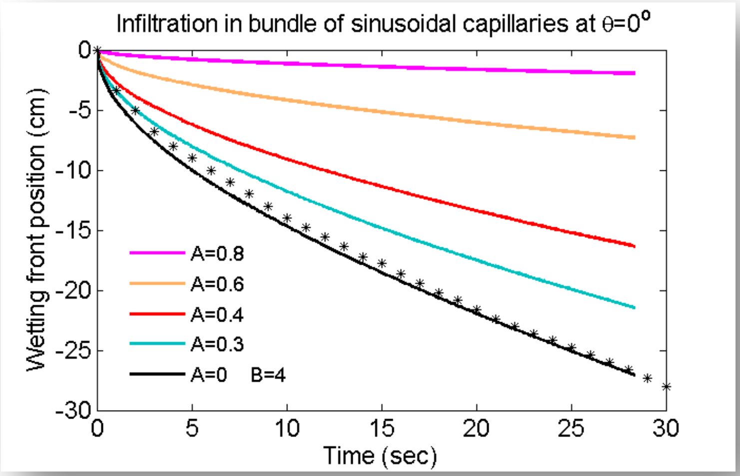
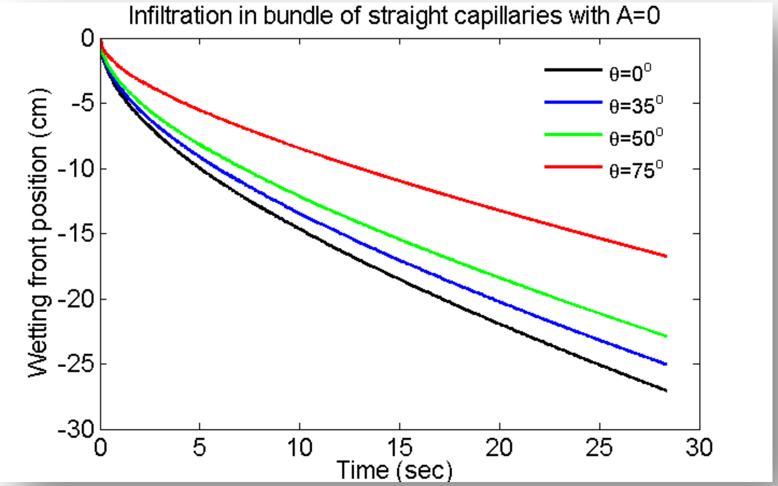
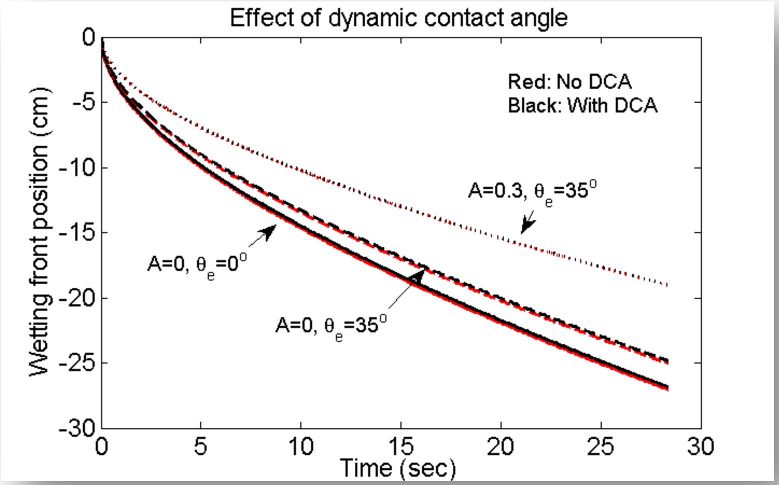
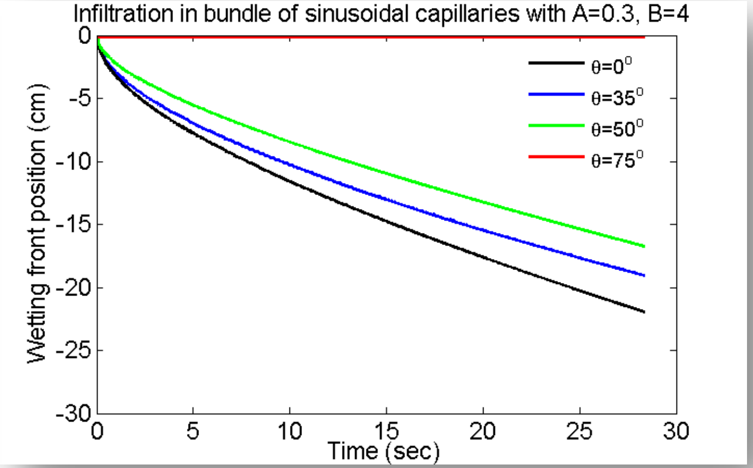


# Saturation overshoot

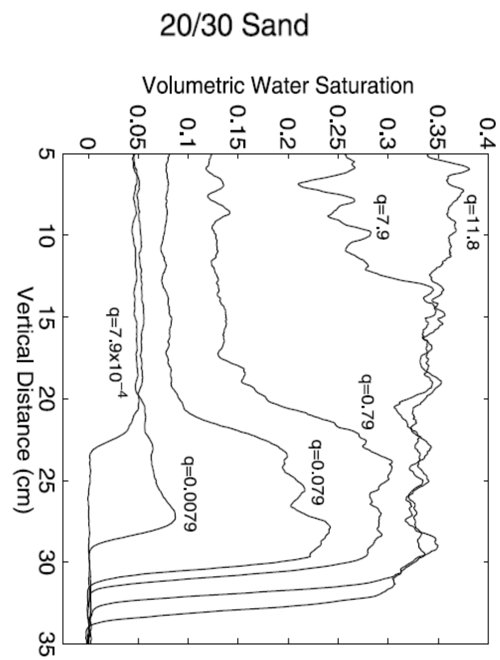



**Figure 5.** Snapshots of the saturation profile versus depth for six different applied fluxes in initially dry 20/30 sand (Accusand) measured using light transmission. At the highest (11.8 cm/min) and lowest ($7.9 \times 10^{-4}$ cm/min) fluxes the profiles are monotonic with distance and no saturation overshoot is observed, while all of the intermediate fluxes exhibit saturation overshoot.

DiCarlo et al, 2010

## Conclusions

- Does finger generation and persistence controlled by the contact angle $0^o<\theta<90^o$ between the water and soil (sub-critical repellent soils)?

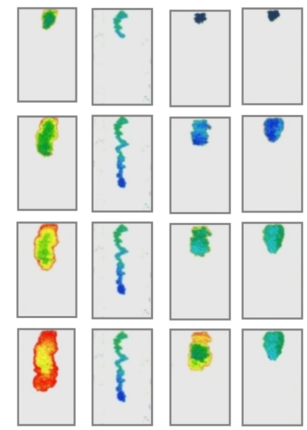
***Yes. The plumes turned to be narrow and longer with saturation overshoot behind the wetting front as contact angle increases.***

- If yes, how do fingers formed and expand in these media ?

***Contact angles increase the water entry value along the finger perimeter which hinders plume's spontaneous propagation. As such, water accumulates behind the wetting front owing to a negative balance between the hindered wetting front propagation and the continuing water influx. Pressure is building up behind the wetting front and increases the weting front velocity until a balance between the out- and influx is reached yielding a constant propagation velocity.***

***Higher application rates increase the pressure at the lateral wetting front of the plume which extends its expansion (dynamic water entry value).***

# Thanks



**Contribution:** *Michal Margolis*
*Qiuling Wang*
*Dr. Yunwu Xiong*
*Dr. Ellen Graber*