



X-ray Computed Tomography-informed models of preferential macropore flow in soils.

Hamza Chaif, François Lafolie, Chloé Caurel, Stéphane Sammartino, Nicolas Beudez,
Anne-Sophie Lissy, Stéphane Ruy, Nathalie Moitrier, **Eric Michel**

Context

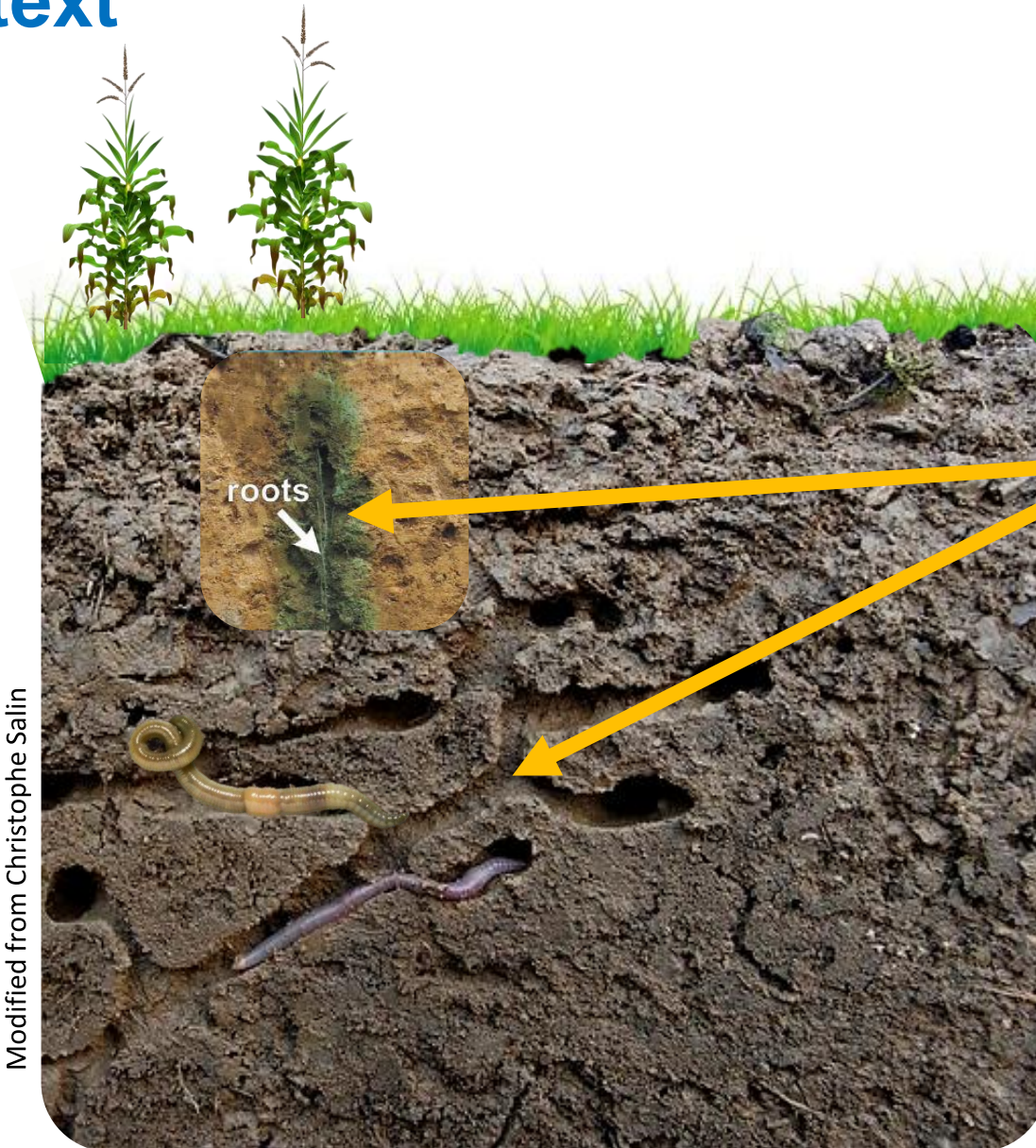


Modified from Christophe Salin

● Earthworms and plants

- contribute to regulation of water fluxes
- ↗ availability of nutrients
- ↗ stability of soil structure

Context



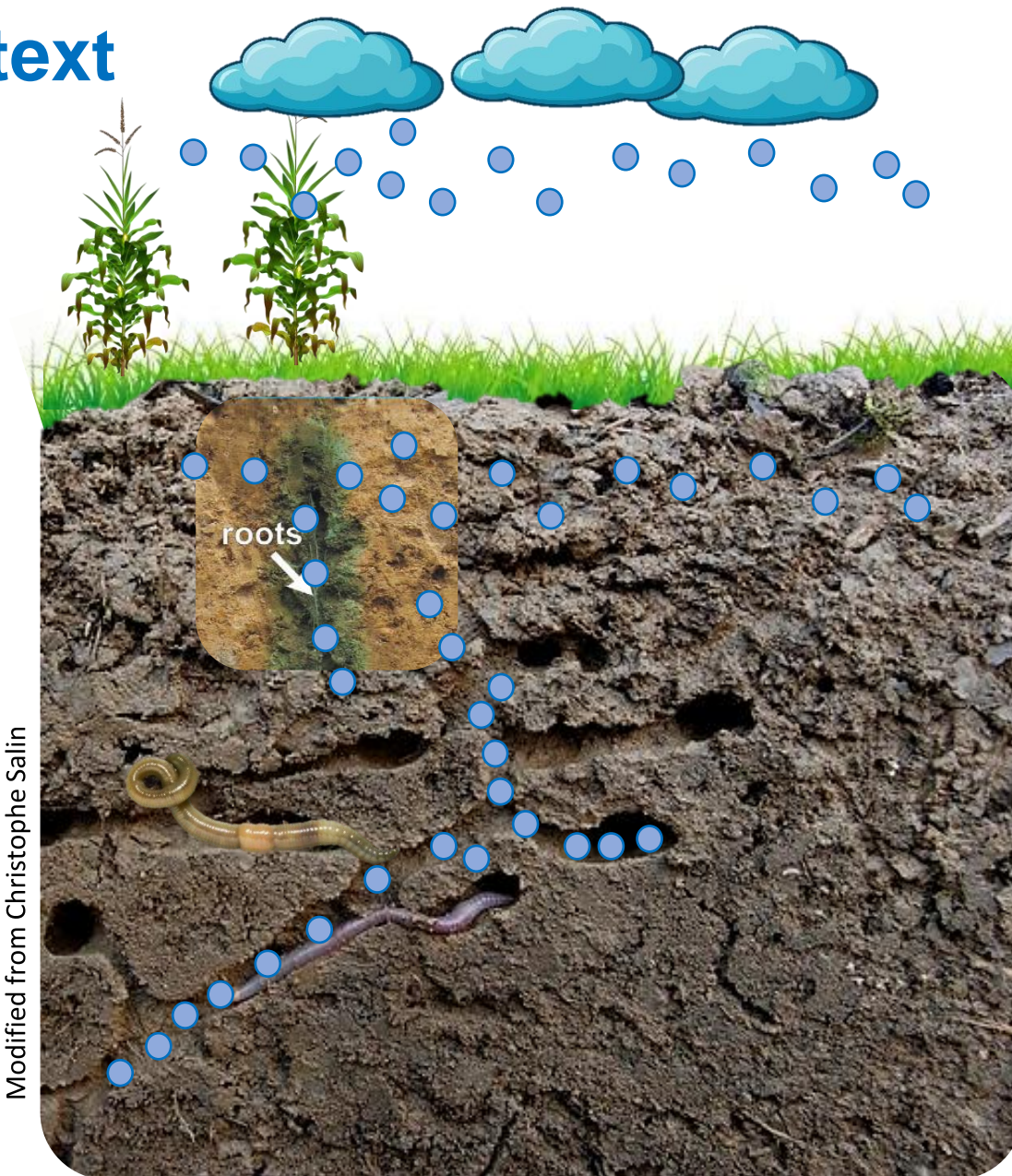
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Macropores (> 300 μm)

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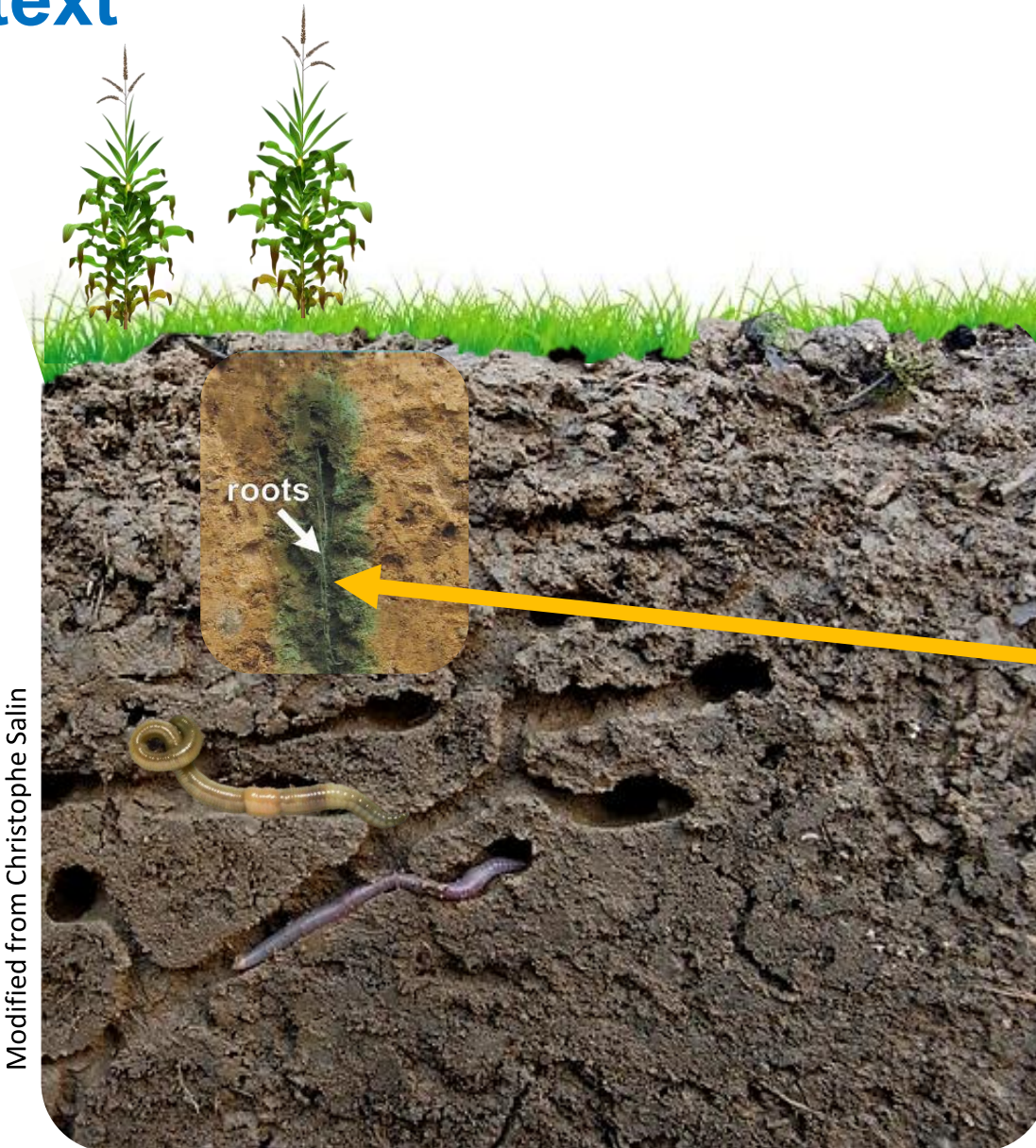
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Fast, gravity-driven, preferential flow

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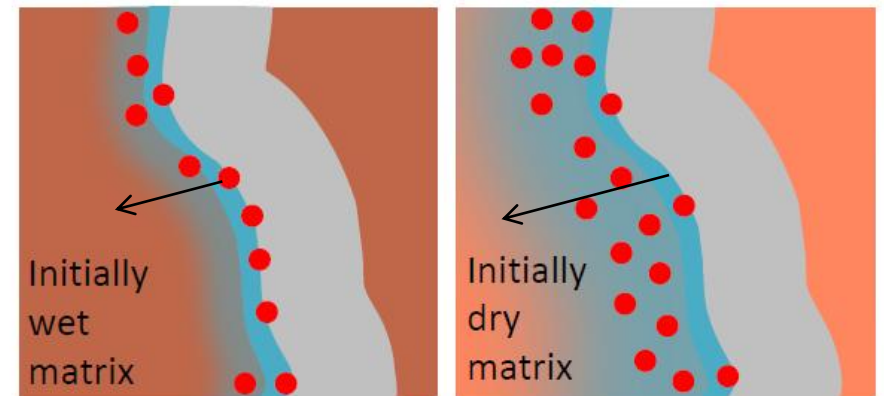
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Fast, gravity-driven, preferential flow

● Macropore – matrix exchanges



increasing macropore matrix transfers

van den Bogaert et al. *Geoderma.*, 2016

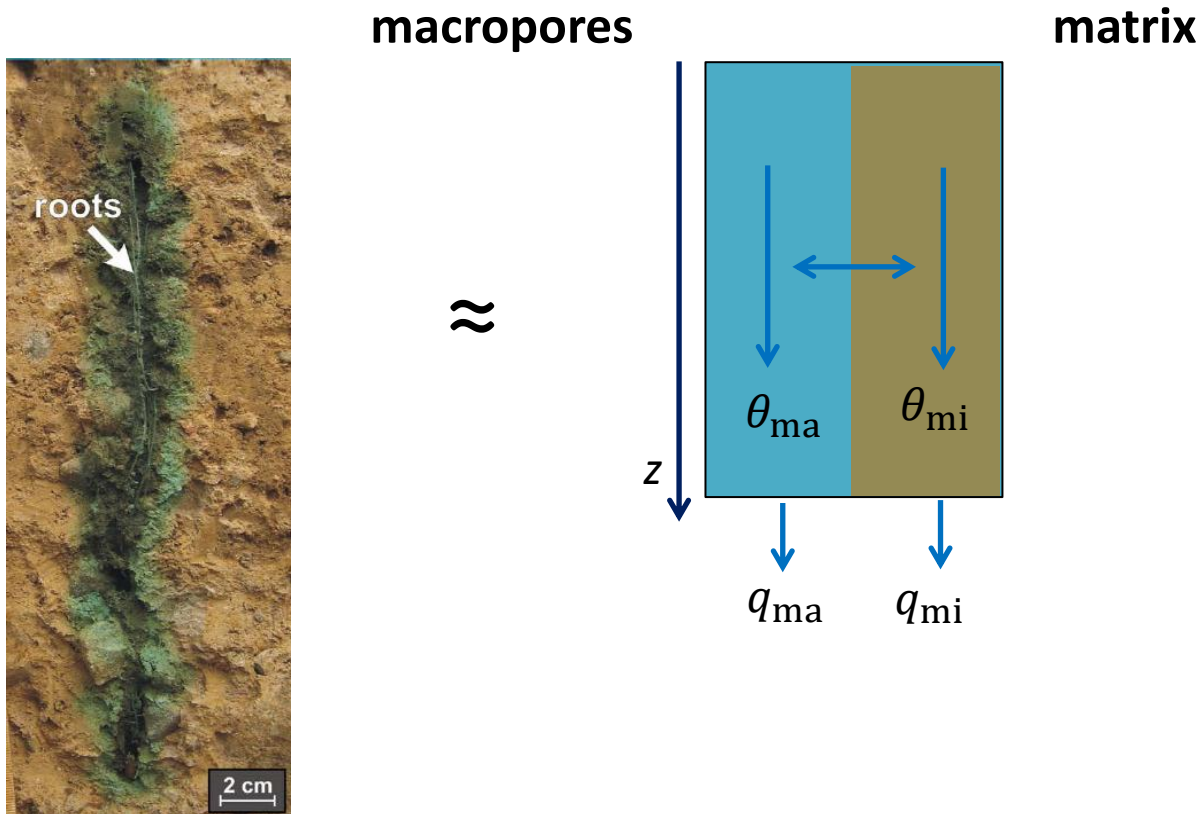
Current operational models of macropore & matrix flow

- 1D compartment models “Double permeability”

- matrix and macropore characterized by effective parameters
- Interface macropore—matrix not described explicitly

- Outputs of model:

- water content $\theta = f(z,t)$
- flow rate $q = f(z,t)$ in each compartment



Cey et al.
J. Cont. Hydrol., 2009

Current operational models of macropore & matrix flow

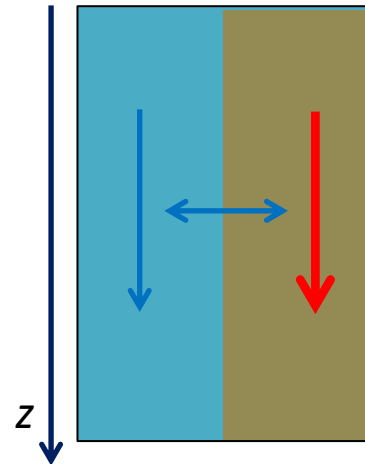
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macropores



matrix

$$q_{mi} = -K_{mi}(\theta_{mi}) \frac{\partial(h-z)}{\partial z}$$

$$\frac{\partial \theta_{mi}}{\partial z} = -\frac{\partial q_{mi}}{\partial z} \pm S$$

$$\frac{\partial \theta_{mi}(h)}{\partial t} + \frac{\partial}{\partial z} \left(-K_{mi}(h) \frac{\partial(h-z)}{\partial z} \right) - S = 0$$

Richards: $K(\theta)$, $\theta(h)$

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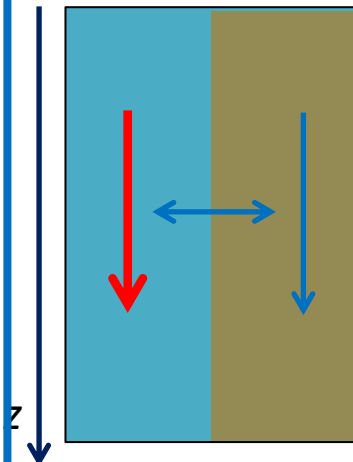
macropores

$$q_{ma} = -b \theta_{ma}^a - v \frac{\partial \theta_{ma}}{\partial z}$$

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$$\frac{\partial \theta_{ma}(h)}{\partial t} + ab \theta_{ma}^{a-1} \frac{\partial \theta_{ma}(h)}{\partial z} - v \frac{\partial^2 \theta_{ma}(h)}{\partial z^2} + S = 0$$

Kinematic (Dispersive) Wave



matrix

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Richards: $K(\theta), \theta(h)$

of macropore & matrix flow

A_{exch} wetted specific surface area of macropores, ($\text{m}^2 \text{m}^{-3}$).

$$A_{\text{exch}} = \gamma \theta_{\text{ma}}^\beta \text{ with } a = 3 - 2\beta$$

Jarvis, Vadose Zone J., 2017

“permeability”

effective parameters

ed explicitly

• Outputs of model:

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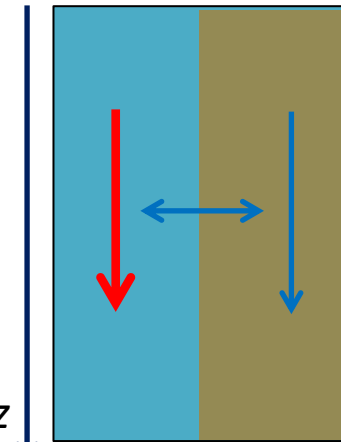
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- Germann & Beven, *Water Resources Research*, 1985.
 Jarvis et al., *Journal of Soil Science*, 1991).
 Di Pietro et al., *Journal of Hydrology*, 2003.

Current operational models of macropore & matrix flow

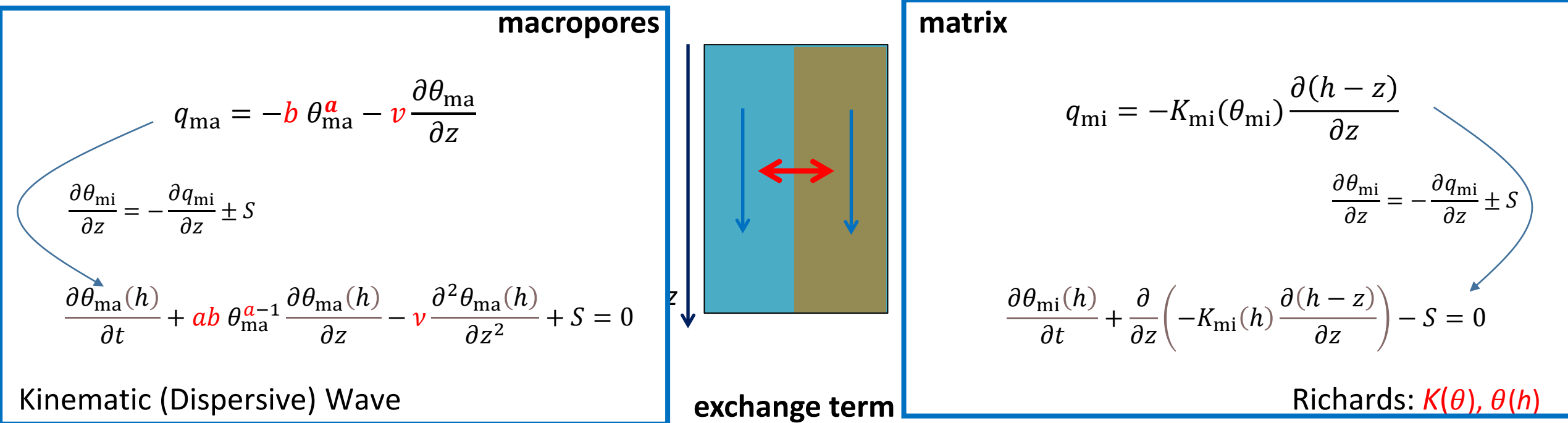


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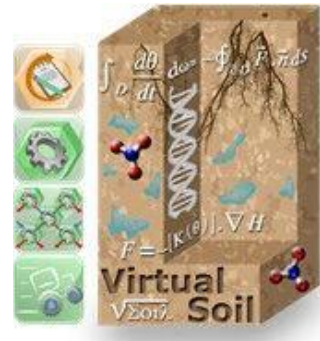
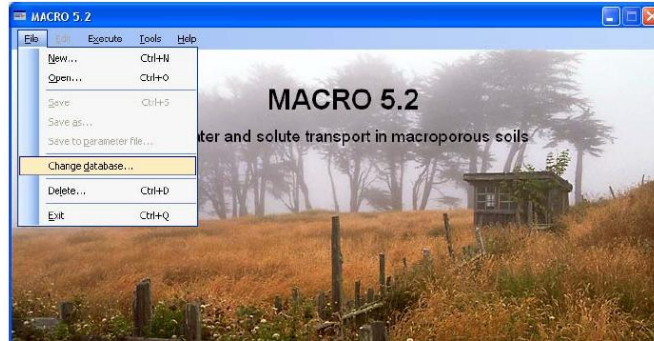


$$S(z,t) = -\frac{K_{mi}(h)}{d} \frac{0 - h}{d} \frac{\theta_{ma}}{\theta_{ma,max}}$$

$d(z)$ = mean half distance between macropores (m)

Current operational models of macropore & matrix flow

- Issue with “ d ”



“The **initial "values of d** for the different layers based on visual observations of the soil structure **were increased considerably to obtain a better fit**”
(Larsson & Jarvis, J. Hydrol., 1999)

“A **value of 10 cm for d** is considered large in relation to the size and scale of aggregation in the Lanna clay soil.”
(Saxena, Jarvis, Bergström, J. Hydrol., 1994)

**d has a physical meaning,
but is calibrated to fit experimental data.**

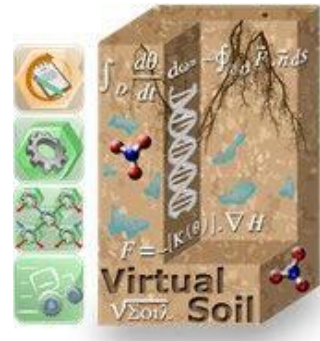
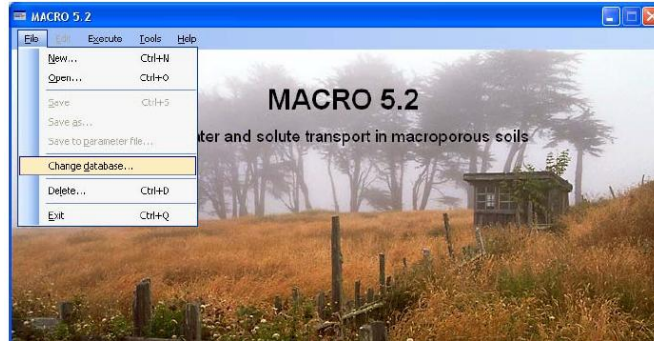
exchange term

$$S(z, t) = - \frac{K_{mi}(h)}{d} \frac{0 - h}{d} \frac{\theta_{ma}}{\theta_{ma,max}}$$

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Current coupled models of macropore & matrix flow

- Issue with “ d ”



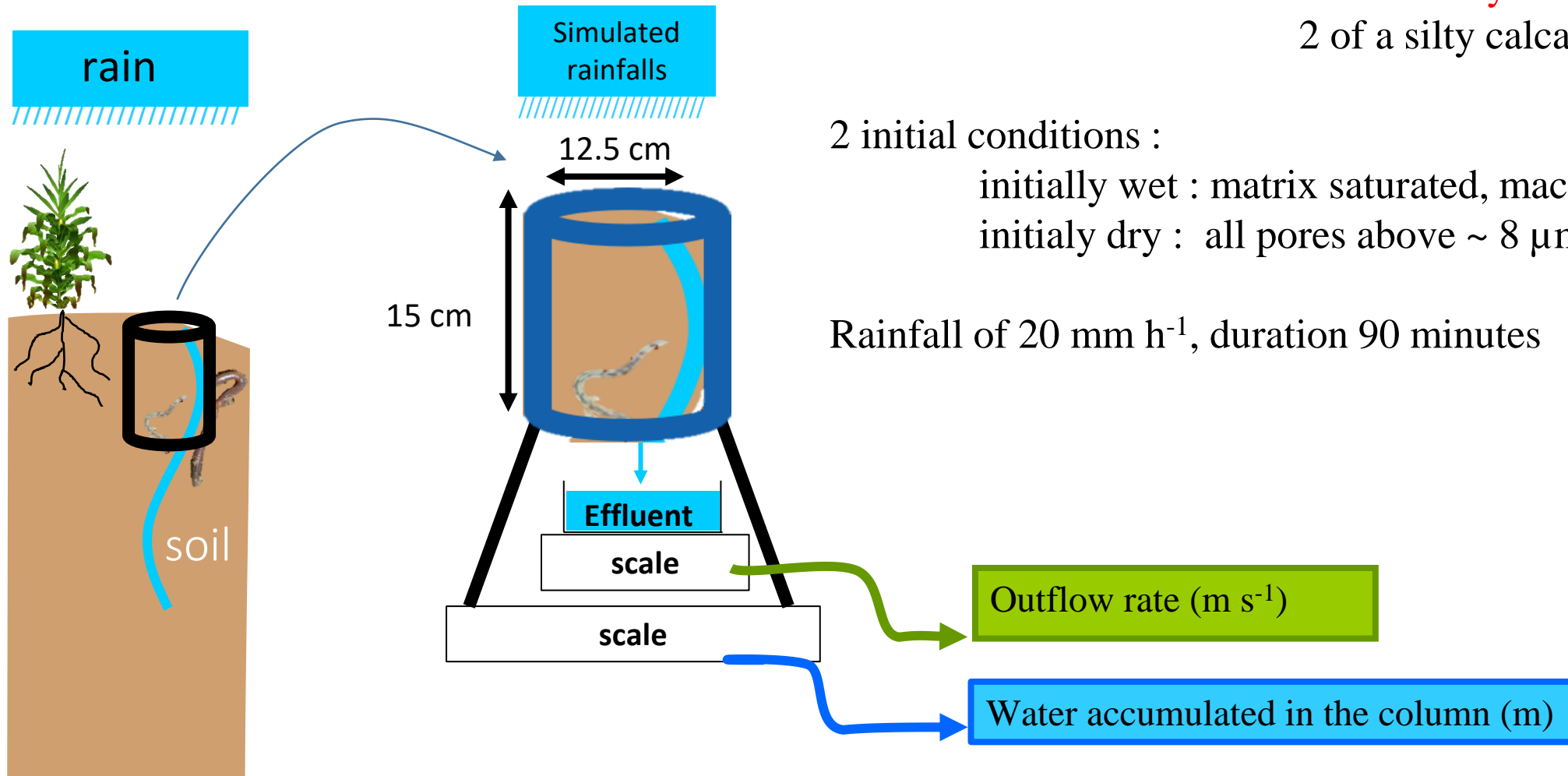
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**d has a physical meaning,
but is calibrated to fit experimental data.**

Why ? Can we fix that ?

Material and methods — simulated rainfall on undisturbed soil cores

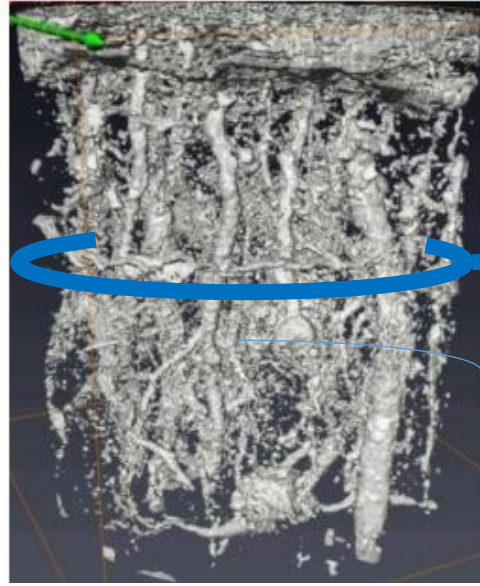
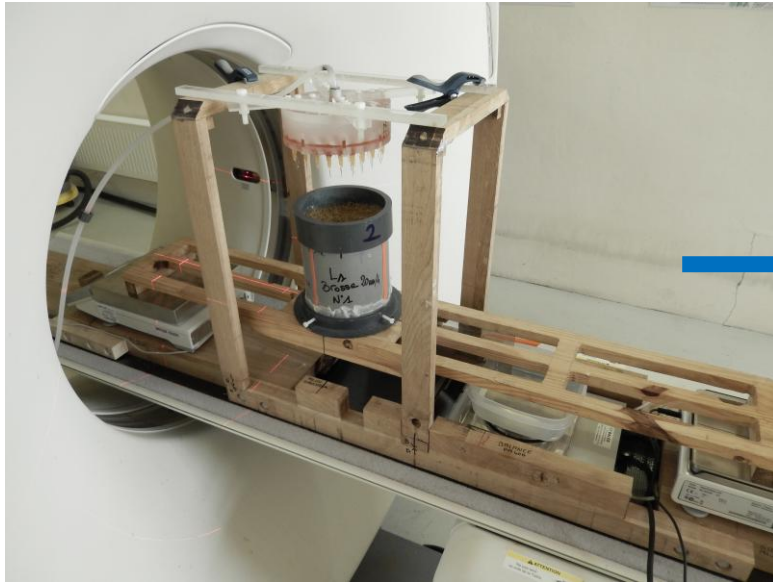


4 undisturbed soil columns: 2 of a loamy calcisol,
2 of a silty calcareic luvisol.

2 initial conditions :
initially wet : matrix saturated, macropores empty,
initially dry : all pores above $\sim 8 \mu\text{m}$ are empty .

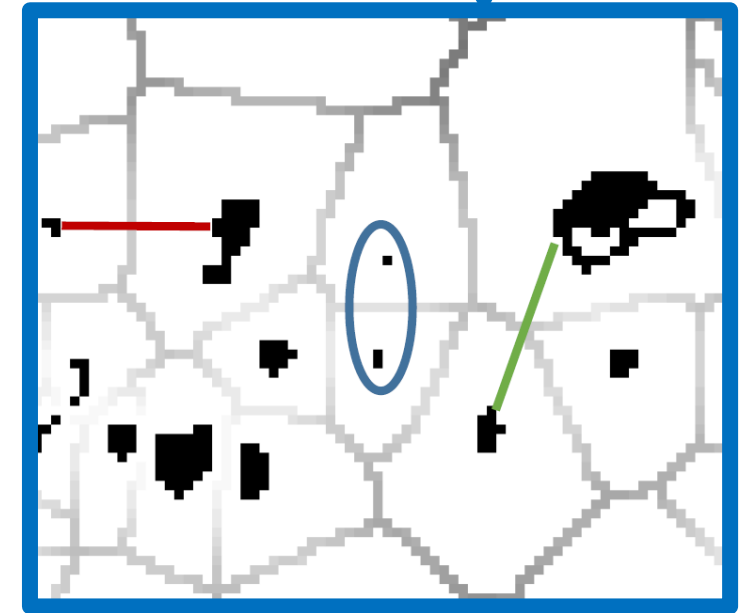
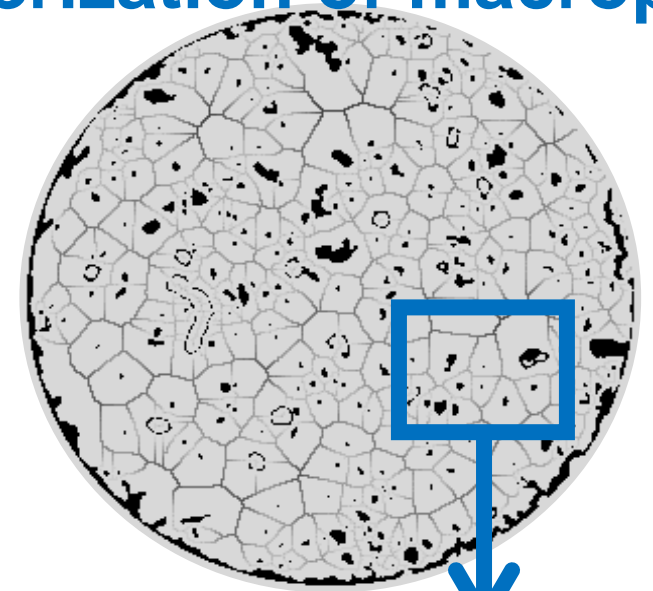
Rainfall of 20 mm h^{-1} , duration 90 minutes

Material and methods — 3D X-ray CT: characterization of macropores



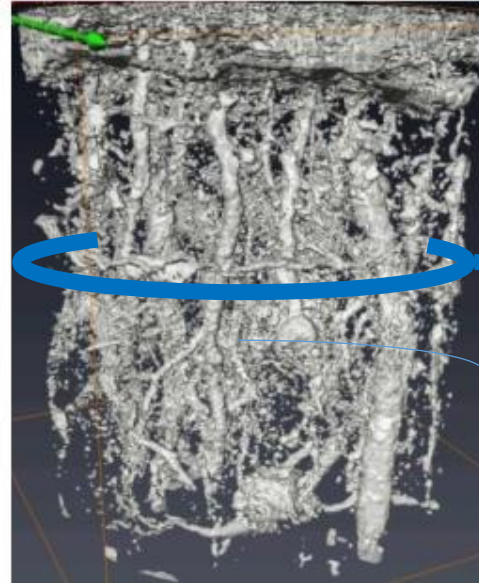
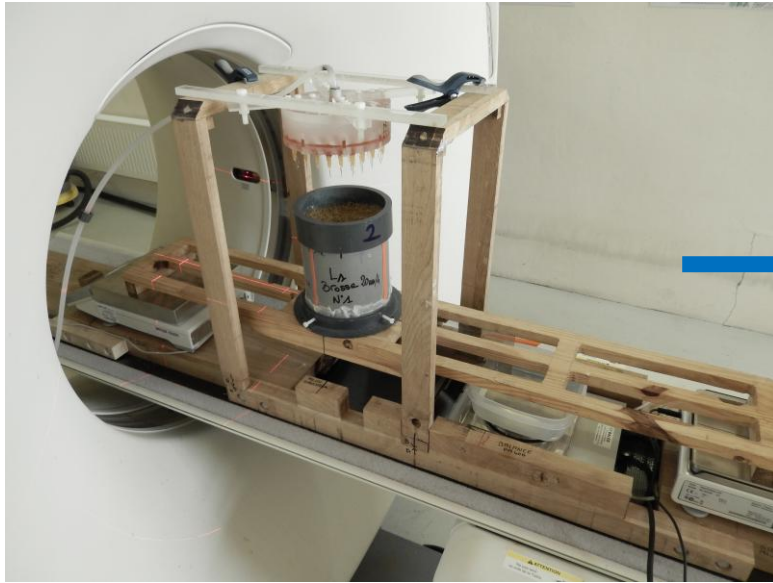
Voxel size
400 μm

400
horizontal
slices



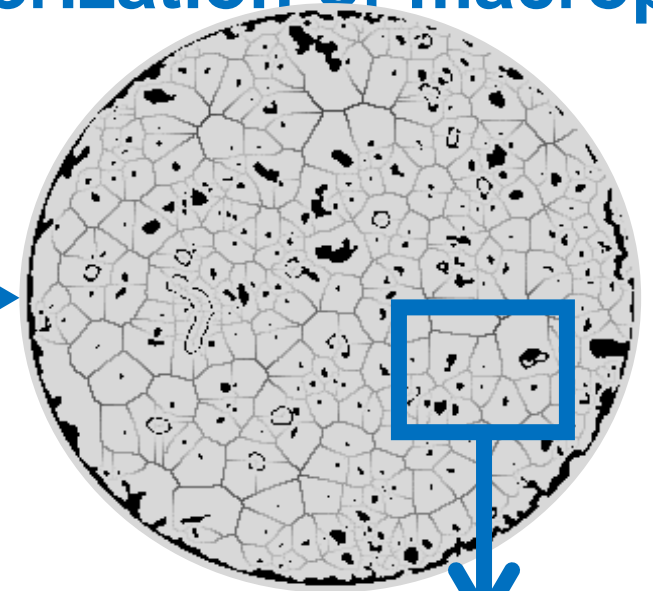
macroporosity

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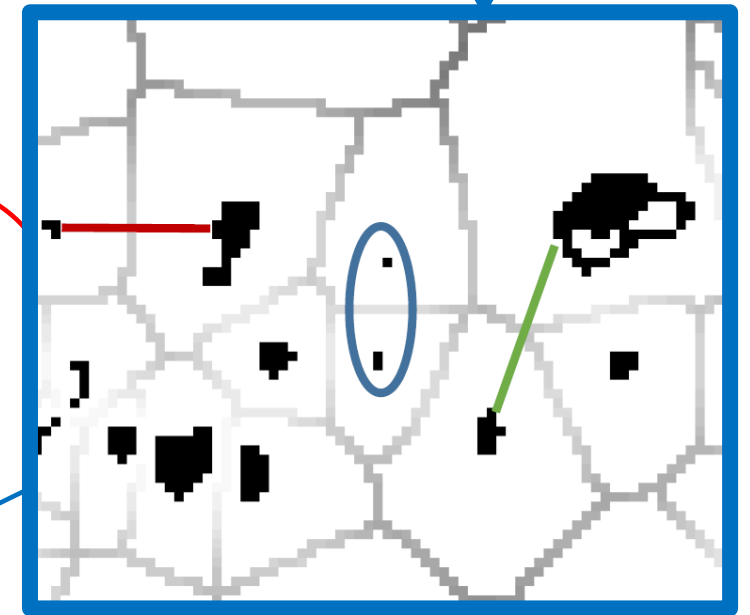


Voxel size
400 μm

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horizontal
slices



macroporosity

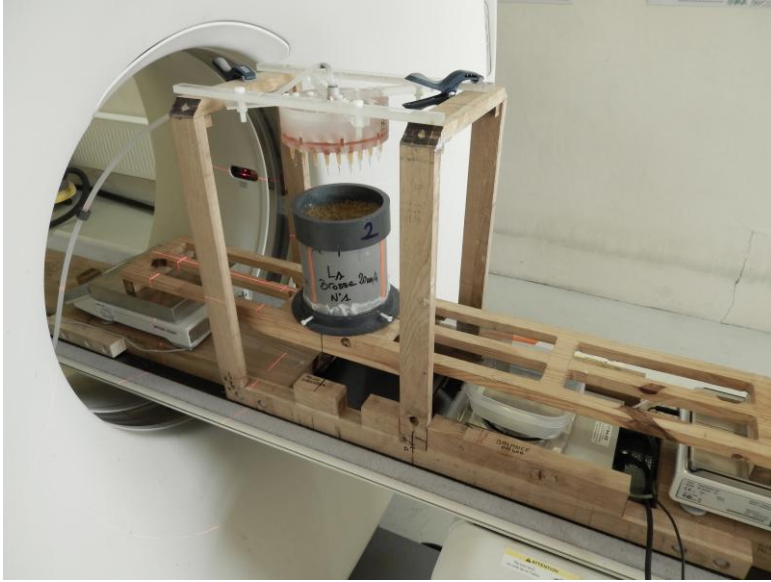


$$S(z, t) = - \frac{K_{mi}(h)}{d} \frac{0 - h}{d} \frac{\theta_{ma}}{\theta_{ma, max}}$$

half distance between
macropores (m)

macroporosity
($\text{m}^3 \text{m}^{-3}_{\text{soil}}$)

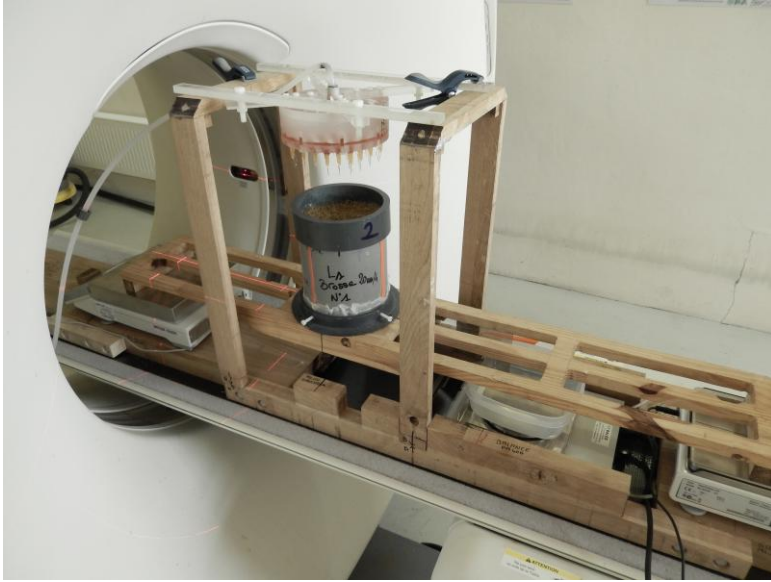
Material and methods — 4D X-ray CT : where is water flowing ?



Scan duration 10 s
30 images per rainfall

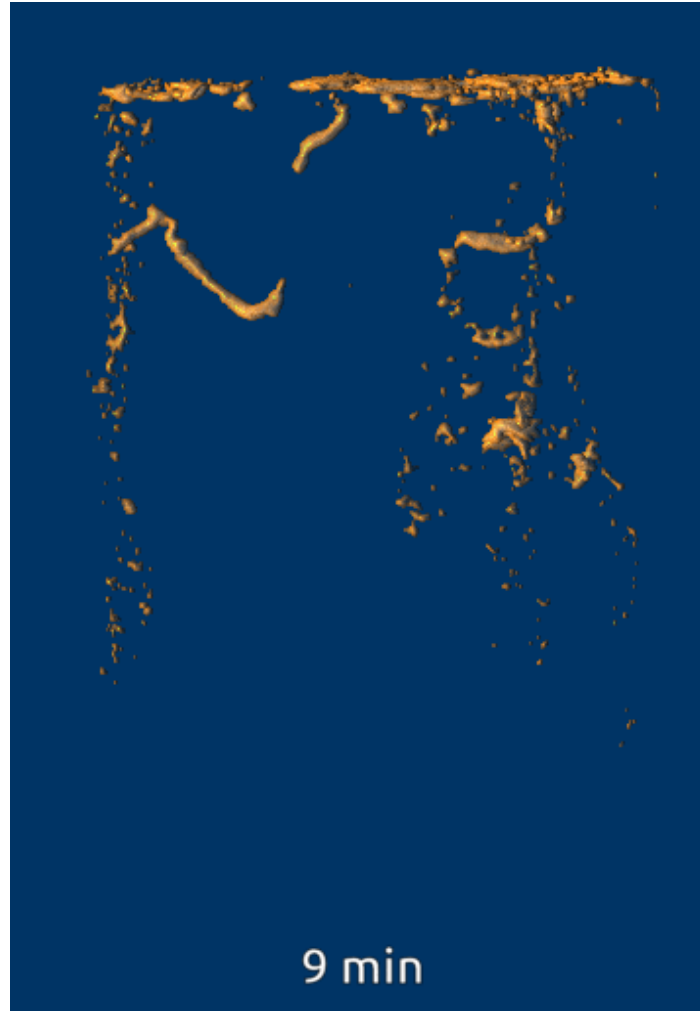
$$\mathbf{Water}(t_i) = \mathbf{image}(t_i) - \mathbf{image}(t_0)$$

Material and methods — 4D X-ray CT : where is water flowing ?



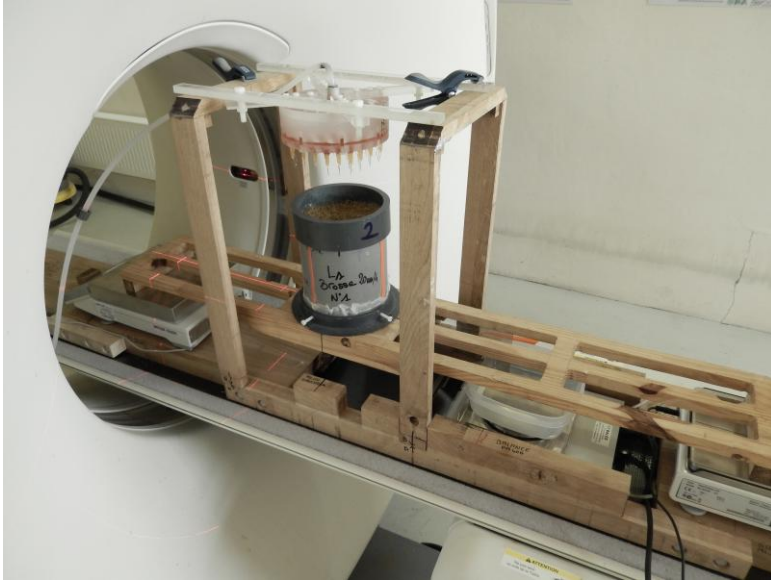
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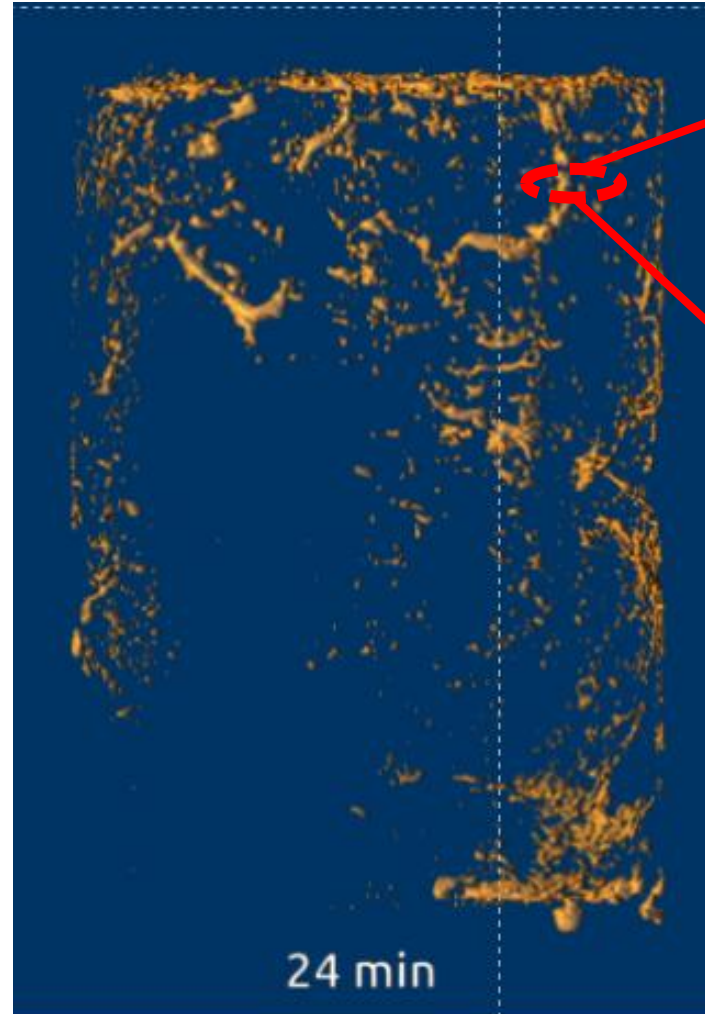


Loamy soil, initially dry

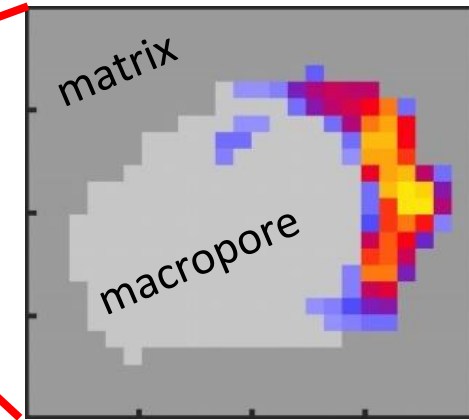
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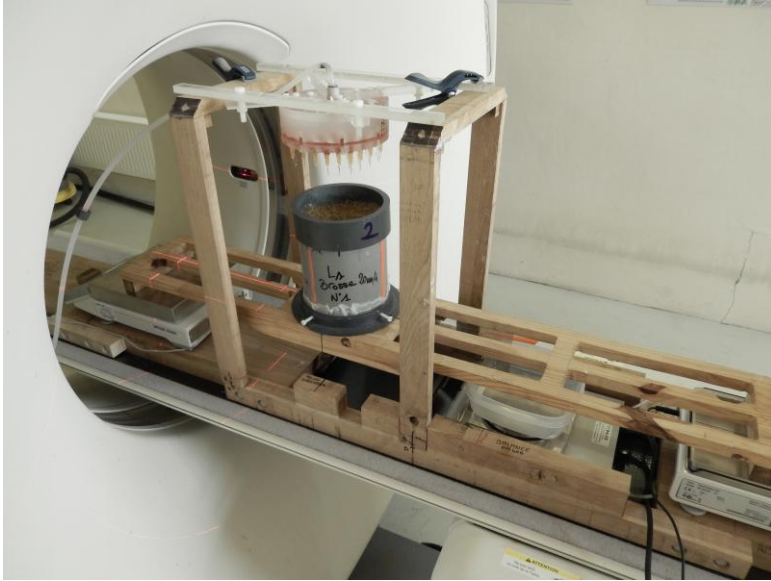


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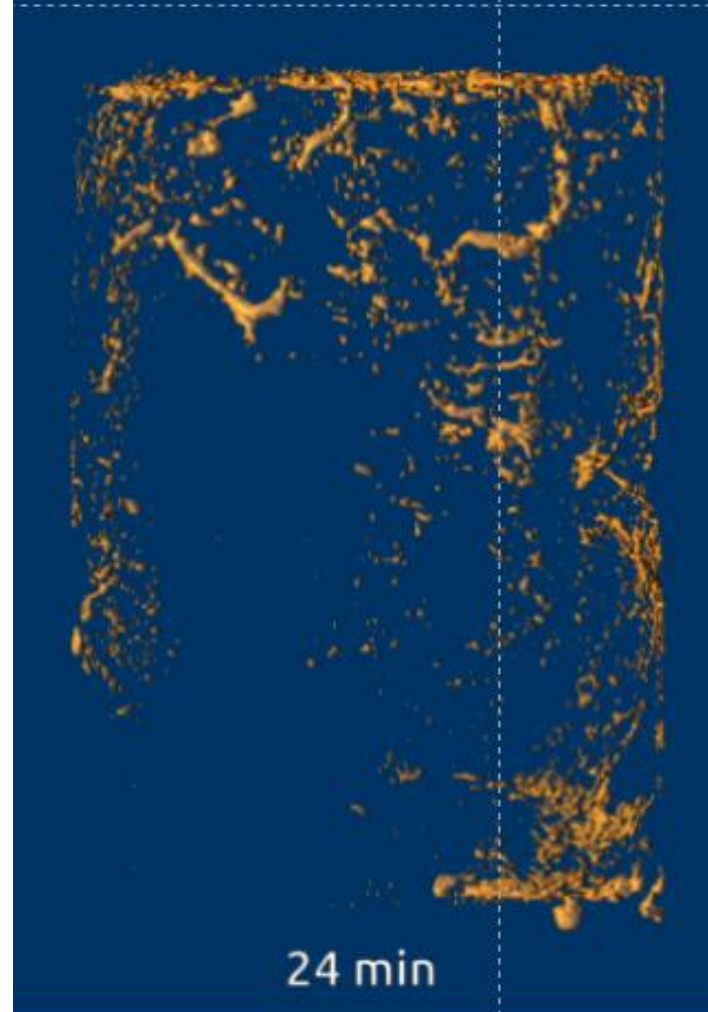


Cross section of an active macropore

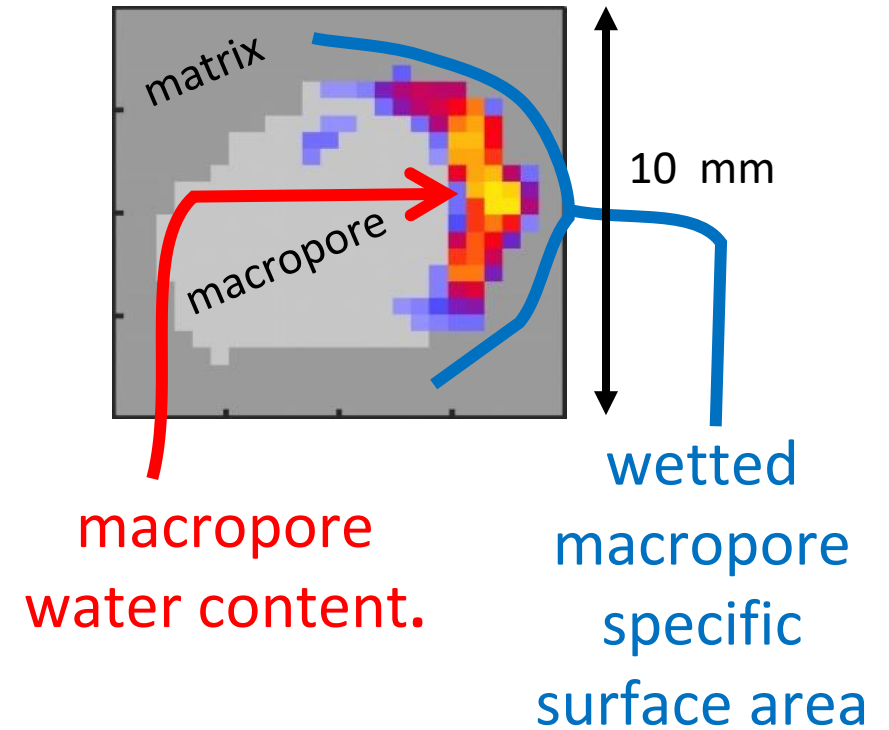
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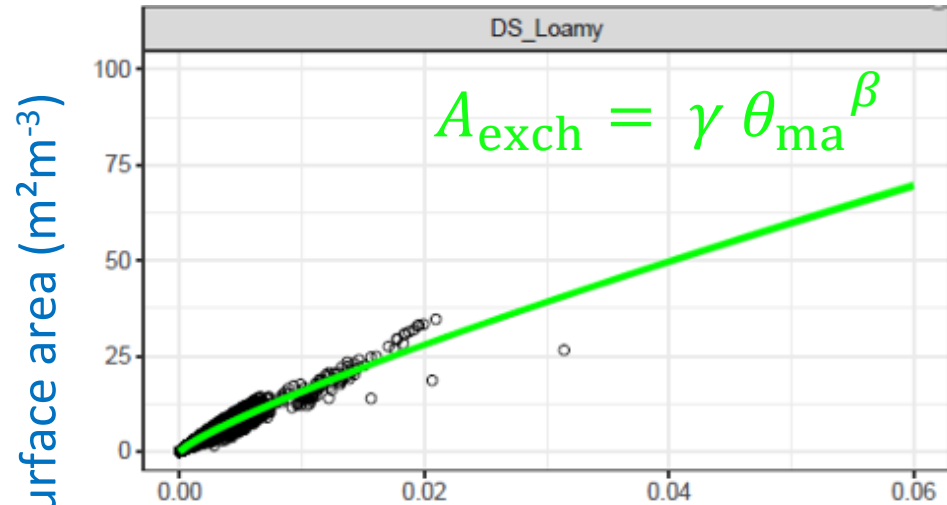
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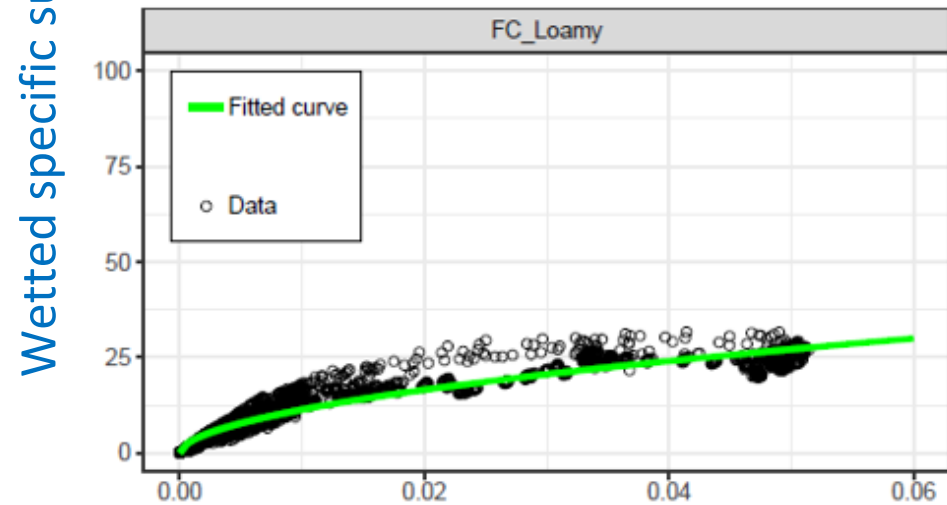


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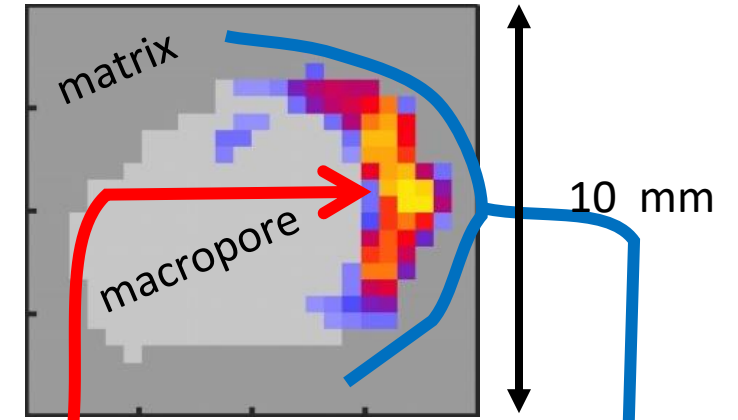
$$\beta = 0.831 \pm 0.002$$

$$a = 3 - 2\beta = 1.34$$



$$\beta = 0.544 \pm 0.002$$

$$a = 3 - 2\beta = 1.91$$



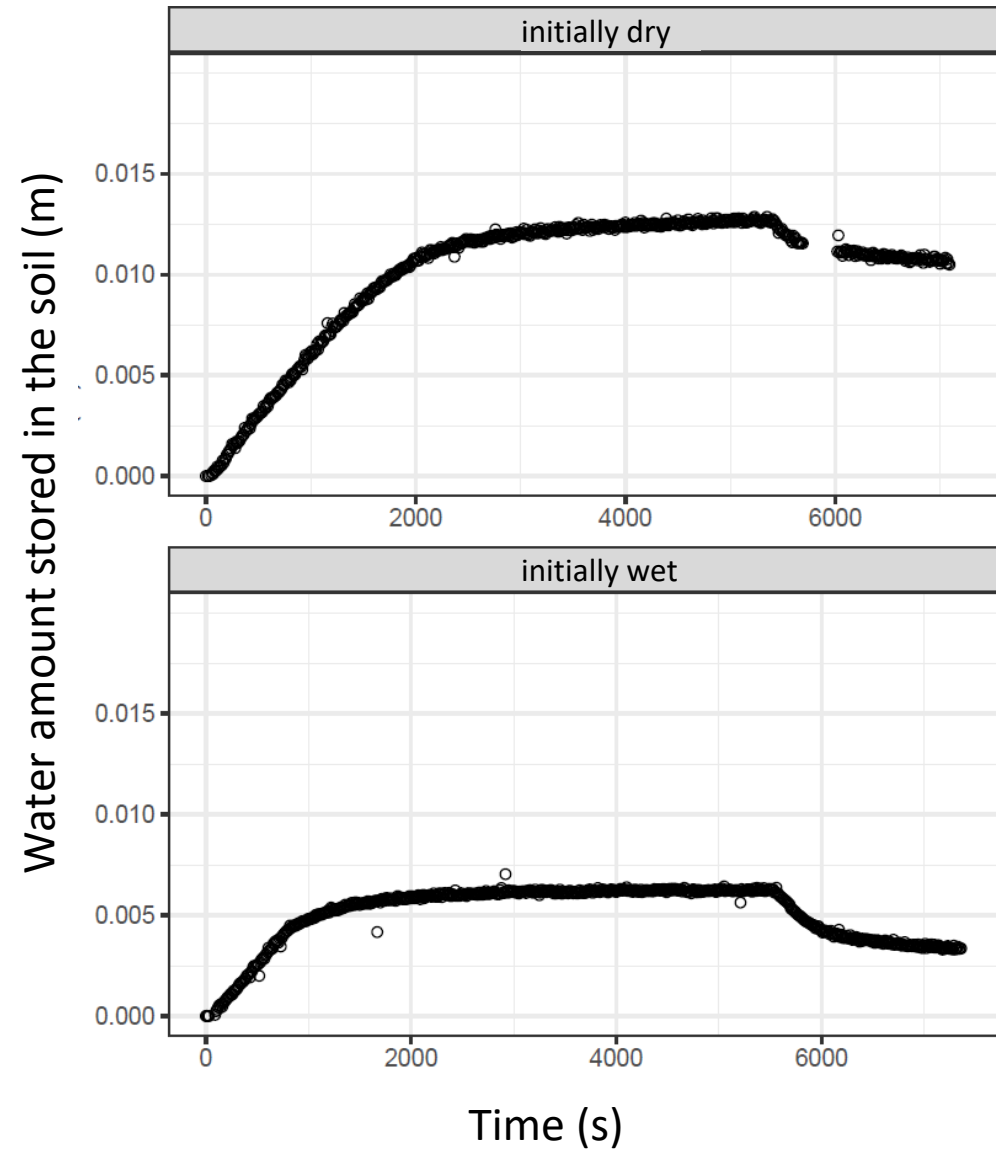
macropore
water content.

wetted
macropore
specific
surface area

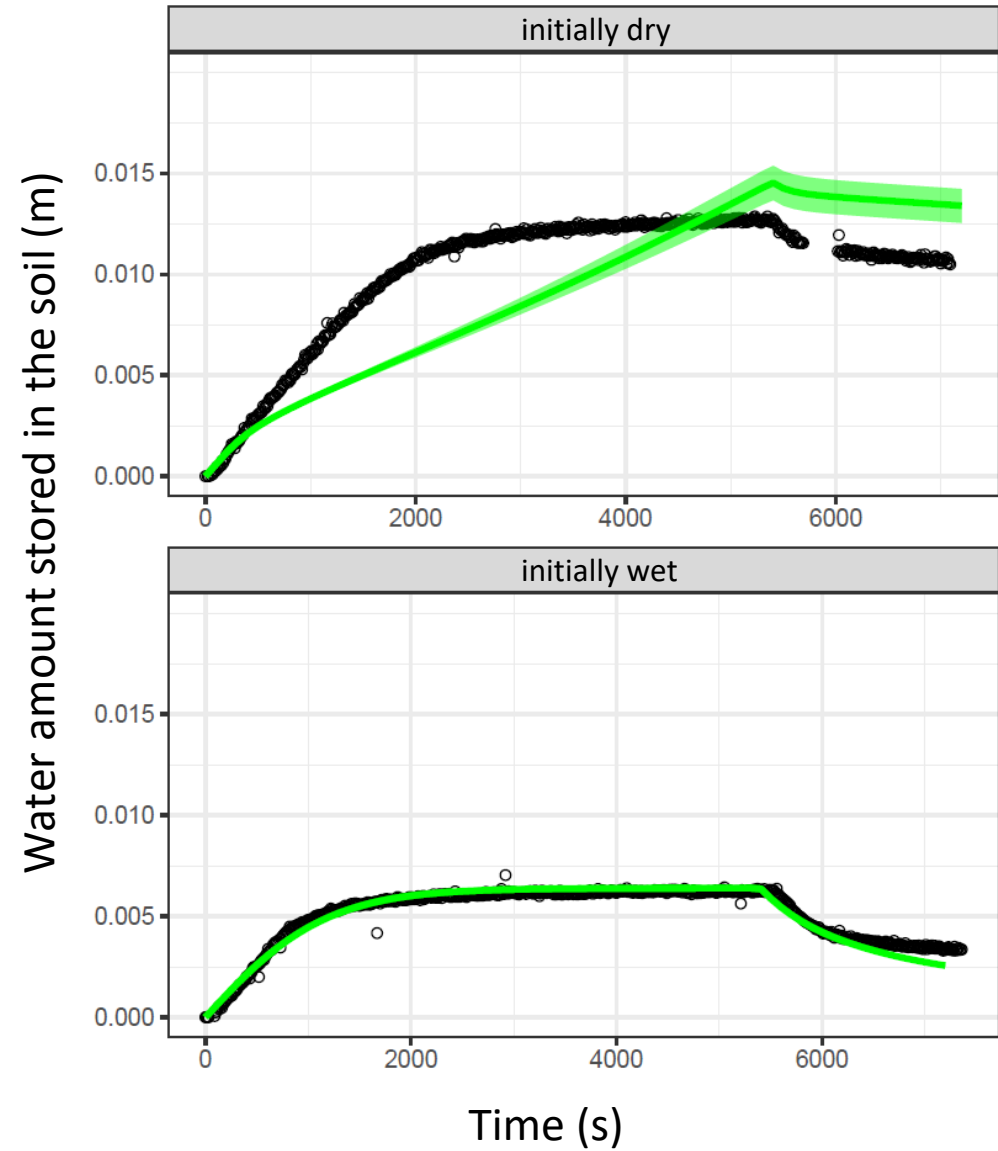
Determined from X-ray CT	Determined from specific exp.	Calibrated
$d(z), \theta_{\text{ma,max}}(z), a,$	$K(\theta), \theta(h),$	b, v

Macropore water content ($\text{m}^3 \text{m}^{-3}$)

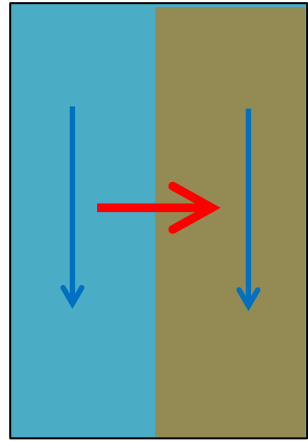
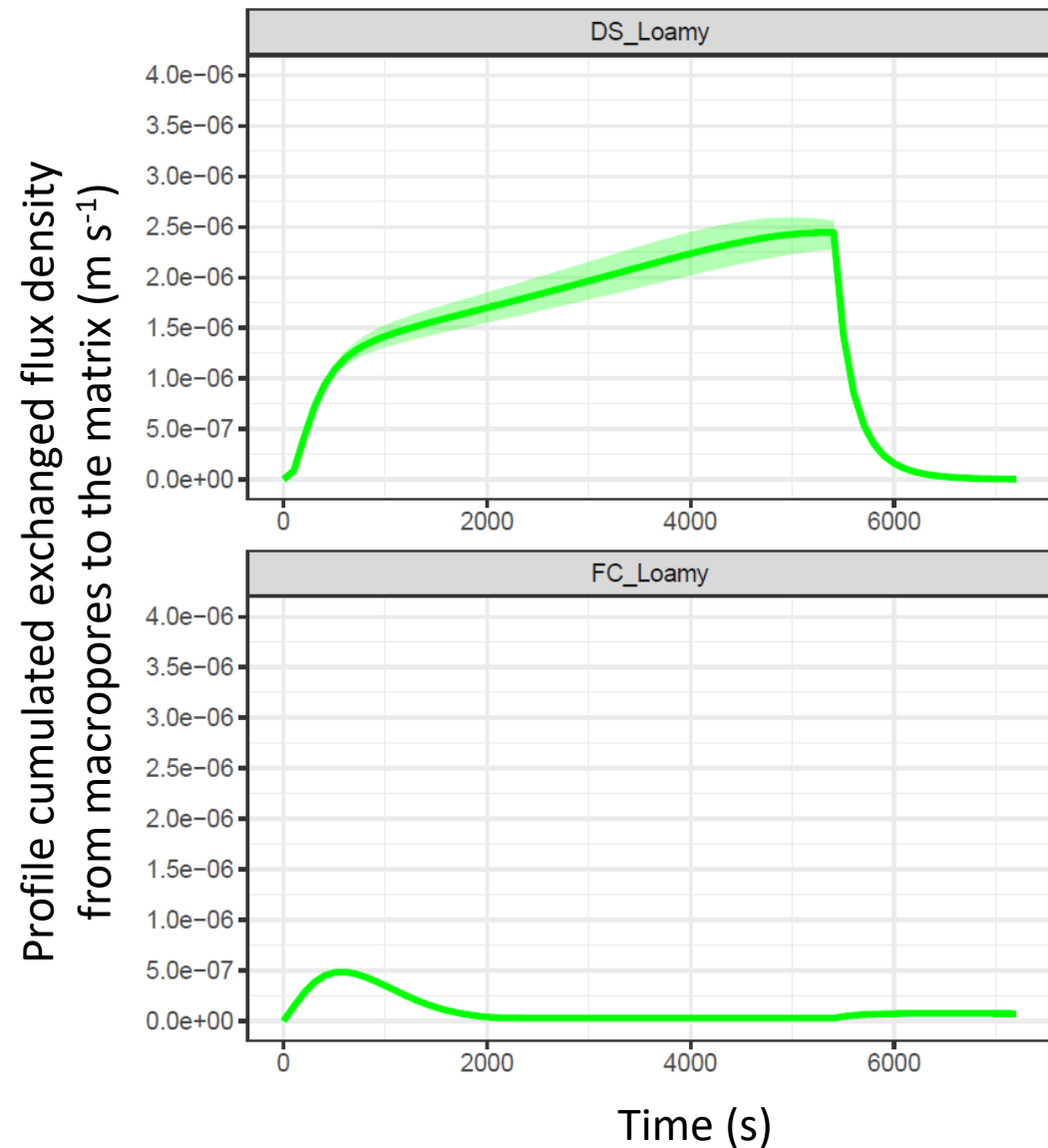
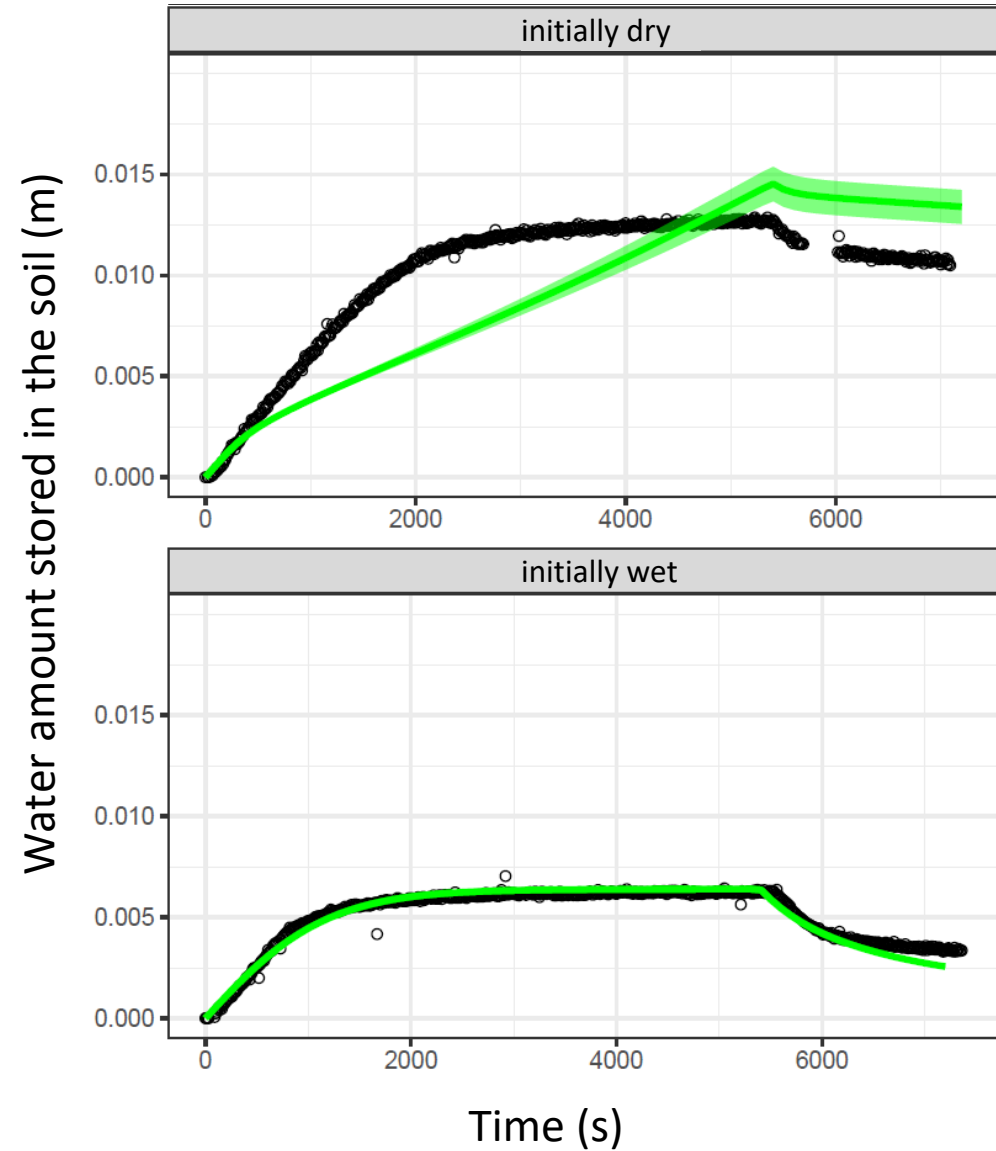
Test of the model



Test of the model



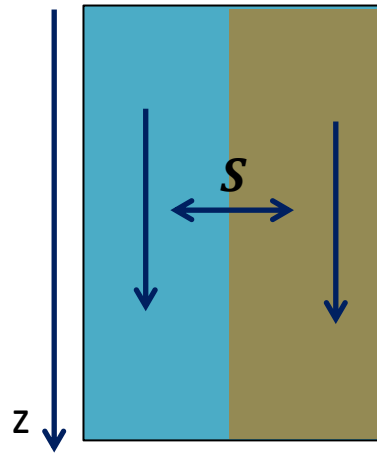
Test of the model



The first-order exchange term does not capture properly the exchange dynamics.

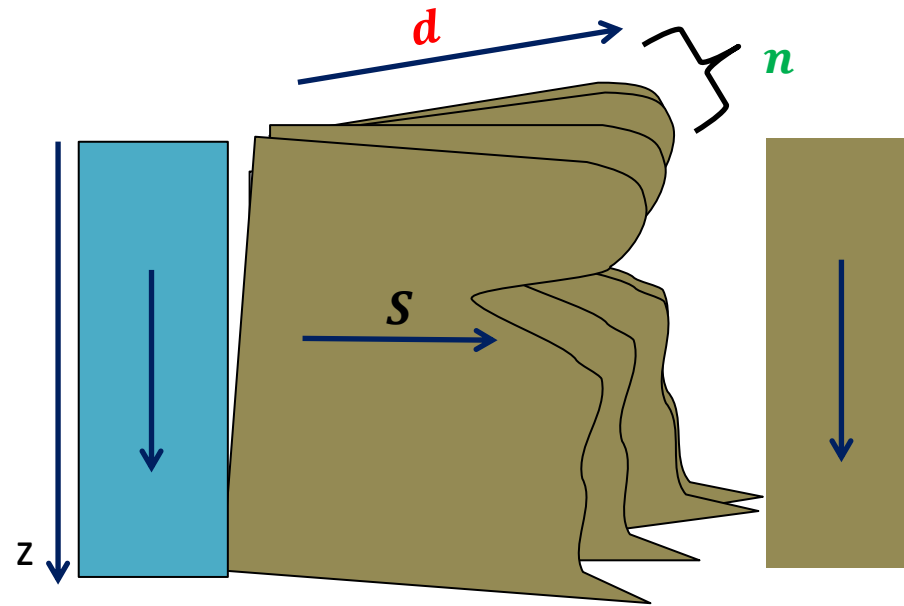
A new — pseudo 2D — model of macropore & matrix flow

macropores matrix



A new, pseudo 2D, macropore – matrix exchange term

- The total specific surface area of the macropore–matrix interface is discretized in n sections
- Each section corresponds to a horizontal representation of the matrix where the horizontal Richards equation is solved to keep track of the horizontal distribution of water in the soil matrix



macropores
Kinematic
Dispersive Wave

matrix
 n horizontal
Richards
equations

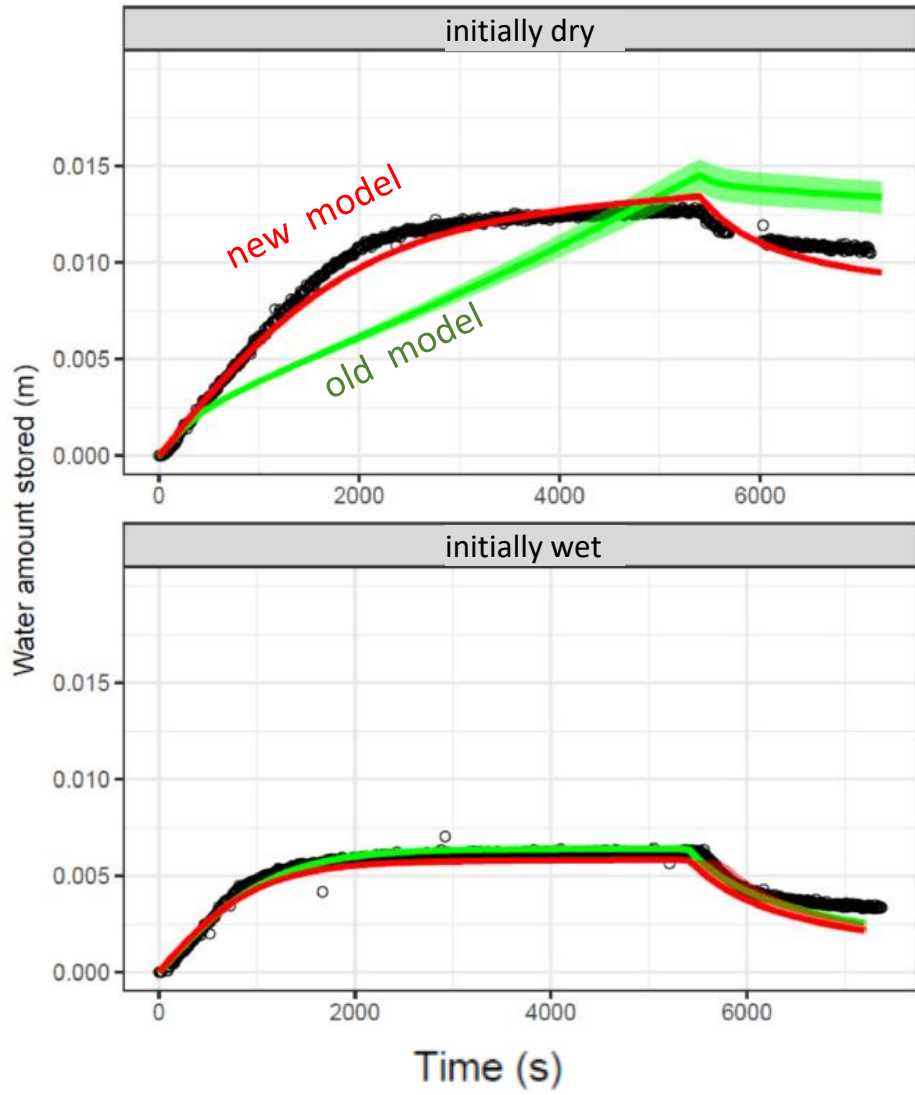
matrix
Vertical
Richards
equation

$$S(z) = \sum_n \left(\text{difference between water content at } t \text{ and } t+dt \text{ in horizontal matrix} \right)_n \times \left(\frac{\text{Exchange Surface}}{n} \right)$$

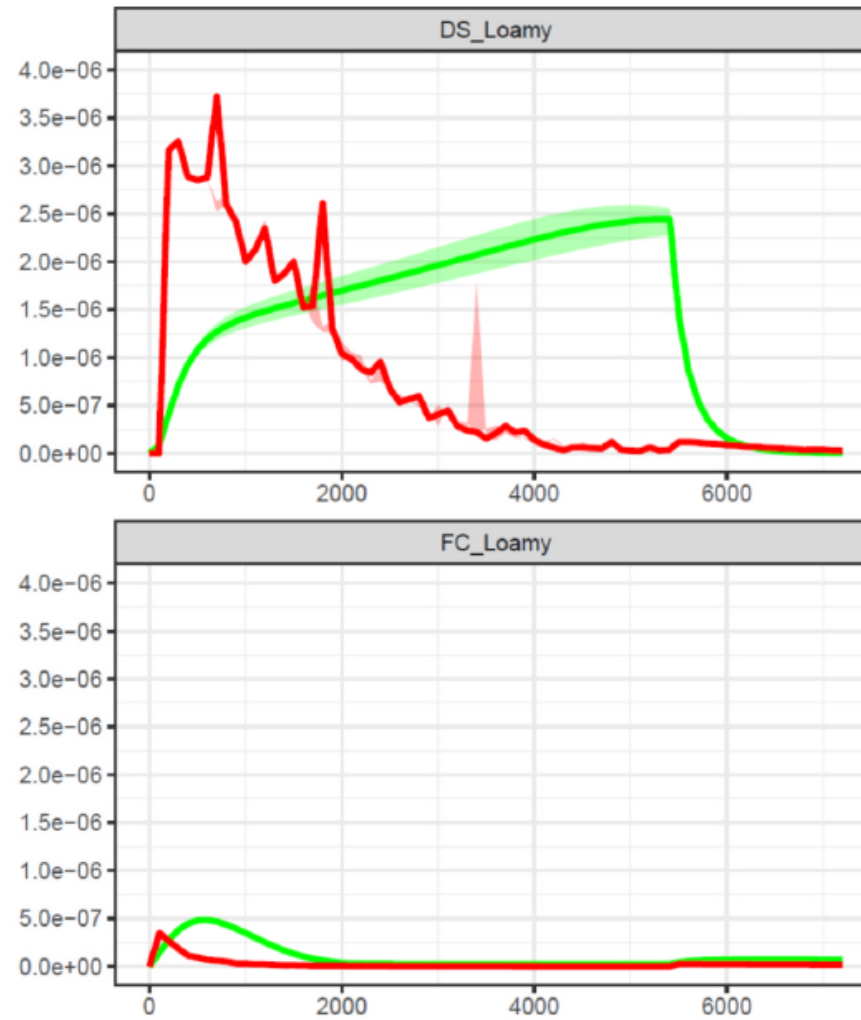
$m^3_{\text{eau}} \text{ s}^{-1} \text{ m}^{-2}_{\text{sol}}$
 $m^2_{\text{sol}} \text{ m}^{-3}_{\text{sol}}$

A new — pseudo 2D — model of macropore & matrix flow

Water amount stored in the soil (m)

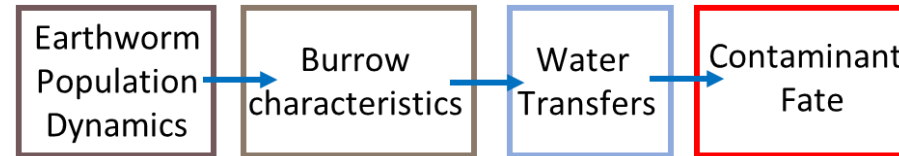
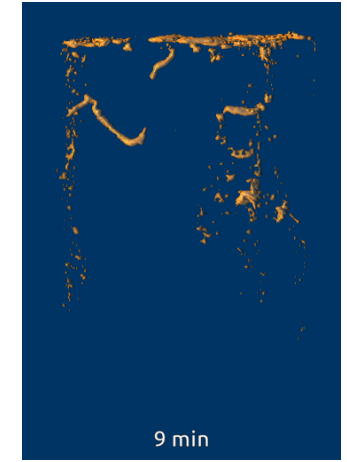
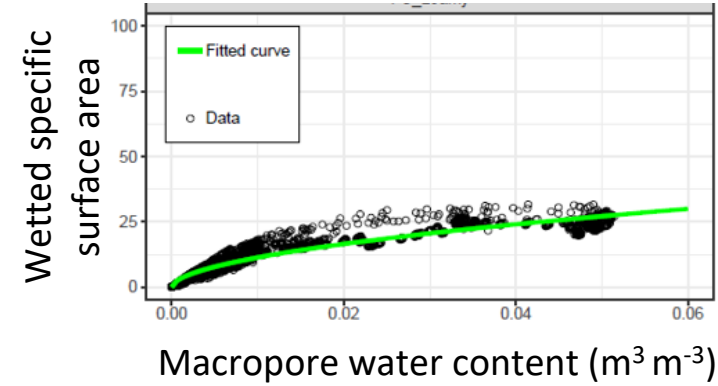


Profile cumulated exchanged flux density from macropores to the matrix (m s^{-1})



Conclusion

- 3D and 4D X-ray CT data were used for the first time to determine the parameters of a permeability model that were to date calibrated to fit the experimental data.
- Made it possible to test the model and propose an improved version.
- The new model opens up the possibility to use **measured or modeled d values**



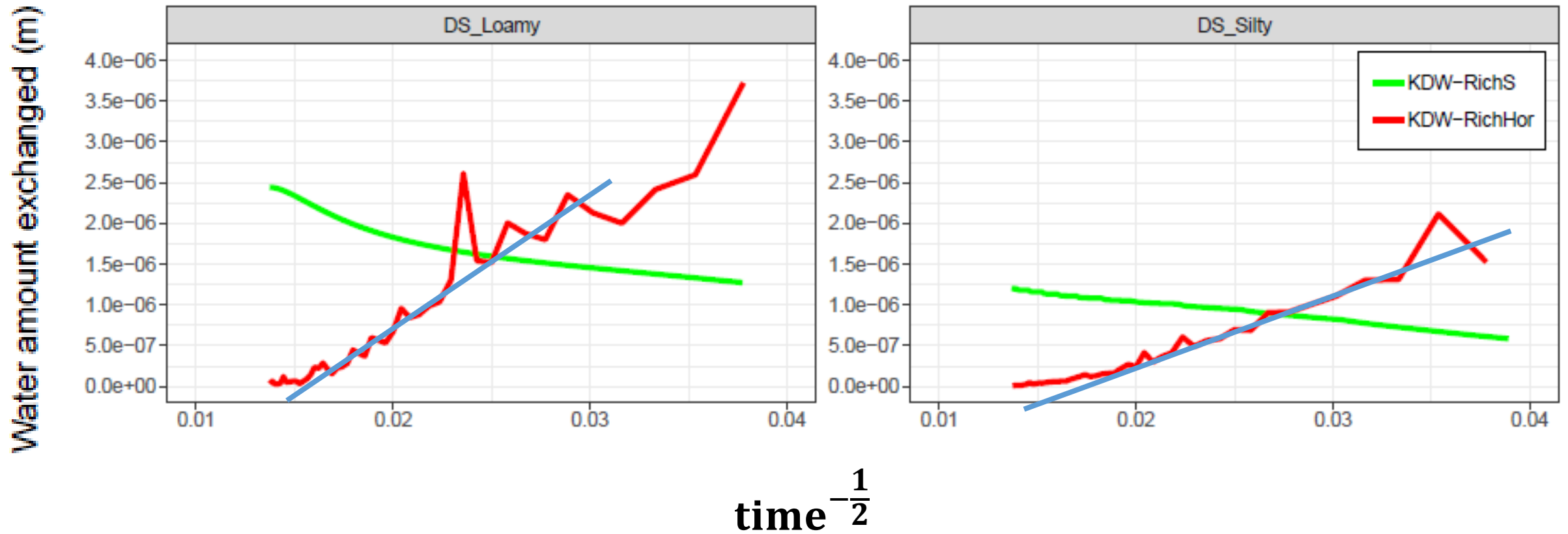
- Both models will be made available in the Vsoil platform

vsoil.hub.inrae.fr/



Link to the related paper

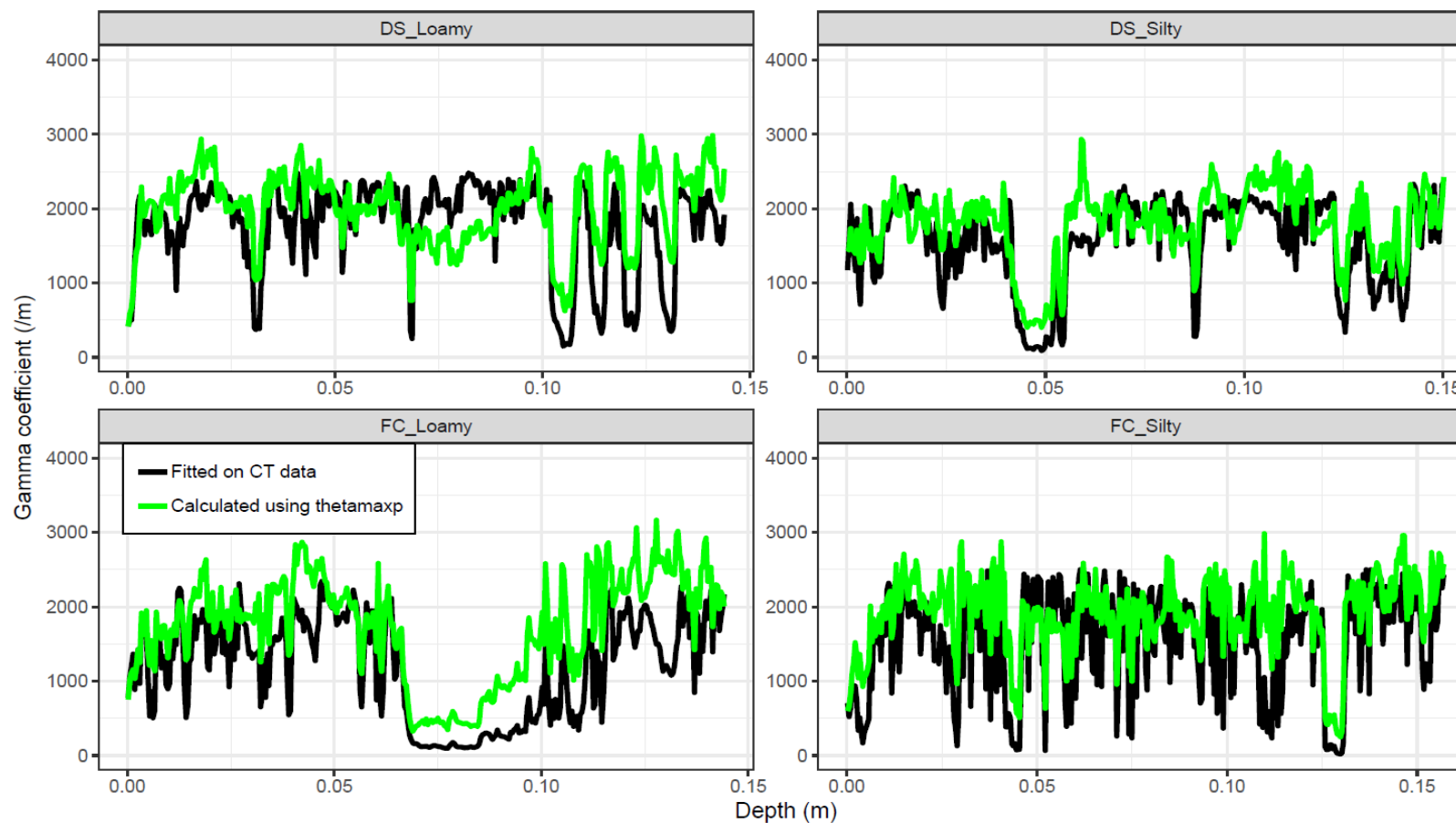
Link between total water amount exchanged and time

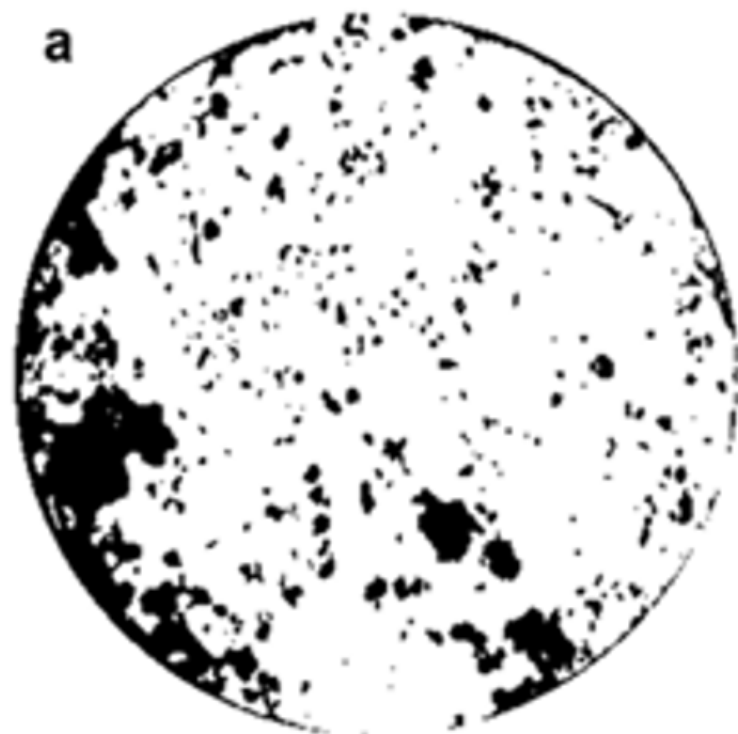


$$A_{\text{exch}} = \gamma \theta_{\text{ma}}^{\beta}$$

$$A_{\text{exch}_{\text{max}}} = \frac{1}{d} (1 - \theta_{\text{ma,max}})$$

$$\gamma = \frac{1}{d} \frac{1}{\theta_{\text{ma,max}}^{\beta}} (1 - \theta_{\text{ma,max}})$$





Binary image of
macroporosity network

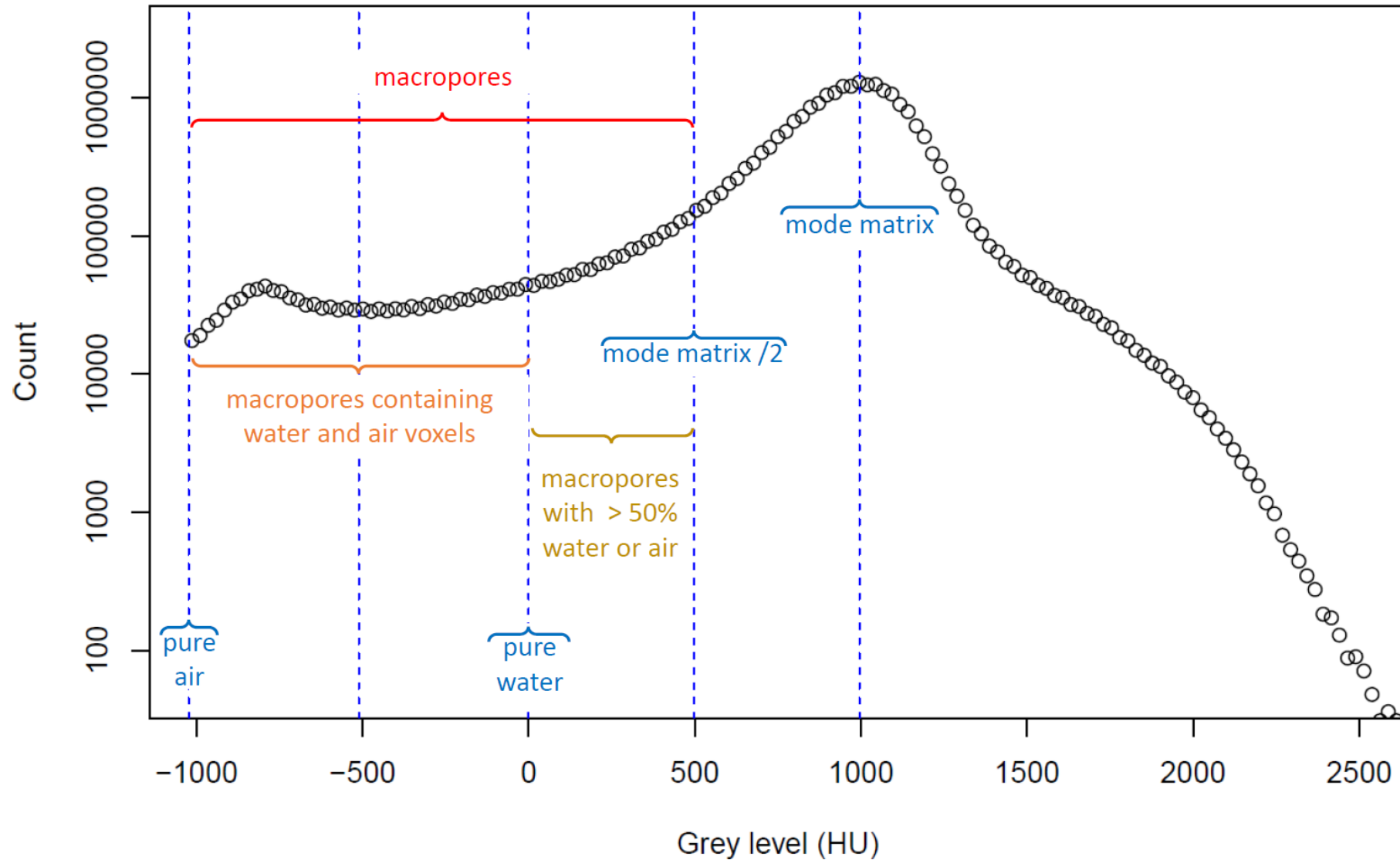


Binary image of water
within macroporosity

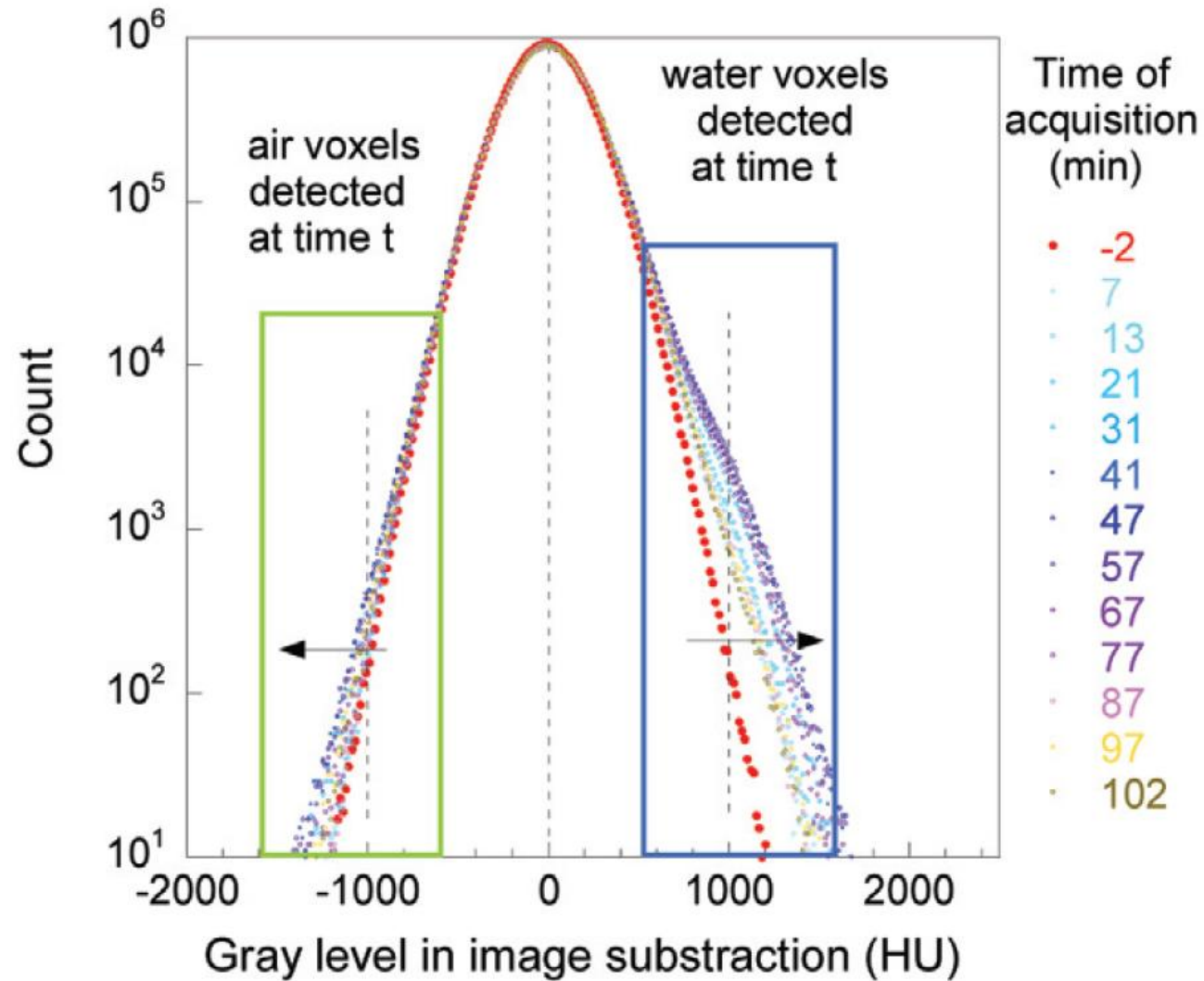
4-grey levels image

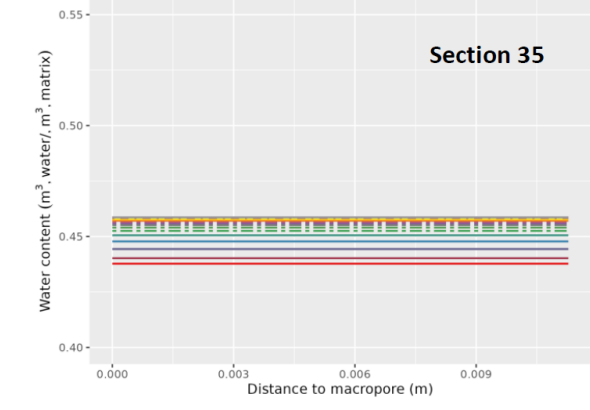
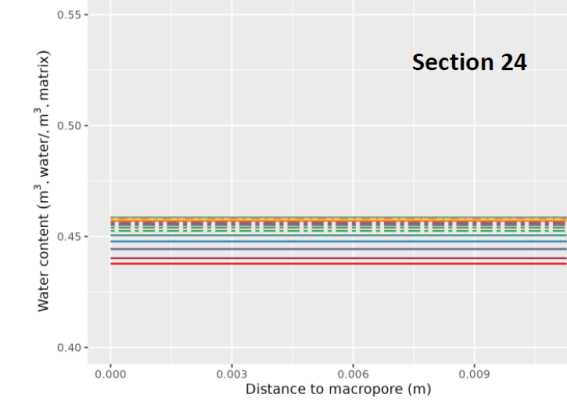
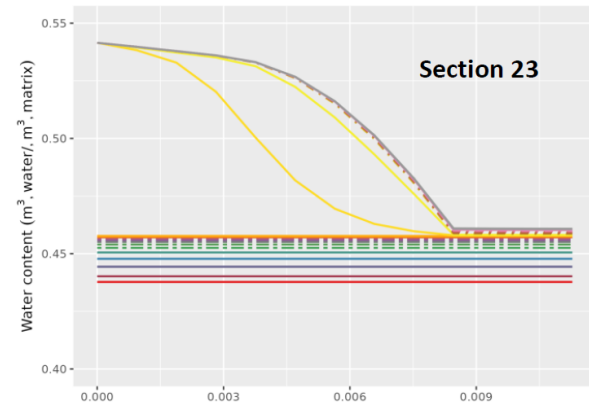
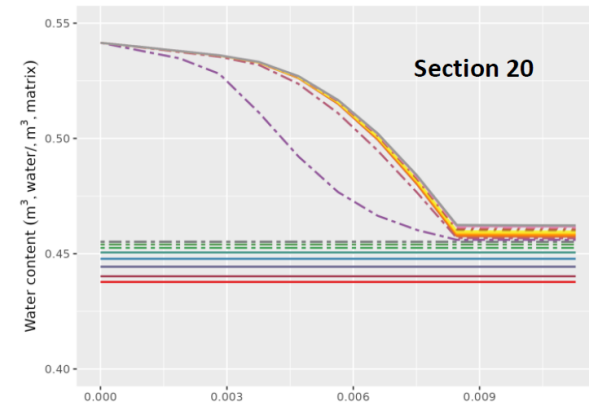
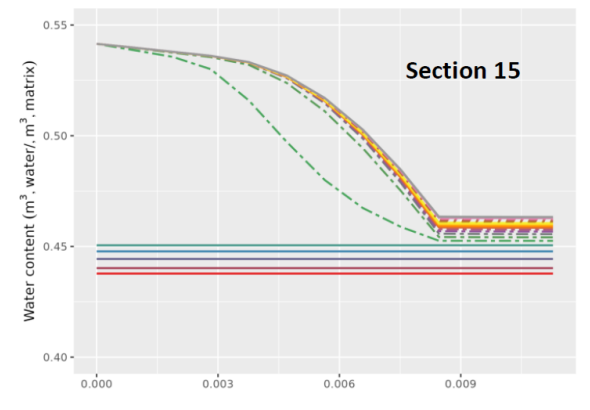
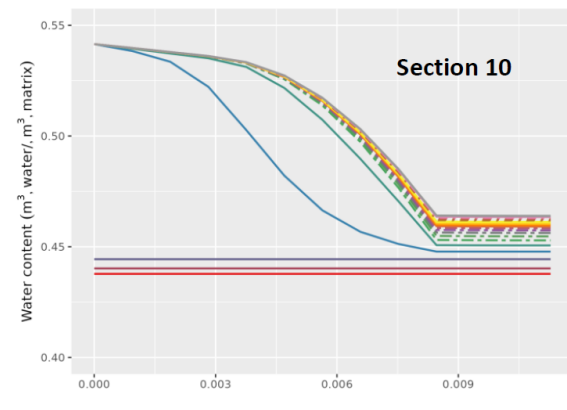
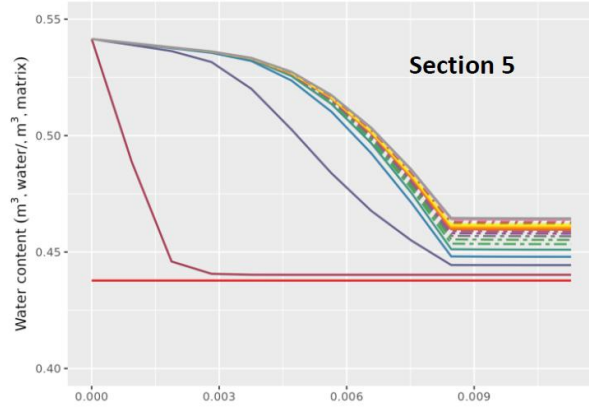
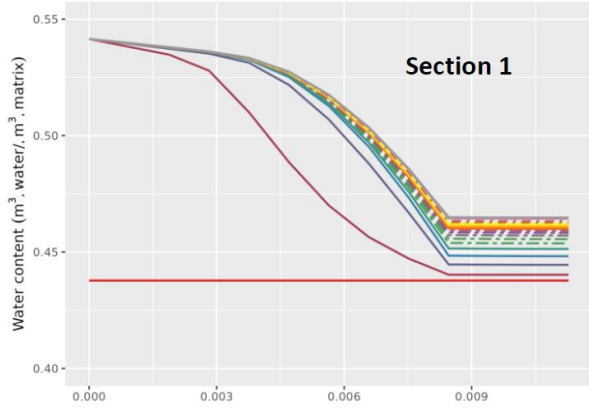
Grey-level histogram

$$\mu_i(\varepsilon_i S_i) = \varepsilon_i(S_i\mu_{water} + (1 - S_i)\mu_{air}) + (1 - \varepsilon_i)\mu_{soilmatrix}$$



Grey-level histogram of subtracted images





times

