EmmaH
UMR 1114 INRA - UAPV
Environnement Méditerranéen et Modélisation des Agro-Hydrosystèmes

INRA SCIENCE & IMPACT

AVIGNON UNIVERSITÉ

Transport dans les sols:

Eau, colloïdes, contaminants,

imagerie, mécanismes, modèles.

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Yvan Capowiez, Stéphane Ruy, Philippe Beltrame

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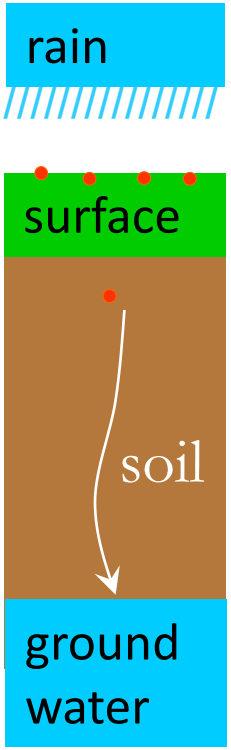
Évolution des services rendus par les sol

Prédire la capacité des sols à:

- servir de filtre protégeant les aquifères
- supporter l'agriculture

Sous l'impact des:

- activités humaines,
- pratiques agricoles
- changement climatique



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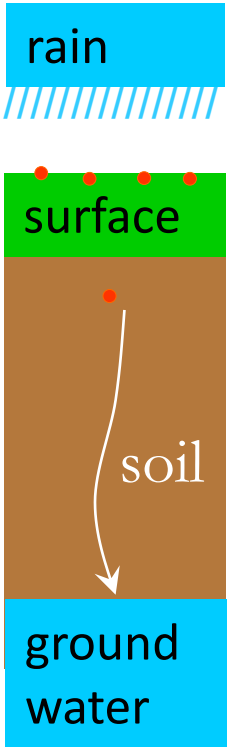


Contaminant transport models

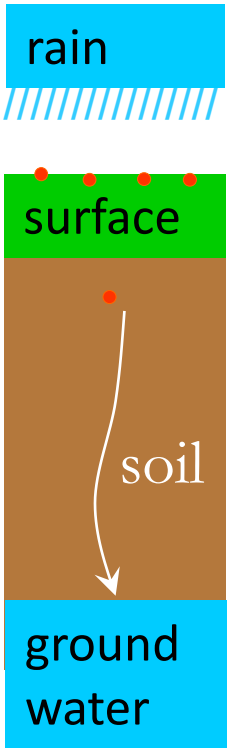
Soil evolution models

generic models of water, solute & colloid transport in soils

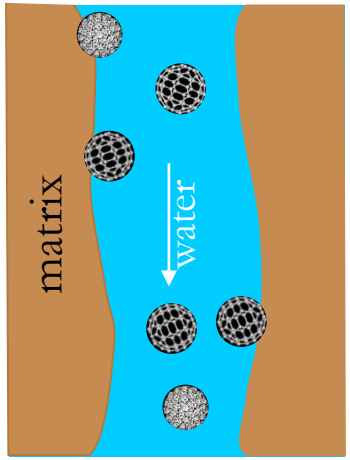
transport mechanisms

Contexte

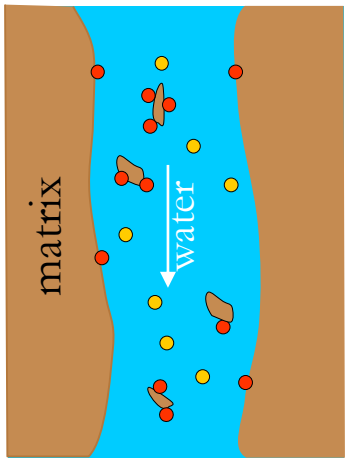
transport de colloïdes dans les sols



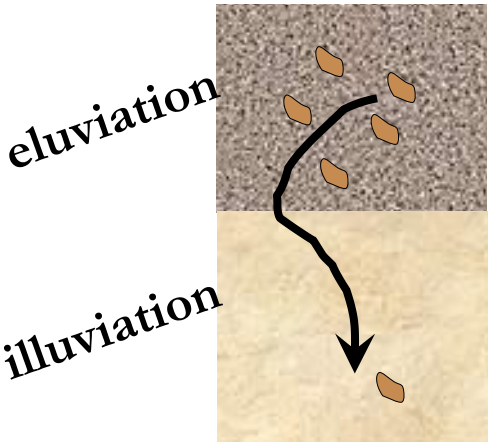
- contaminants



- Vecteurs de contaminants adsorbés



- Acteurs d'un processus de formation des sols



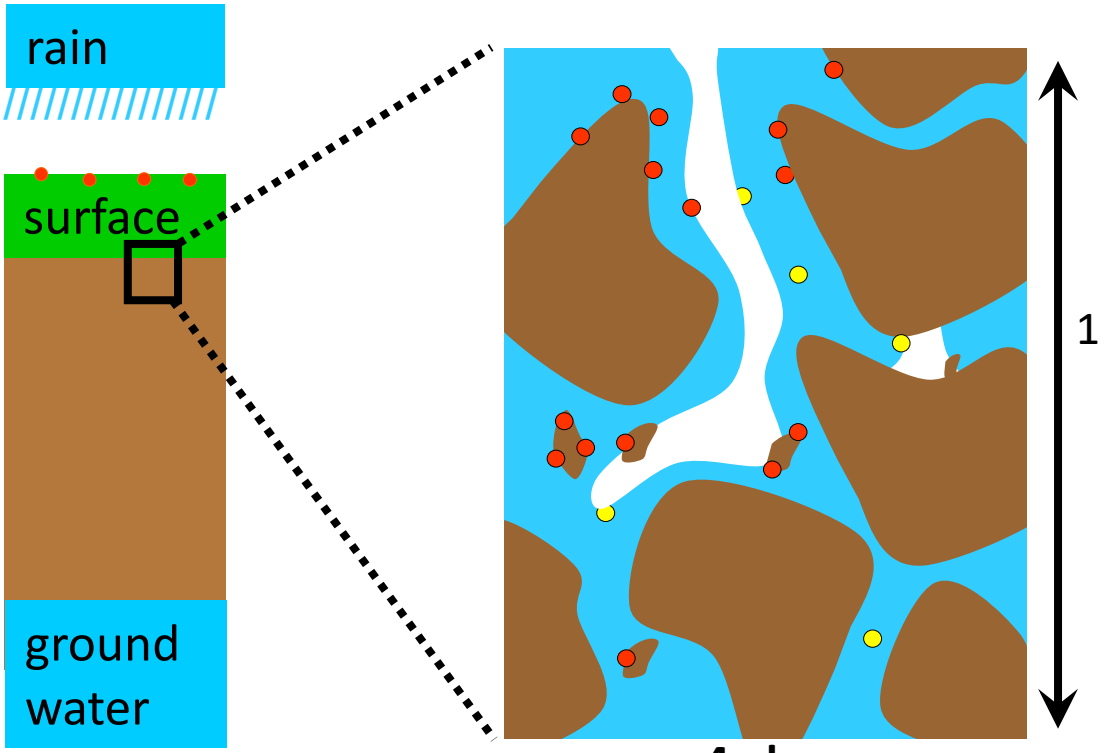
Groundwater quality

Soil evolution

natural soil colloid mobilization mechanisms ?

colloid retention mechanisms ?

preferential macropore flow



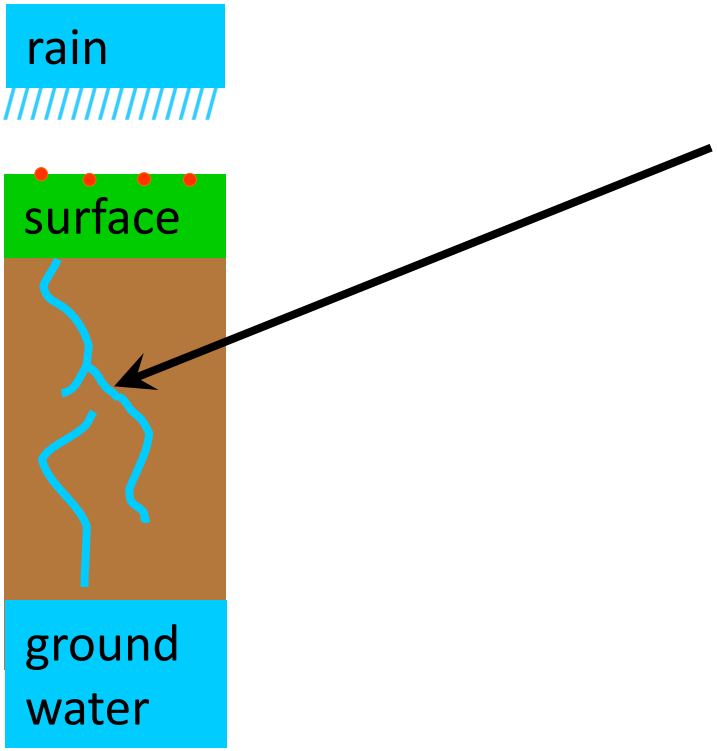
Matrix:

- Capillary pores,
- Darcy-Richards law applies

4 phases:

water, immobile soil, colloids, air

preferential macropore flow



Macropores :

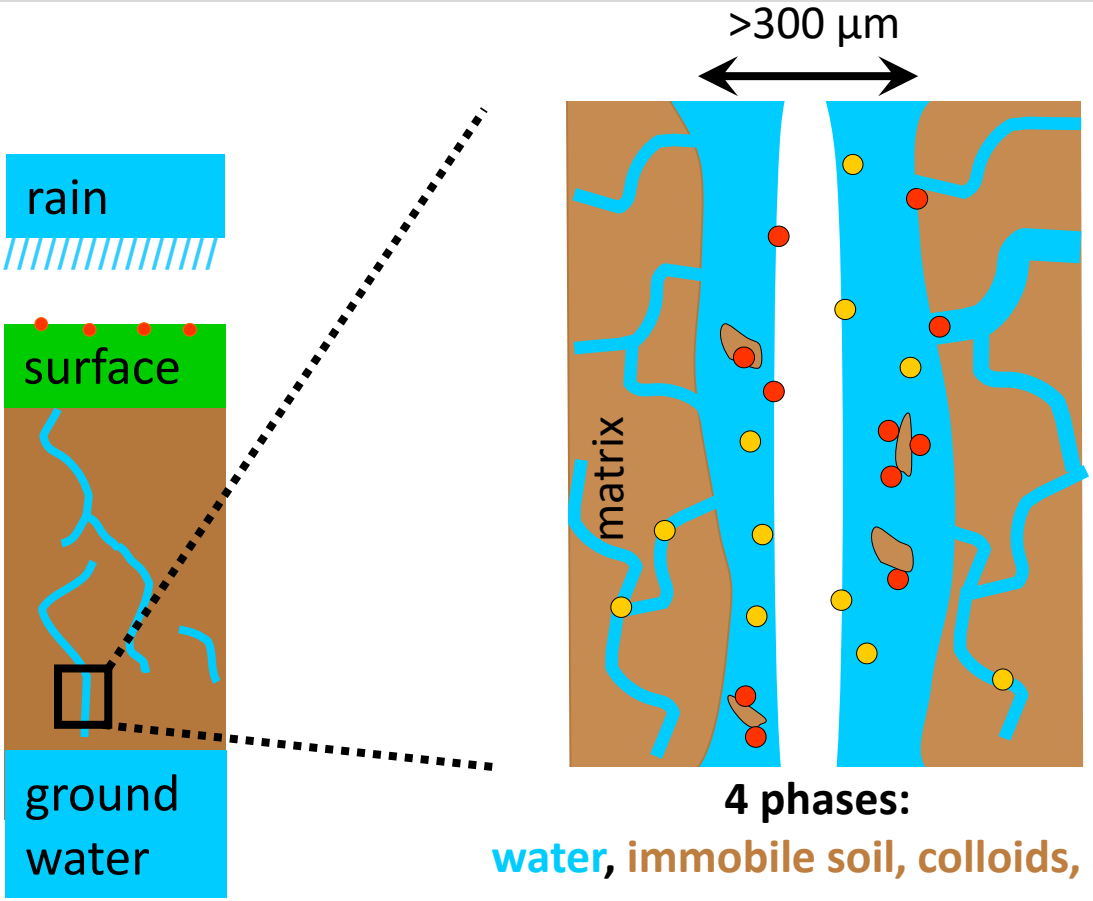
- earthworm burrows,
- space left by decayed roots

→ gravity driven water transport

→water bypasses the soil matrix

Contexte

preferential macropore flow



4 phases:

water, immobile soil, colloids, air

- relation macropore network geometry and transfert ?

- how does macropore flow affect colloid mobilization?

retention ?

Macropore flow...

relation macropore network geometry and transfert

modeling macropore flow

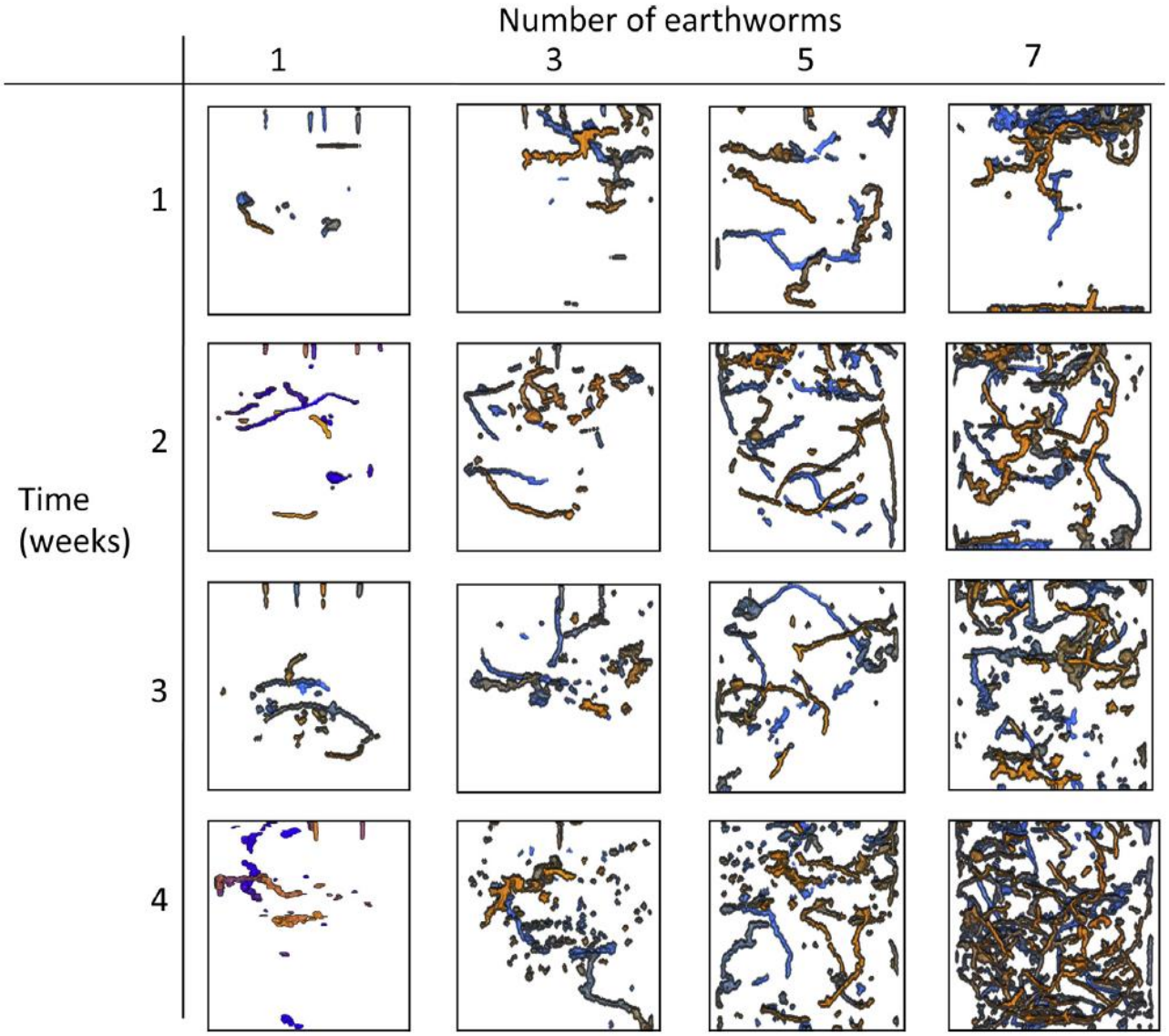
Colloid transport

relation macropore flow natural colloid mobilization

magnetic resonance imaging

Preferential macropore flow

relation macropore network ⟷ water & colloid transfert ?



Capowiez et al. *Pedobiologia*, **2014**

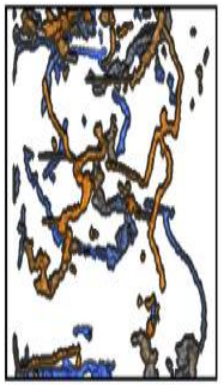
Preferential macropore flow

relation macropore network ⟷ water & colloid transfert ?

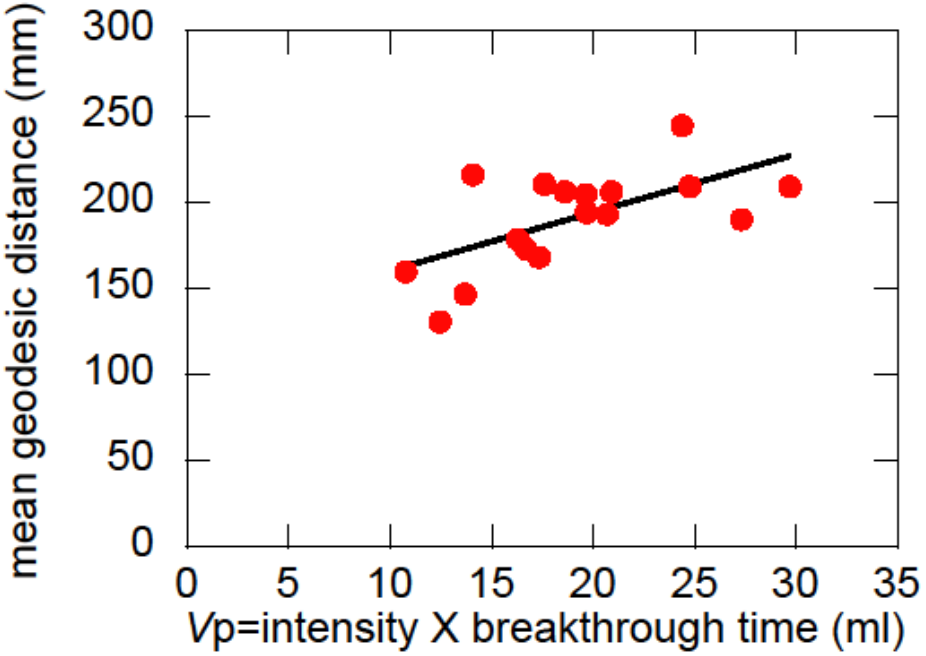
Colloïdes:

Aucune relation statistique entre
quantités de colloïdes naturels élués et
caractéristiques des galeries !

Eau:



Distance géodésique moyenne



Explique seulement 14% de la variation de V_p :

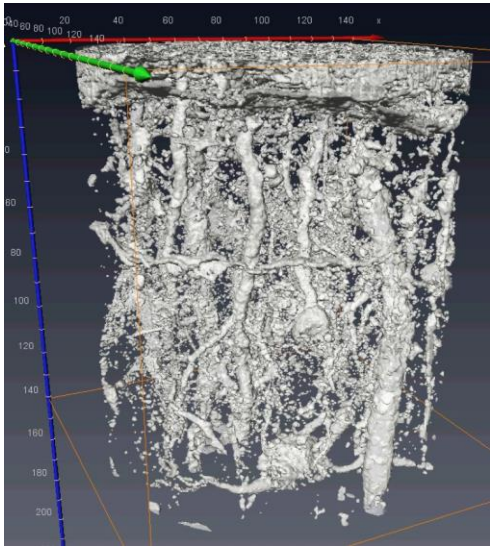
Tous les pores ne sont peut être pas actif !

Capowiez et al. *Pedobiologia*, **2014**

Preferential macropore flow

vers une identification du réseau de macropore actif

Macropore network imaged with X-ray CT



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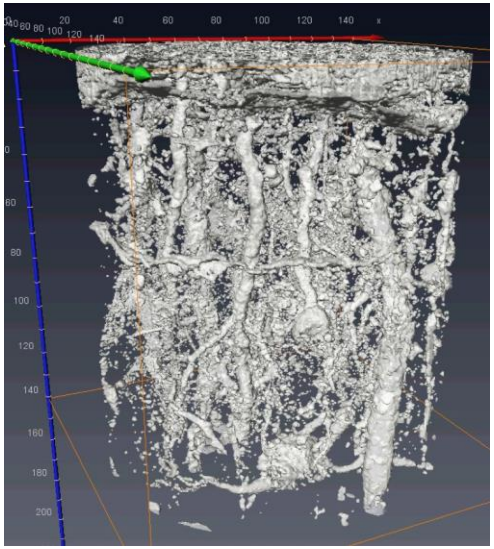
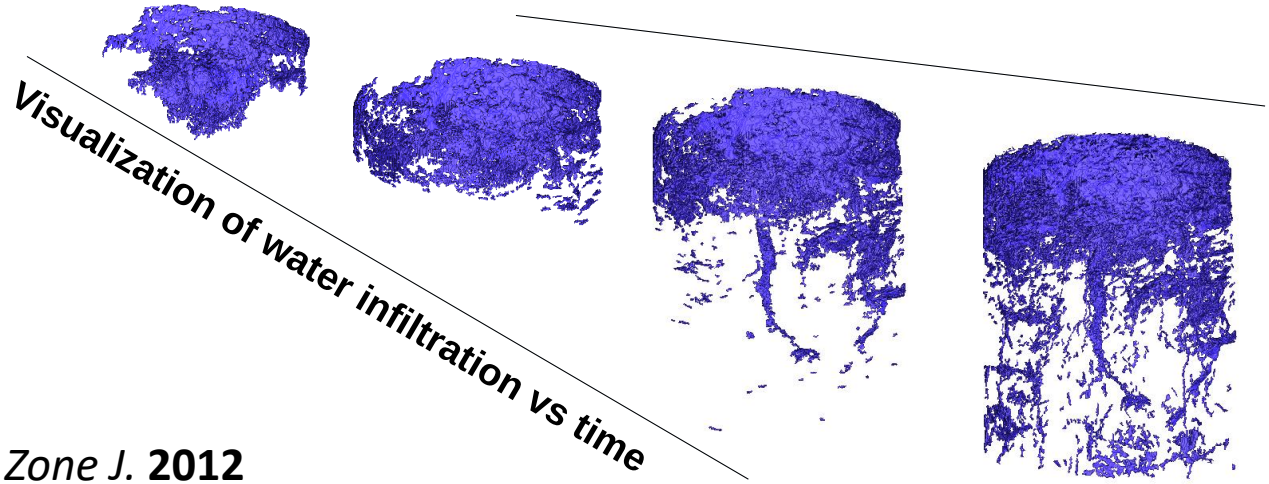


Time lapse X-ray CT imaging

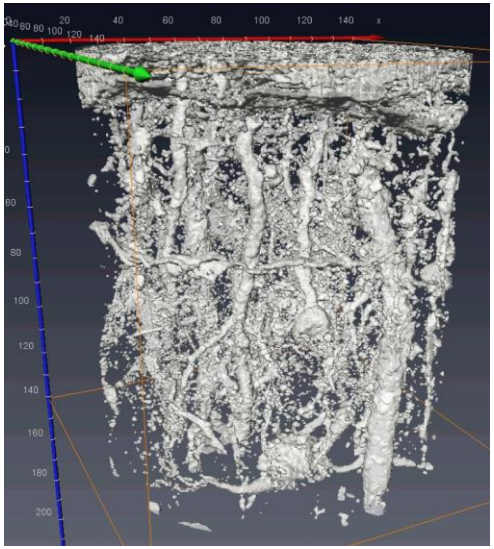


Sammartino et al. *Vadoze Zone J.* **2012**

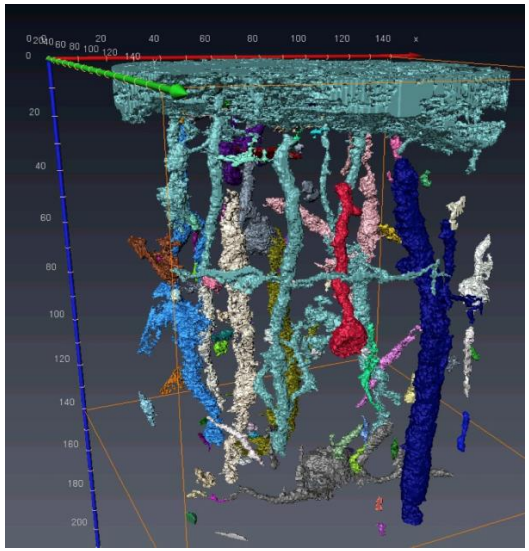
Preferential macropore flow

vers une identification du réseau de macropore actif

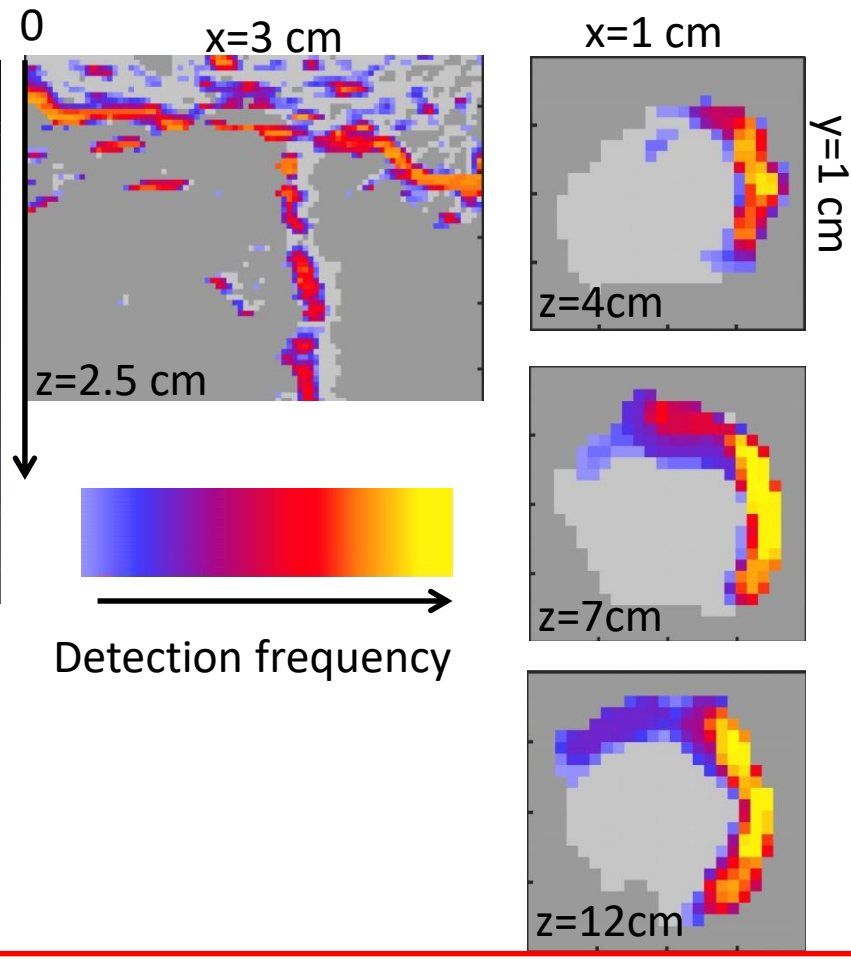
Total macropore network



Functional part of the macropores network



Water-soil interfacial area



Sammartino et al. *Vadoze Zone J.* **2015**

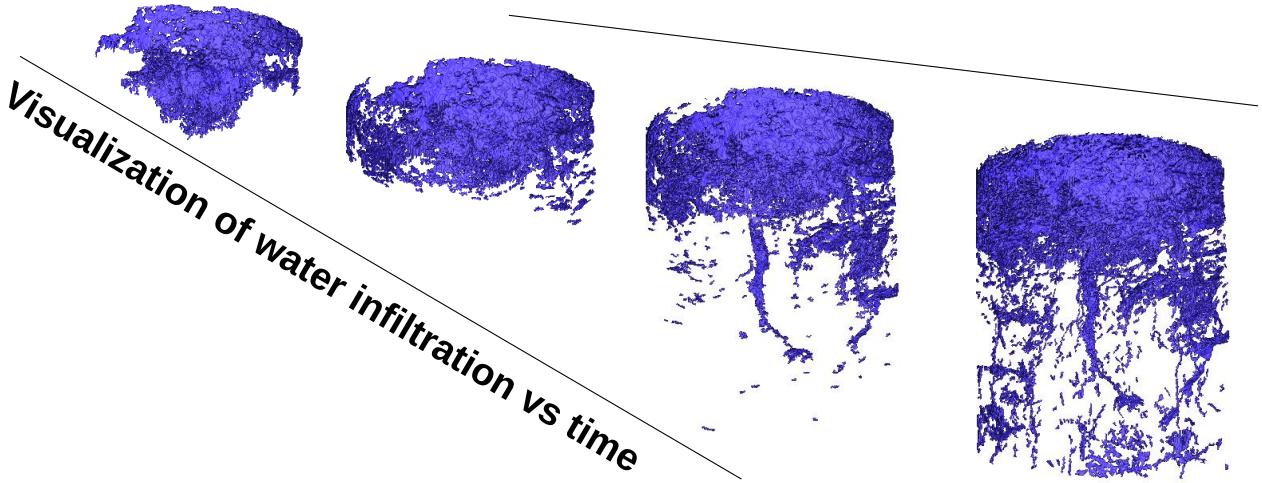
stephane.sammartino@univ-avignon.fr

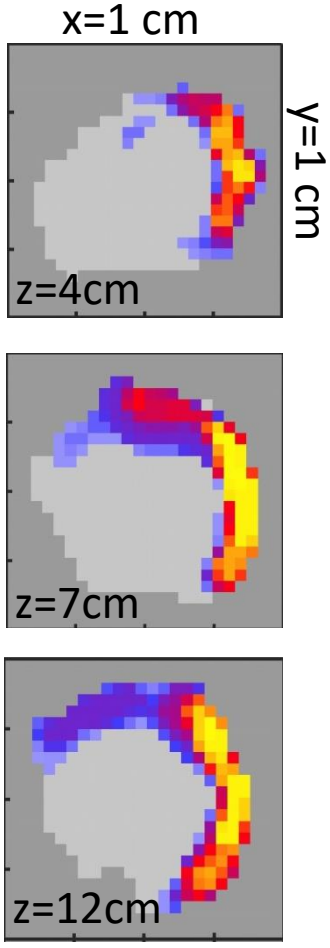
improved qualitative knowledge of flow processes

Useful for models ?

Preferential macropore flow

modélisation





- macropores: taille > 0.3 mm
- la capillarité ne s'applique pas:
  le modèle de Darcy-Richards n'est pas une option.
- la gravité est le moteur de l'écoulement
- les macropores ne sont pas saturés
- l'eau s'écoule sous forme de films

Quel(s) modèle(s) ?

Preferential macropore flow

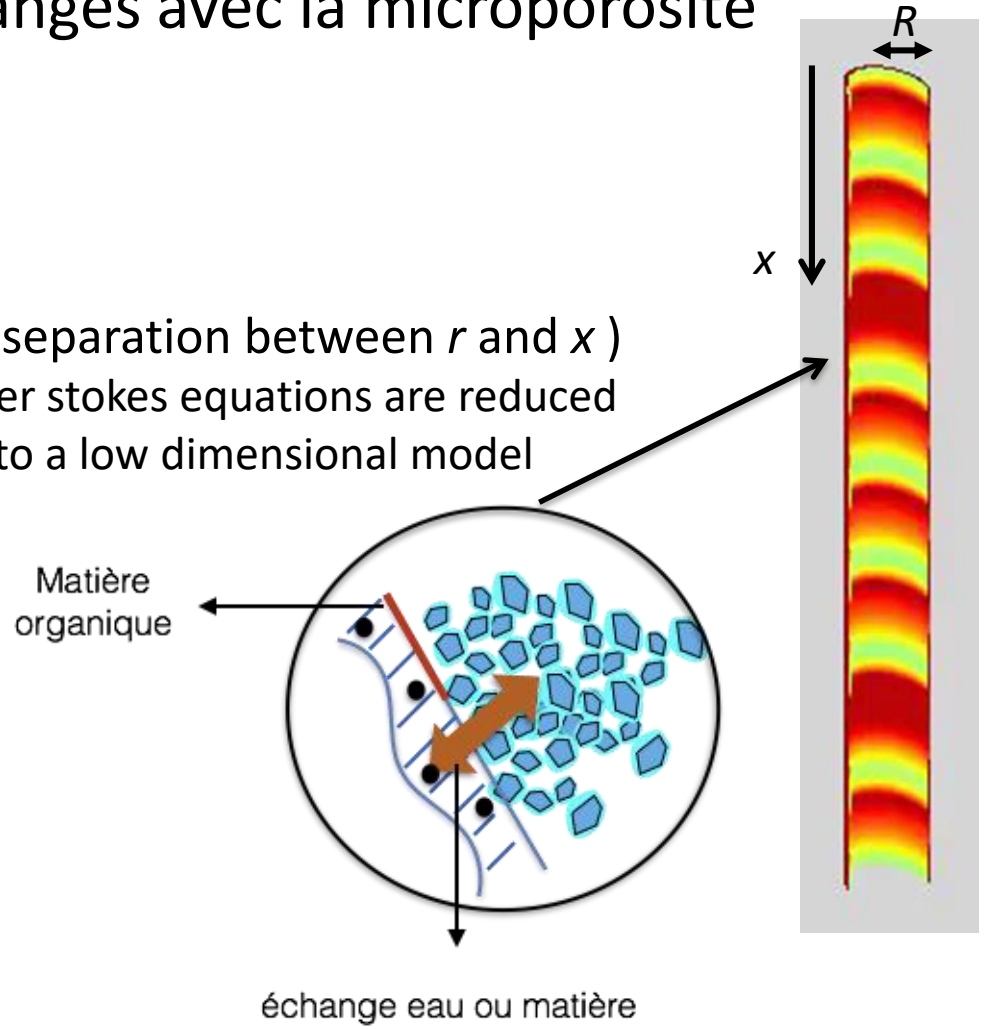
Film flow in a macropore

Equations de Navier-Stokes prenant en compte mouillabilité et échanges avec la microporosité

Assumptions

- Low macropore saturation
  —> No capillary liquid bridge
- Axisymmetric problem
- longwave approximation

(scale separation between *r* and *x*)
Navier stokes equations are reduced to a low dimensional model



Physical parameters

- Viscosity
- Surface tension
- **Wettability** → partial wetting.
- exchange with microporosity

Beltrame. *Europhysics Letters.* **2018**
philippe.beltrame@univ-avignon.fr

Preferential macropore flow

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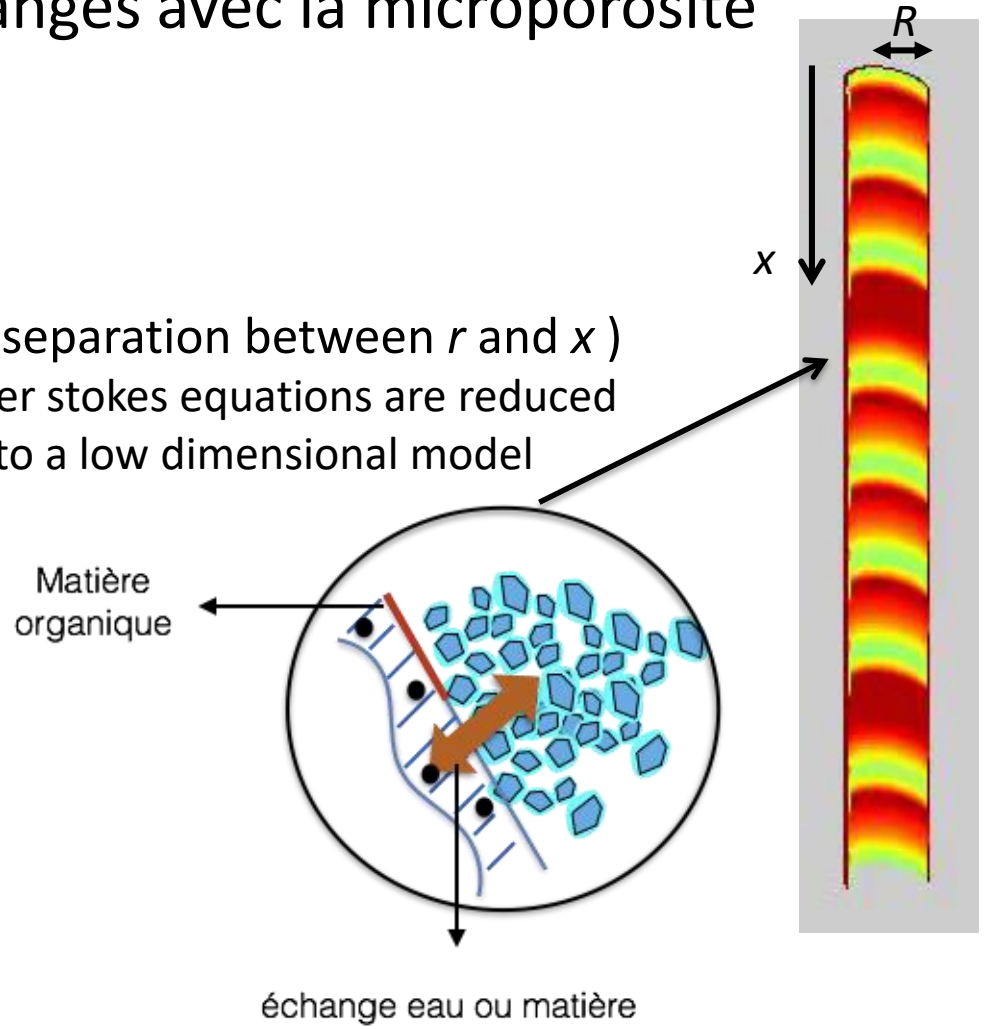

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Beltrame. *Europhysics Letters.* **2018**
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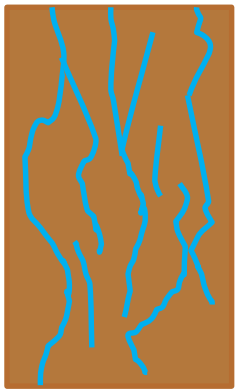
Modèle des ondes cinématiques

$$\frac{\partial f}{\partial t} = -c(\theta)\frac{\partial f}{\partial z}$$

$$f(t,z) = b\,\theta^{a}$$



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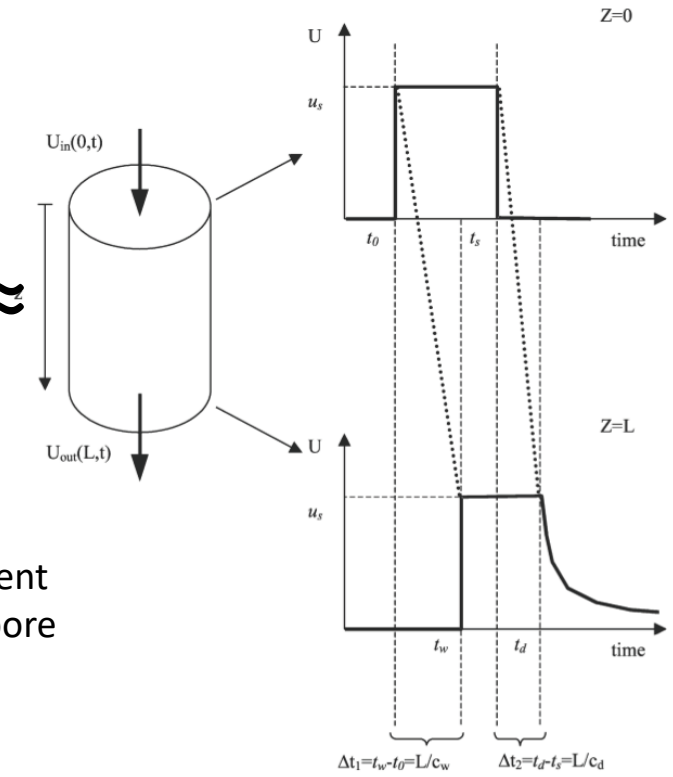
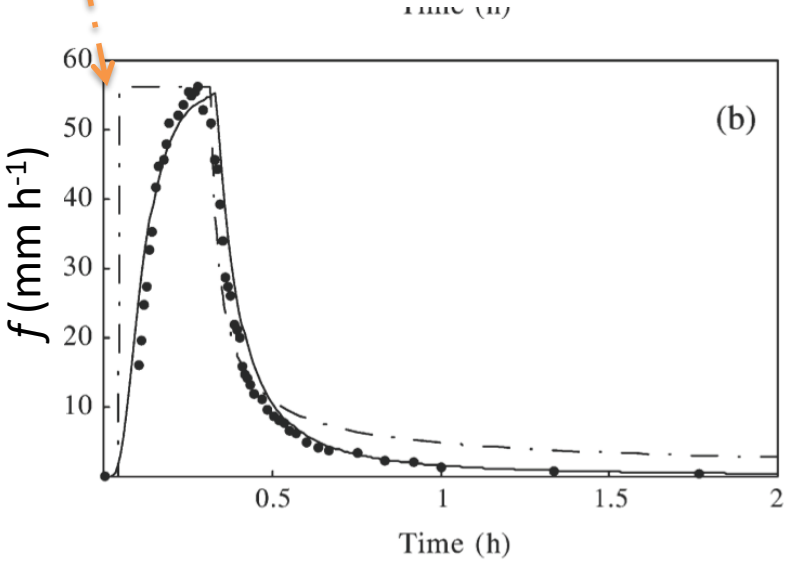


Equivalent macropore



Beven &Germann, **1981**

Interaction Sol – Eau

Modèle des ondes cinématiques

Modelo de las Ondas Cinemáticas

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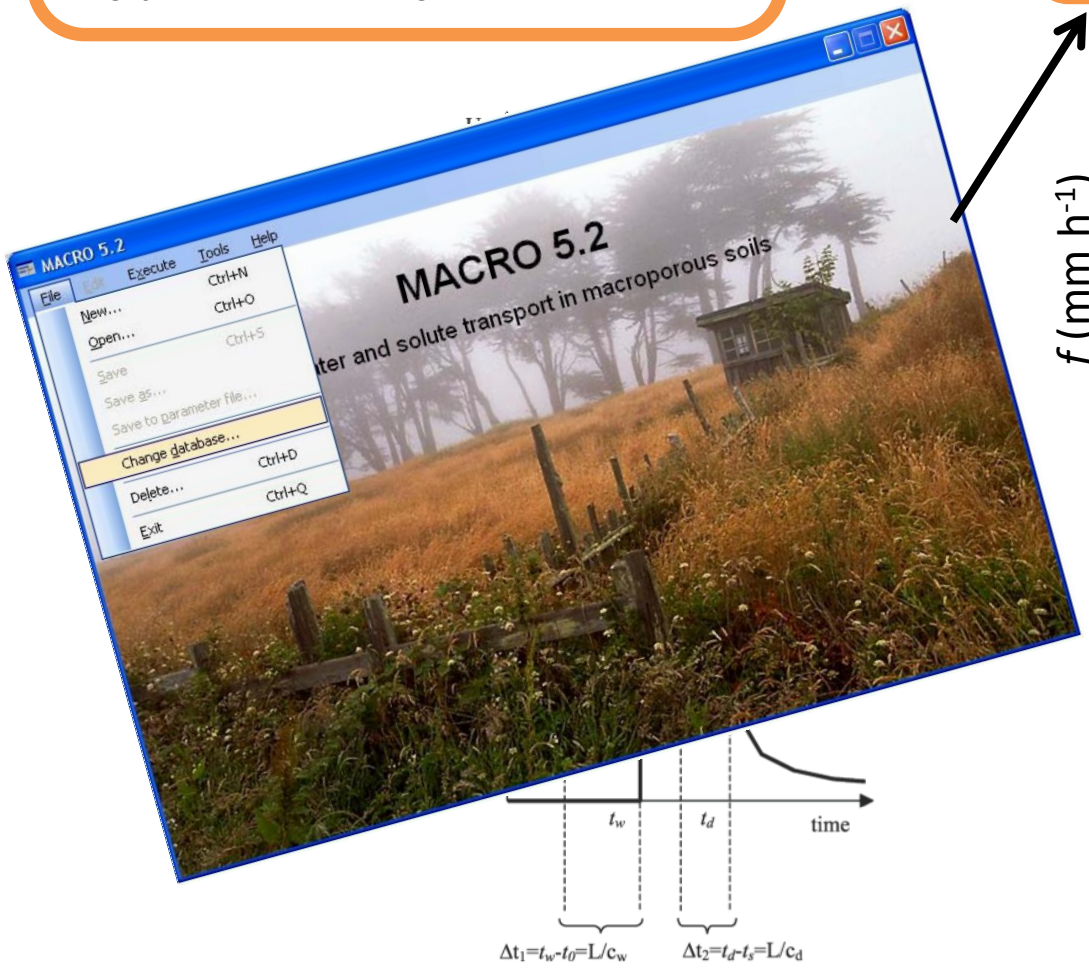
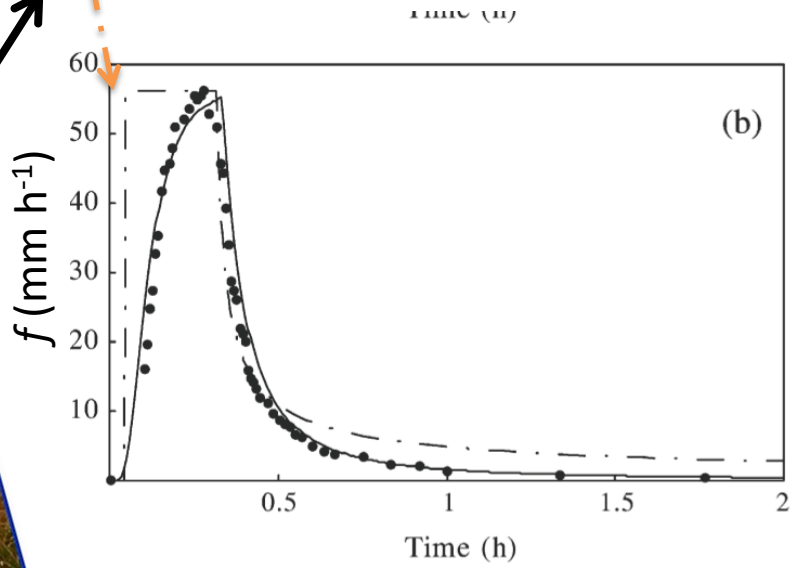




Beven &Germann, **1981**

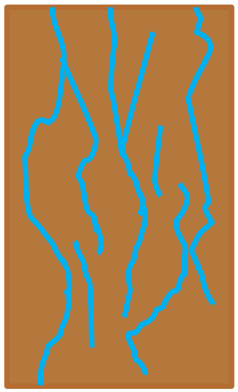
Interaction Sol – Eau

Modèle des ondes cinématiques

Modelo de las Ondas Cinemáticas

$$\frac{\partial f}{\partial t} = -c(\theta)\frac{\partial f}{\partial z} + \nu_f \frac{\partial^2 f}{\partial z^2}$$

$$f(t,z) = b\,\theta^{a}$$



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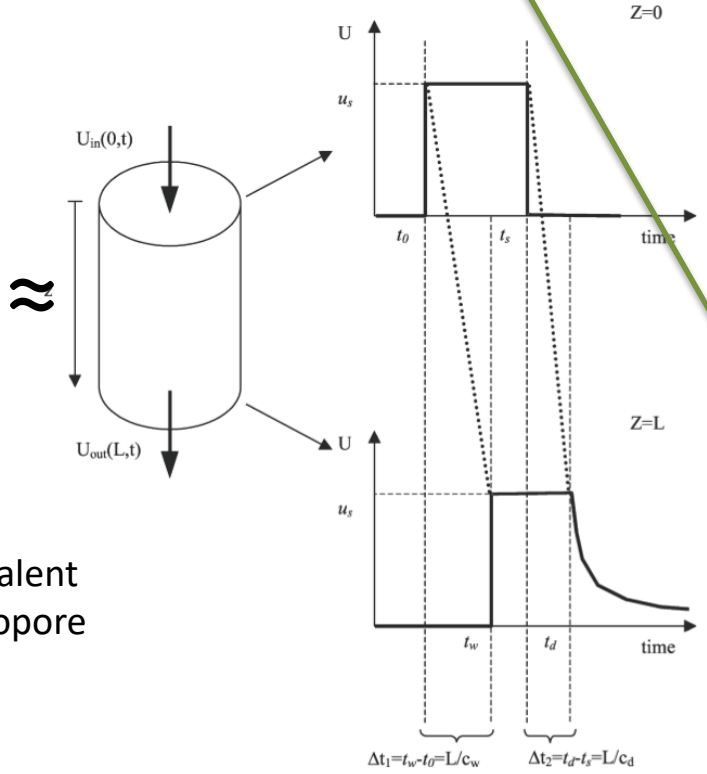
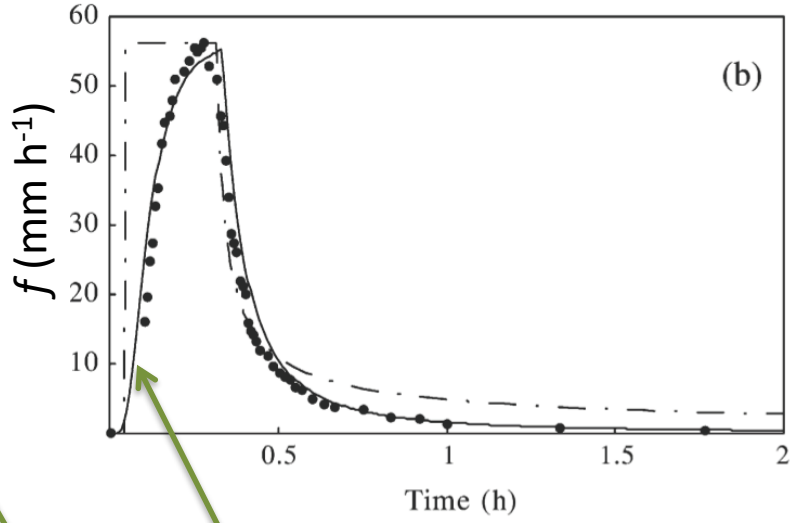




$$f(t,z) = b\,\theta^{a} - \nu_\theta \frac{\partial \theta}{\partial t}$$

Di Pietro, Ruy, Capowiez, *J. Hydrol.* **2003**

Preferential macropore flow

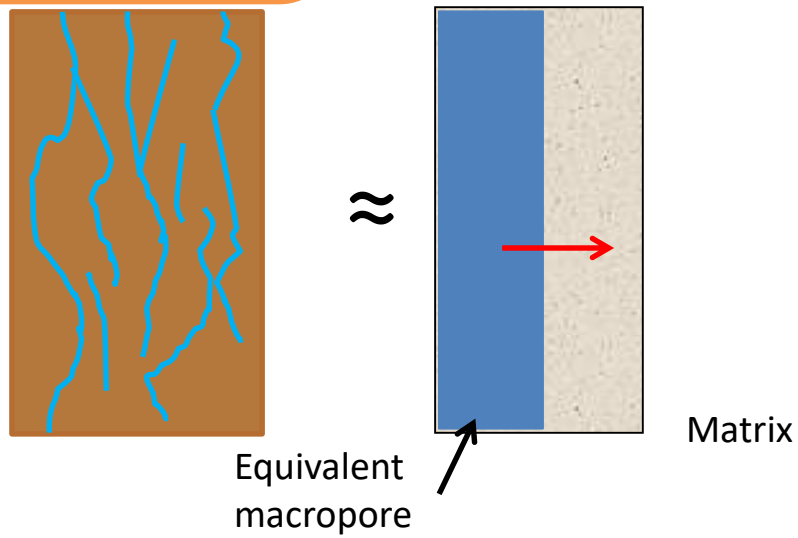
Kinematic Dispersive Wave model

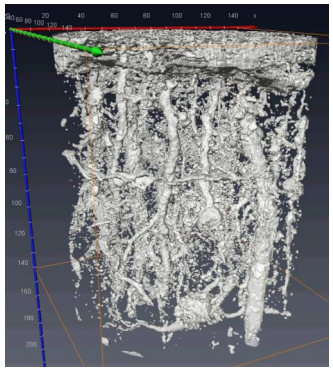
Modelo de las Ondas Cinemáticas

$$\frac{\partial f}{\partial t} = -c(\theta_{\text{mac}})\frac{\partial f}{\partial z} + \nu_f \frac{\partial^2 f}{\partial z^2} - S$$

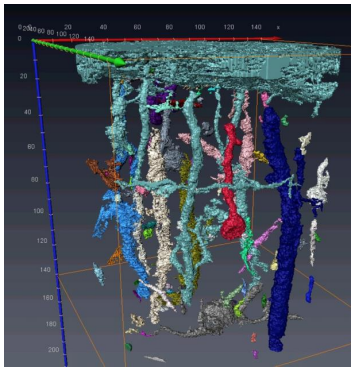
Ecuación de Darcy-Richards

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left(K(h)\frac{\partial H}{\partial z}\right) + S$$



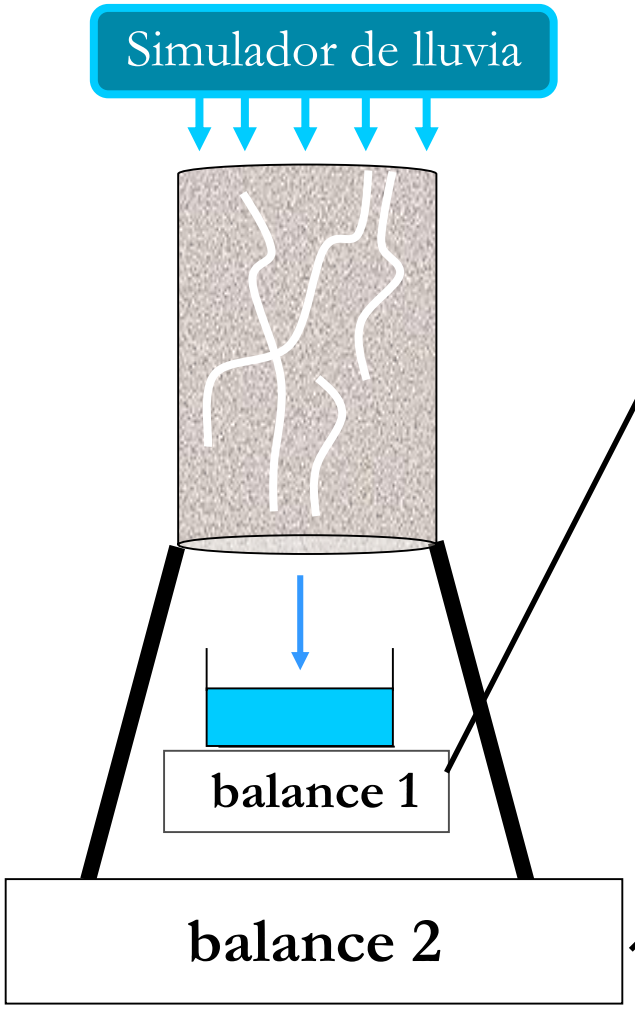


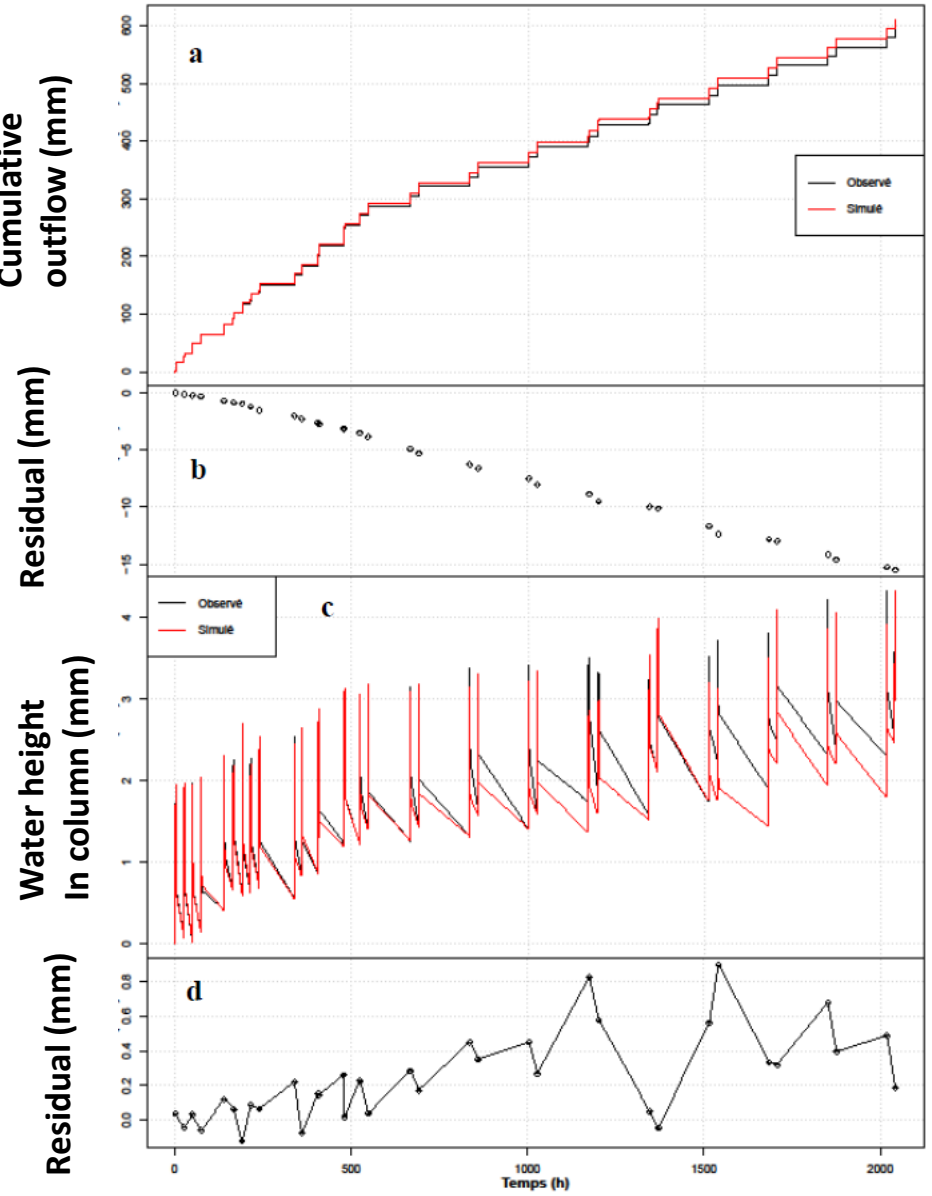
$$S = -\frac{K(h)}{d} \times \frac{0-h}{d} \times \frac{\theta_{\text{mac}}}{\theta_{\text{mac\_max}}}$$



Interaction Sol – Eau

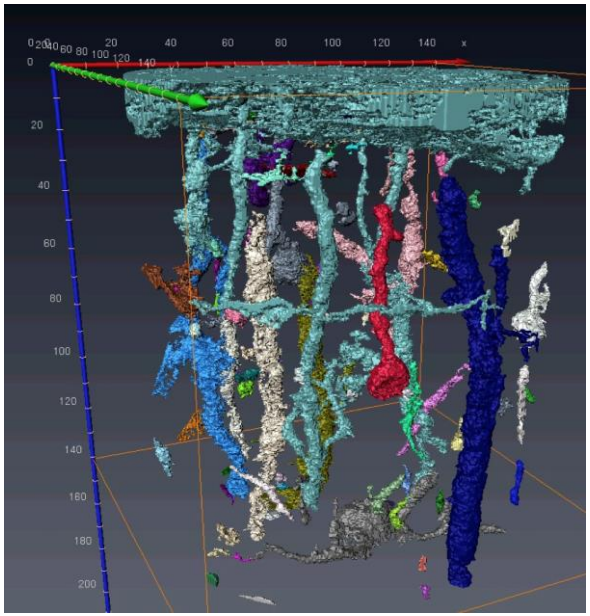
Modèle des ondes cinématiques

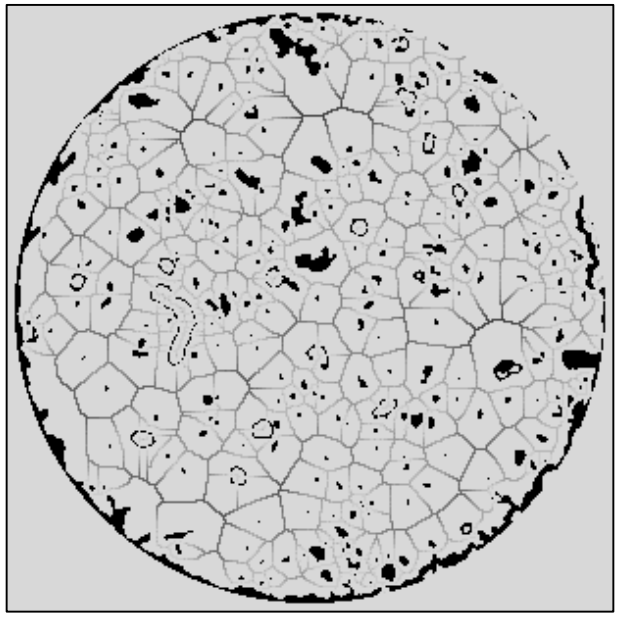




Preferential macropore flow

Linking model X-ray CT images





Using the 3D images to determine a priori values of model parameters:

$$d = f(z)$$

$$\theta_{\text{mac\_max}} = f(z)$$

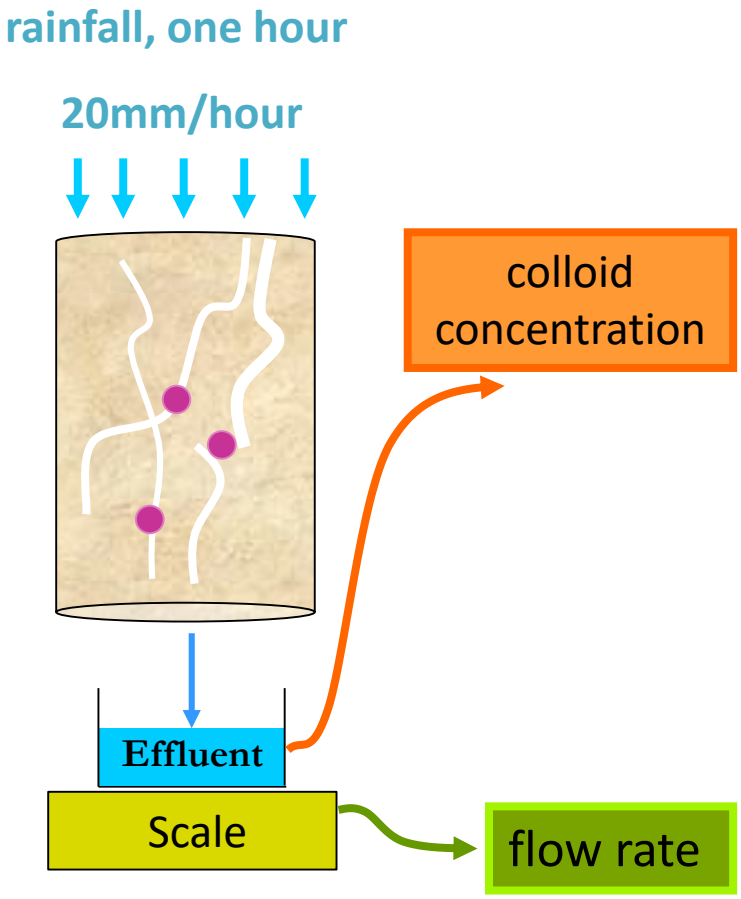
$$S = -\frac{K(h)}{\boldsymbol{d}} \times \frac{0-h}{\boldsymbol{d}} \times \frac{\theta_{\text{mac}}}{\boldsymbol{\theta_{\text{mac\_max}}}}$$

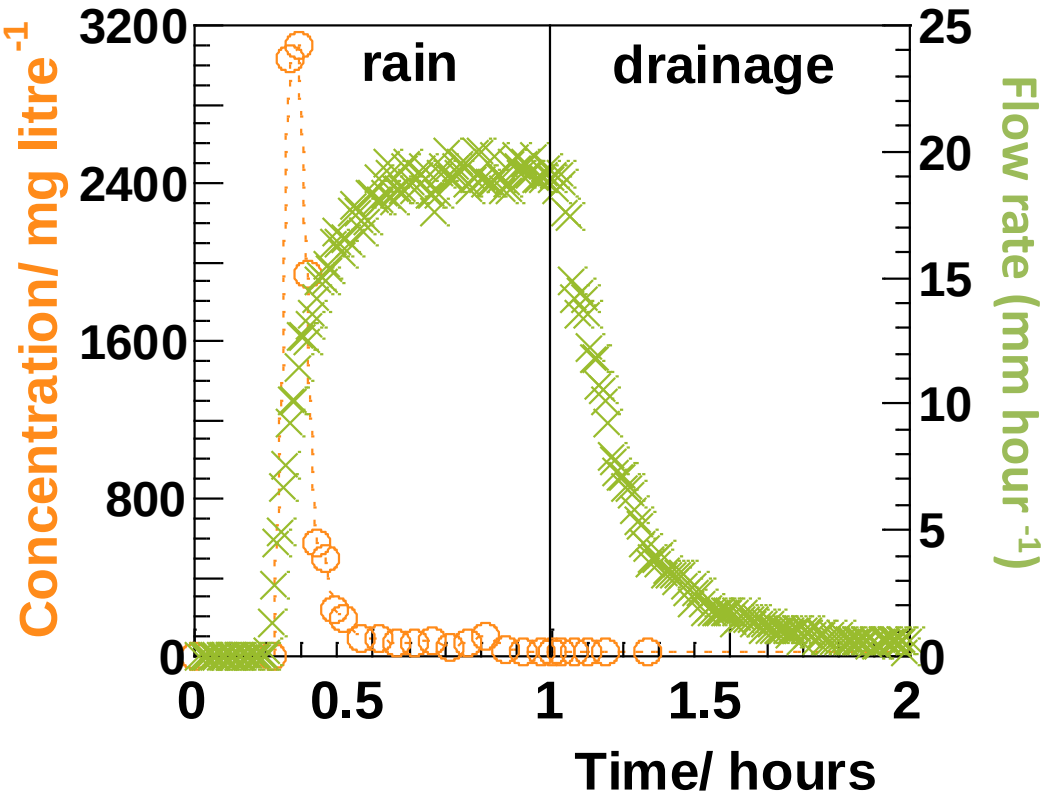
- n'améliore pas la reproduction des données expérimentales
- Diminue l'incertitude sur les valeurs des parametres déterminés par modélisation inverse

Lissy, *PhD Thesis,* **2018**

natural soil colloid mobilization

experimental set up and questions





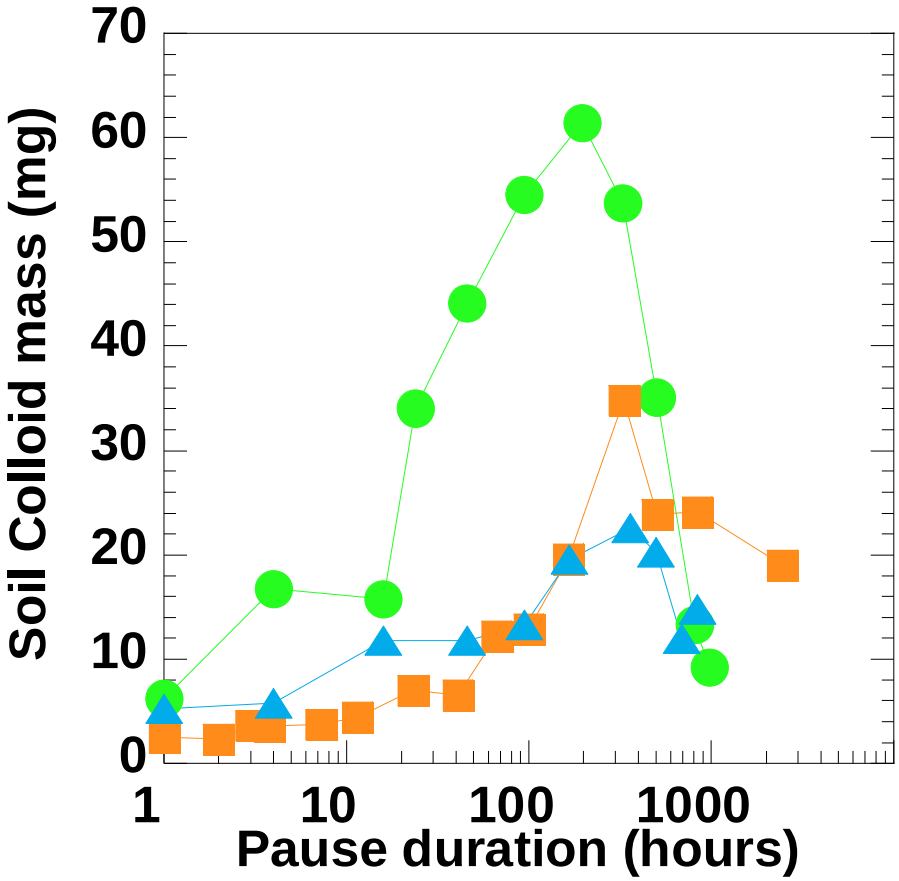
Peak during transient flow rate regime

La durée d'une période sèche entre deux pluies influence t-elle la hauteur du pic ?

natural soil colloid mobilization

results

Majdalani et al. *Eur. J. Soil. Sci.* **2008**, 59, 147-155



natural soil colloid mobilization

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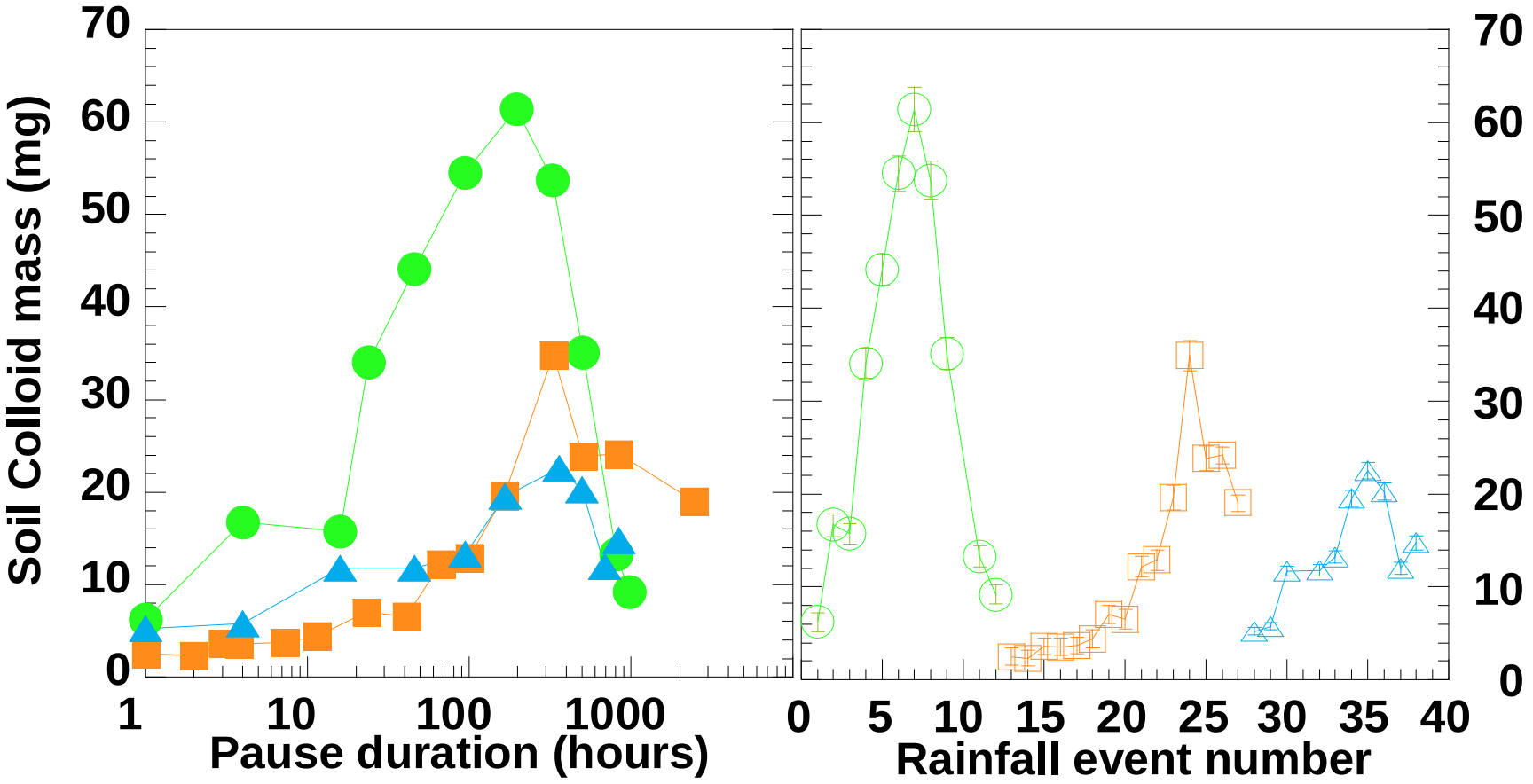

natural soil colloid mobilization

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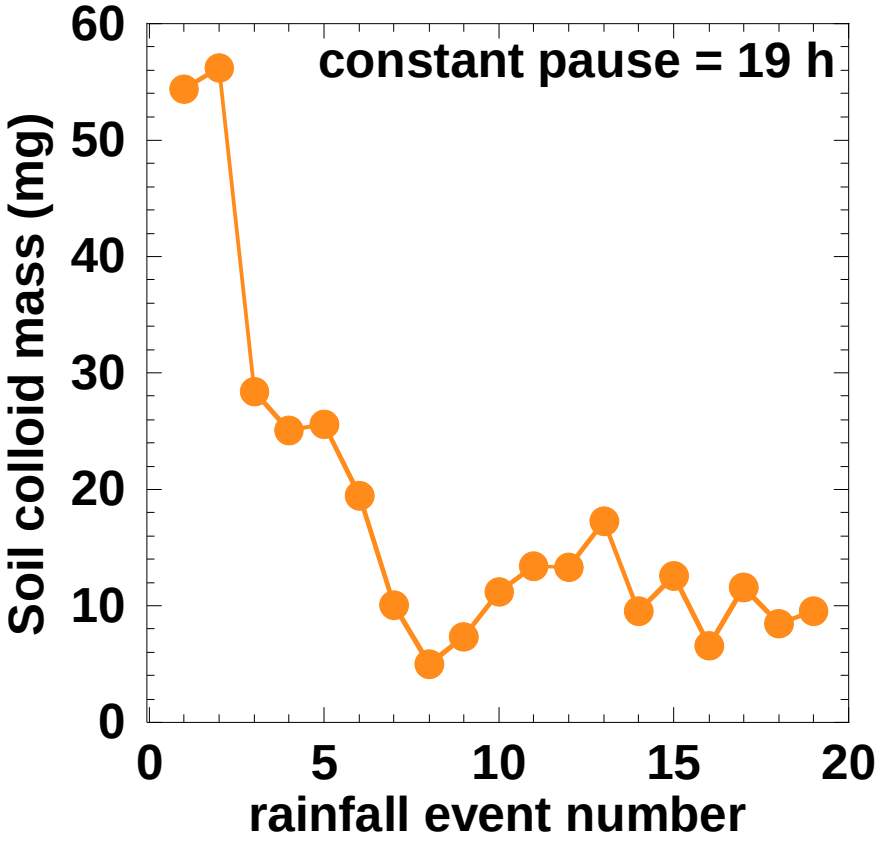
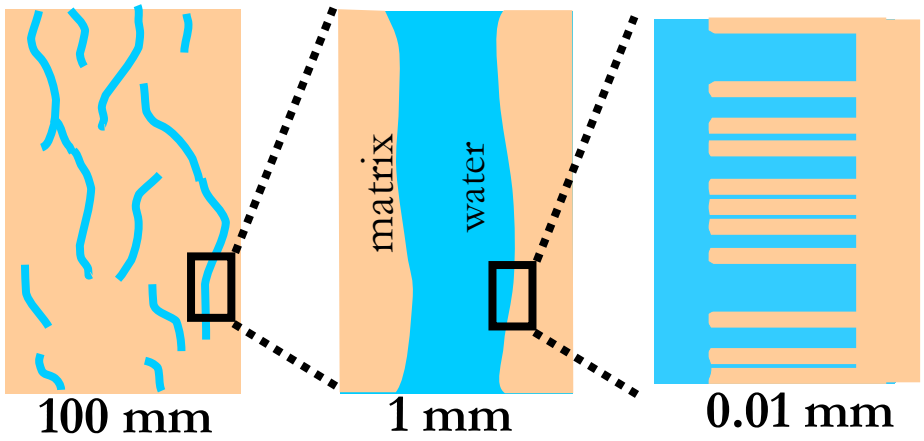


Constant rain interruption duration does NOT reproduce the pattern

colloid mobilization conceptual model



capillary pressure

r=100nm: 10^6 Pa

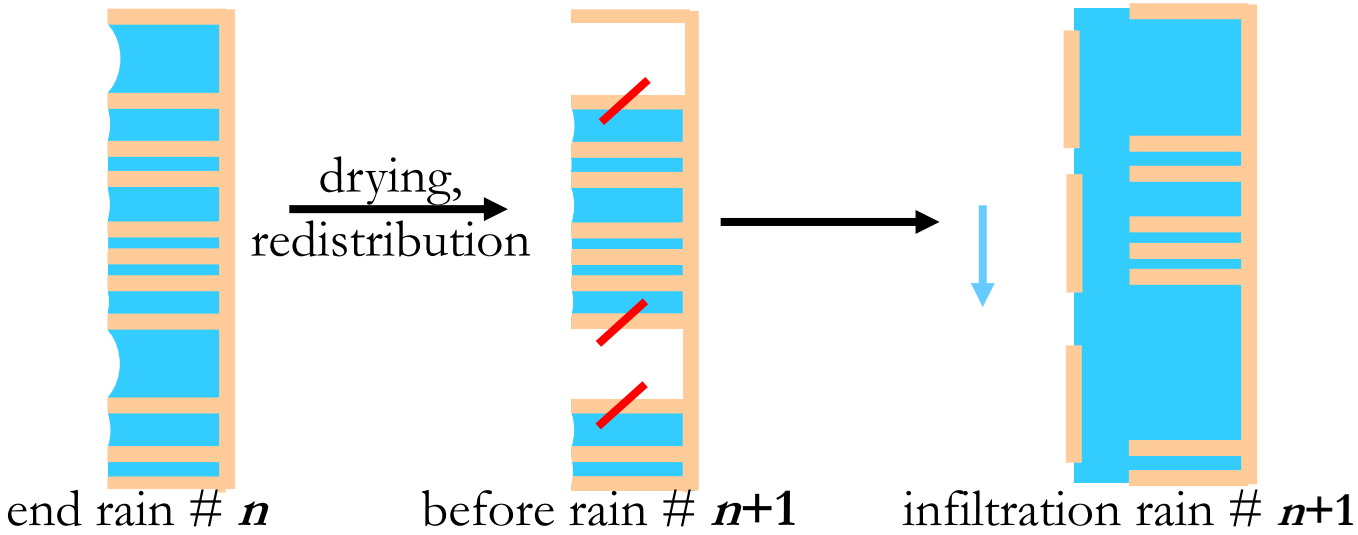
r=10μm : 10^3 Pa

rheometry:

10^2 Pa<yield stress<10^6 Pa

Ghezzehei et al , 2001

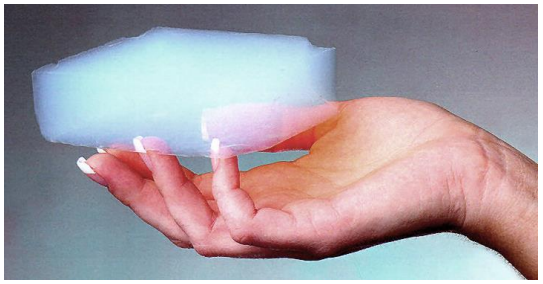
Hypothesis: differential capillary stresses weaken the walls separating an empty and a full pore.

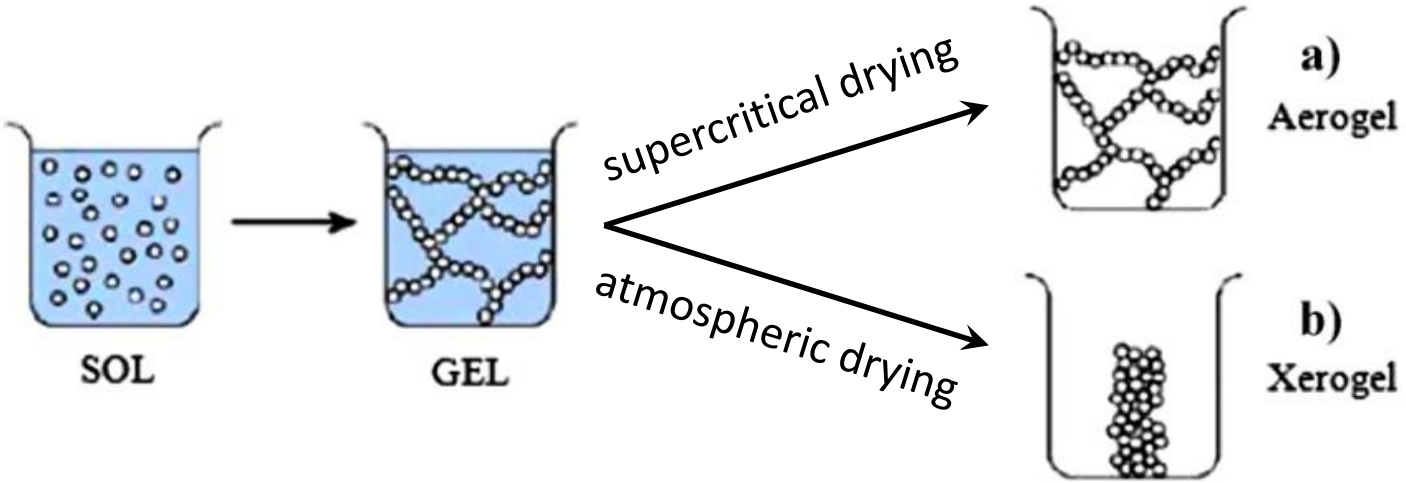


Michel et al. *Vadose Zone J.*, **2010**

colloid mobilization conceptual model

Zarzycki, et al. *Journal of Material Science*
Synthesis of glasses from gels: the problem of monolithic gels.**1982**

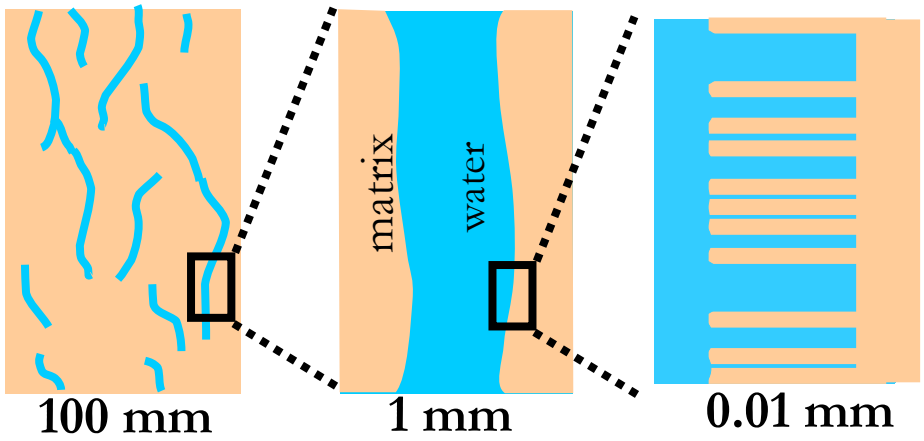




Sketch adapted from García-González et al. 2011.

Michel et al. *Vadose Zone J.*, **2010**

colloid mobilization conceptual model



capillary pressure

r=100nm: 10^6 Pa

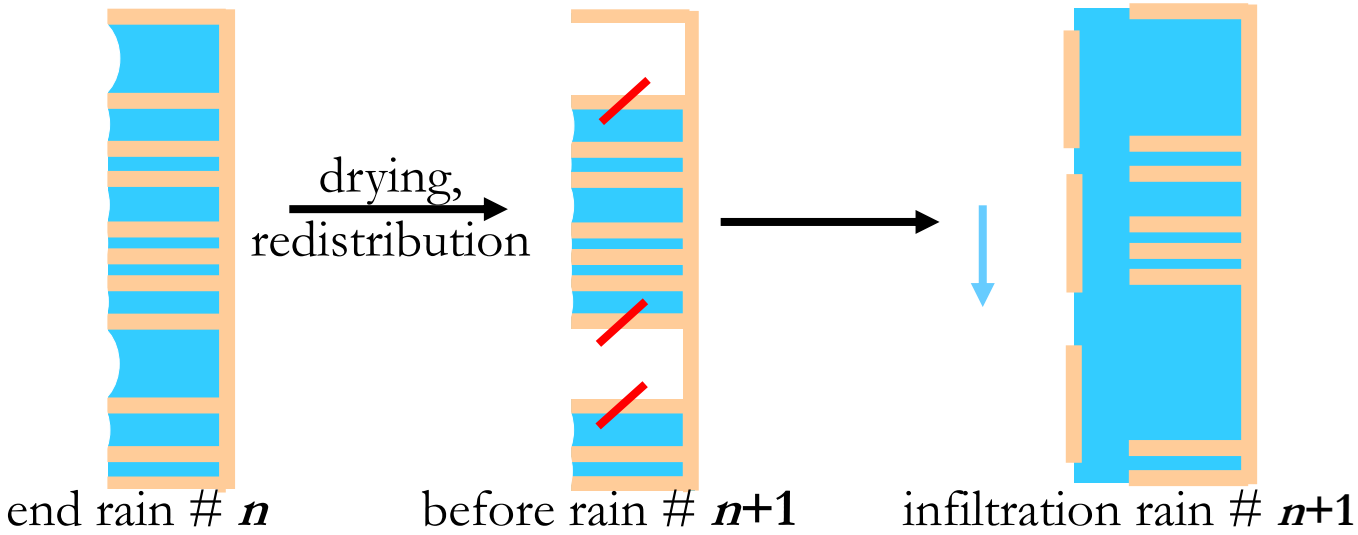
r=10μm : 10^3 Pa

rheometry:

10^2 Pa<yield stress<10^6 Pa

Ghezzehei et al , 2001

Hypothesis: differential capillary stresses weaken the walls separating an empty and a full pore.



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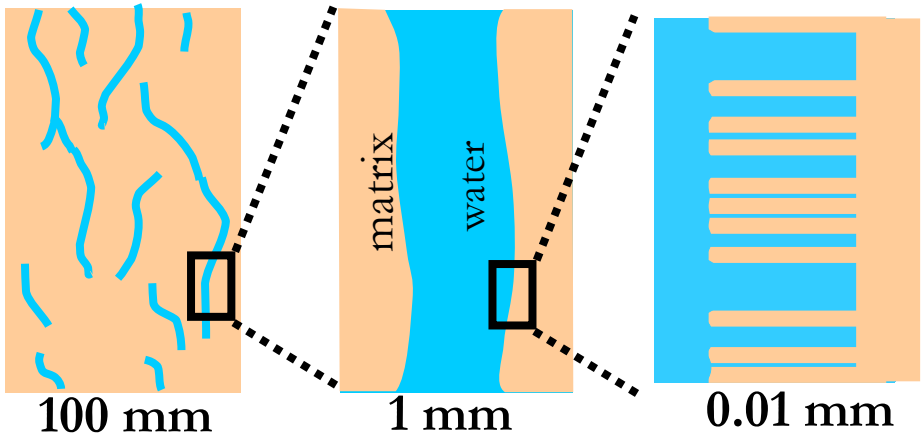

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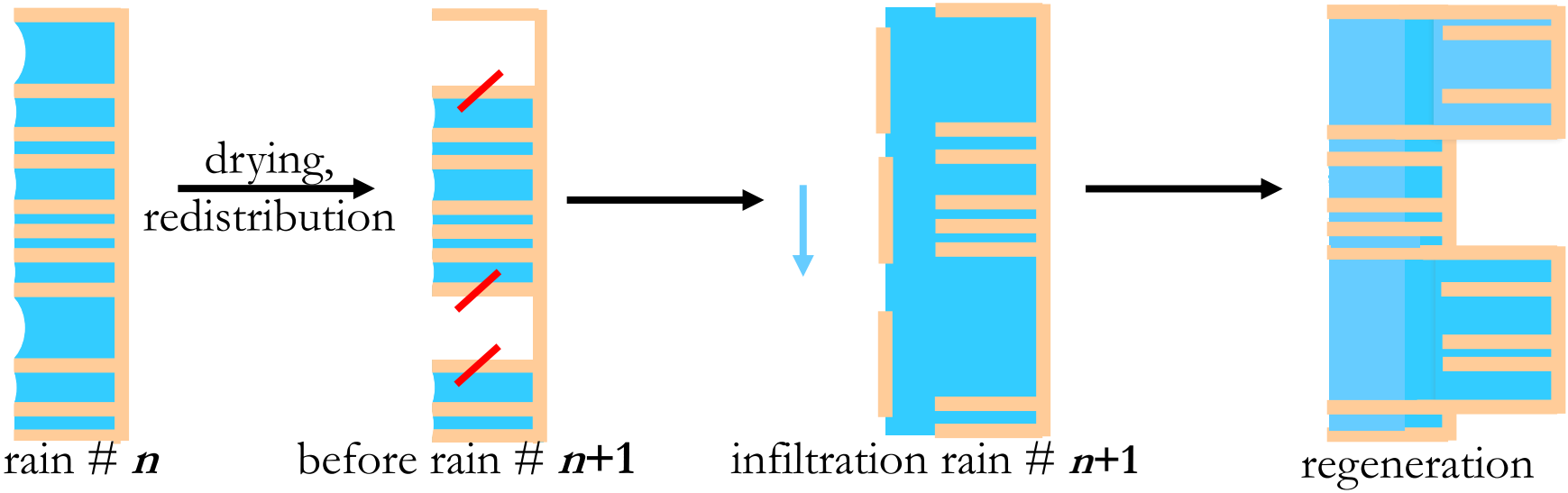
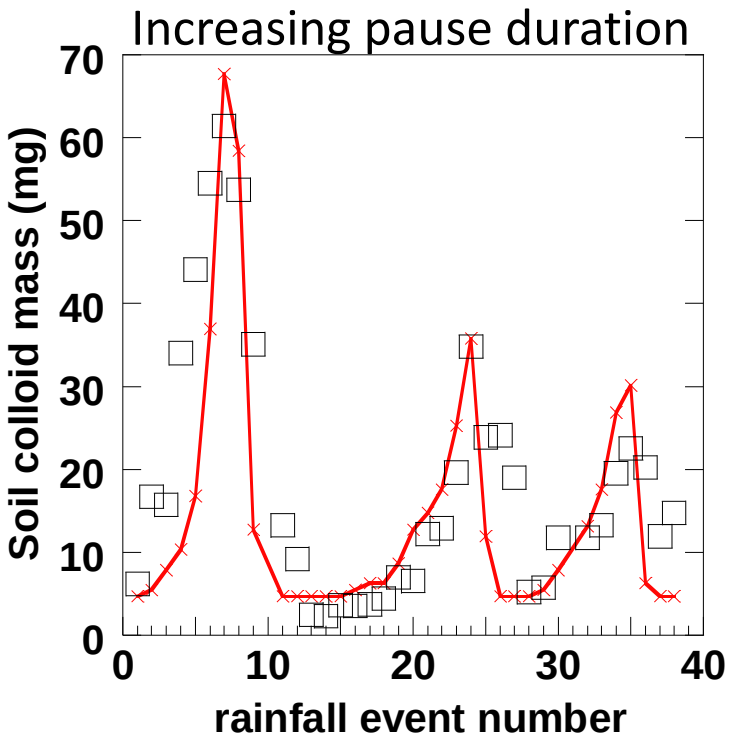


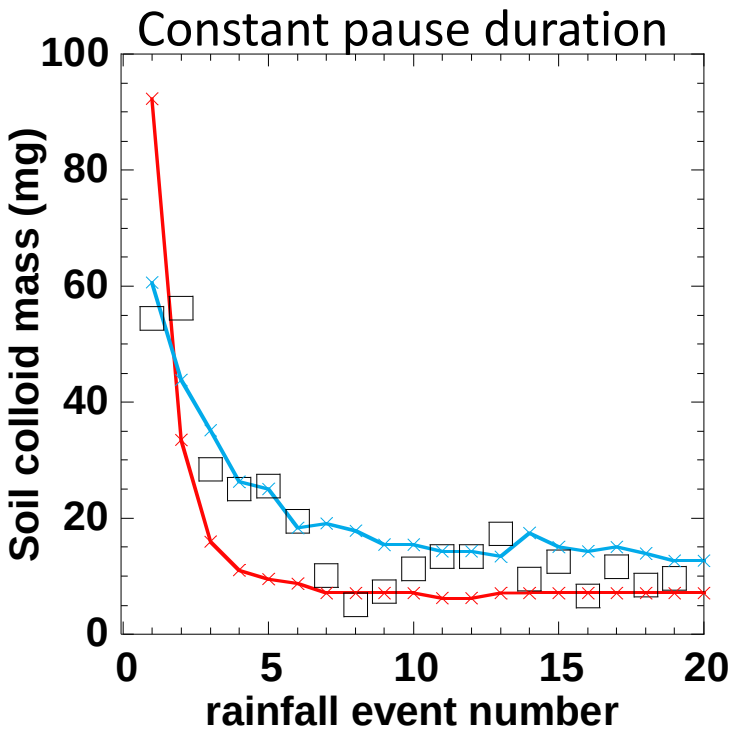
Michel et al. *Vadose Zone J.*, **2010**

natural soil colloid mobilization

numerical model (Vsoil platform)

Michel et al. , *Eur. J. Soil Sci.*, **2014,** *65* (3), 336-347.



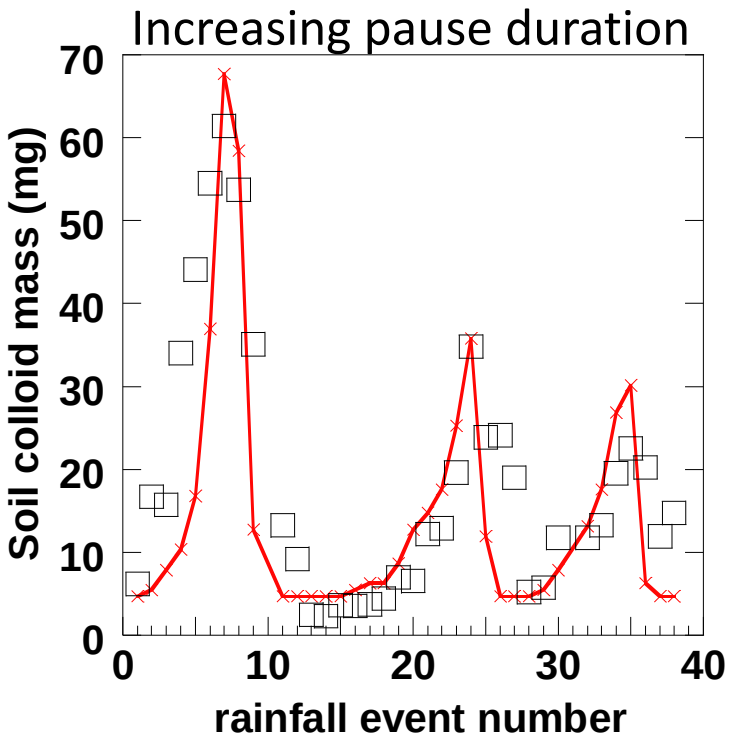


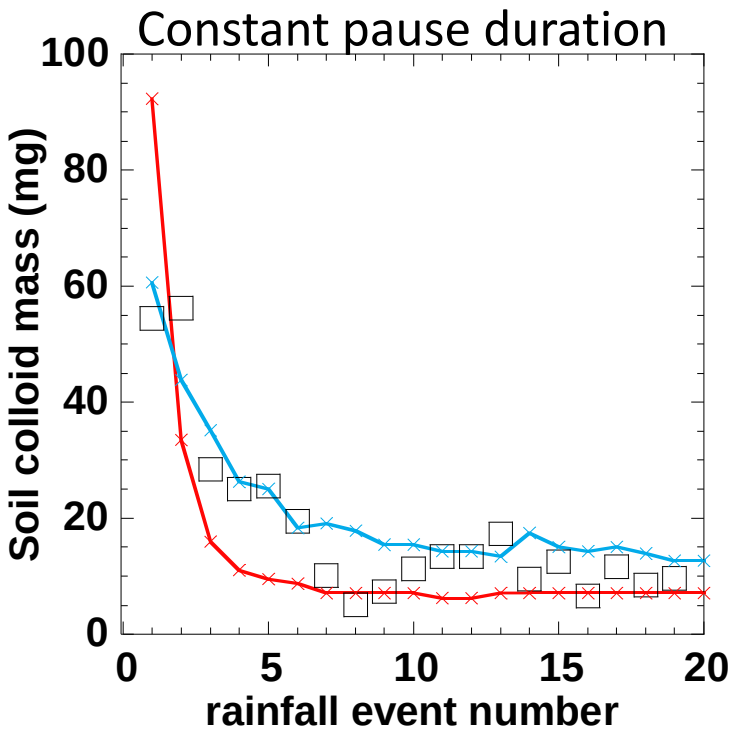
e_0 =1×10−9 ms^{-1},
Δ*h*max= 150 µm
r_{regen}= 400 µm
c =0.40 mg wall^{-1},

natural soil colloid mobilization

numerical model (Vsoil platform)

Michel et al. , *Eur. J. Soil Sci.*, **2014,** *65* (3), 336-347.





Strengthen the hypothesis of mobilization by differential capillary stresses.
Link between pore structure modifications & leaching.

Provides a physically based regeneration mechanism

Eliminates the necessity to estimate the initial size of the pool of leachable colloids

natural soil colloid m

EARTH SURFACE PROCESSES AND LANDFORMS
Earth Surf. Process. Landforms **43**, 45–63 (2018)

Published online 3 May 2017 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/esp.4147

State of Science

Sediment detachment and transport processes associated with internal erosion of soil pipes

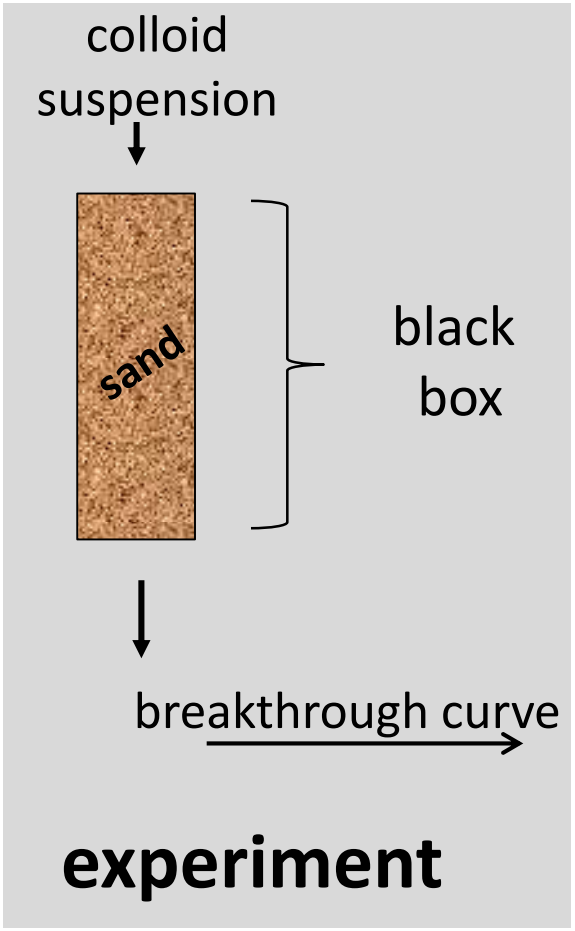
Glenn V. Wilson,[1]* Robert Wells,[1] Roger Kuhnle,[1] Garey Fox[2] and John Nieber[3]

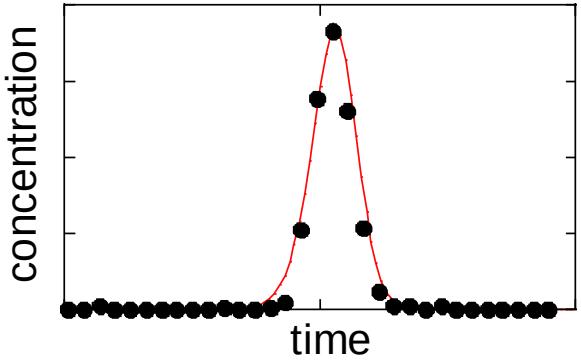
Figure 7. Sediment entering a soil pipe by interception of runoff by a pipe collapse feature in Goodwin Creek Experimental Watershed (GCEW).

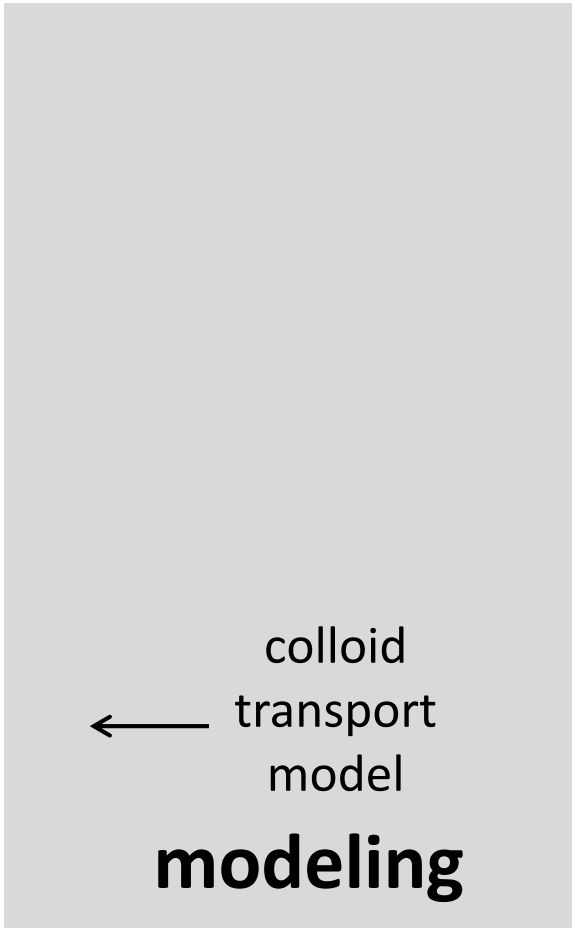
Open the black box !

Transport of colloids monitored by MRI

Lehoux et al. *Water Research,* **2017**,123, 12-20







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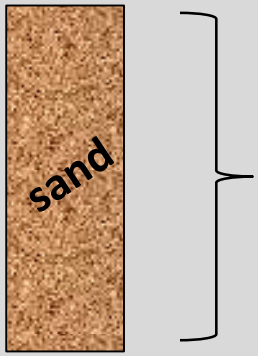
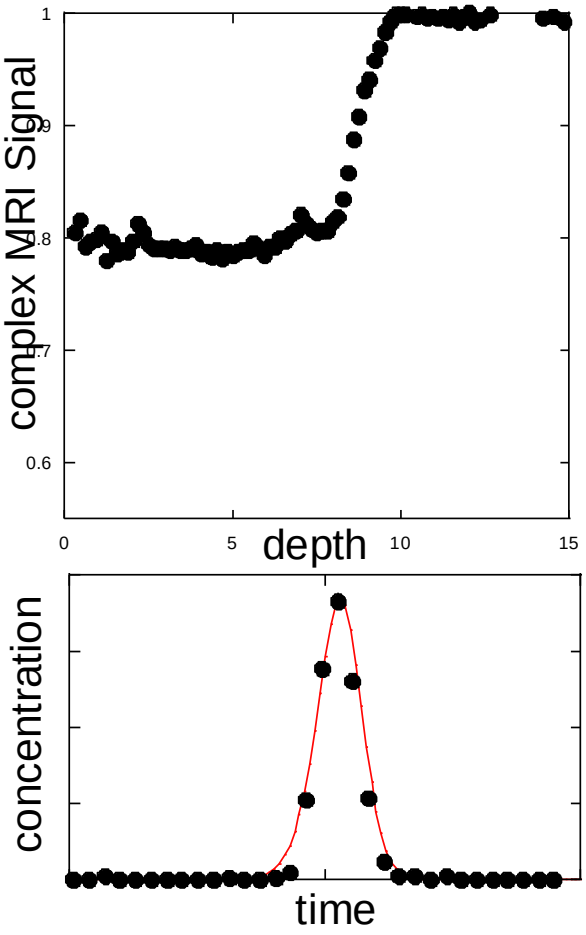
colloid suspension



Complex MRI Signal profiles

breakthrough curve

experiment



colloid transport model

modeling

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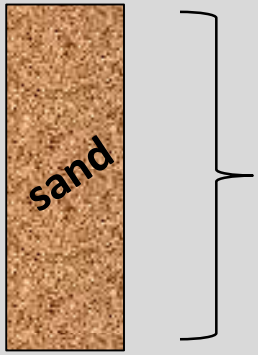
Lehoux et al. *Water Research,* **2017**,123, 12-20

colloid suspension



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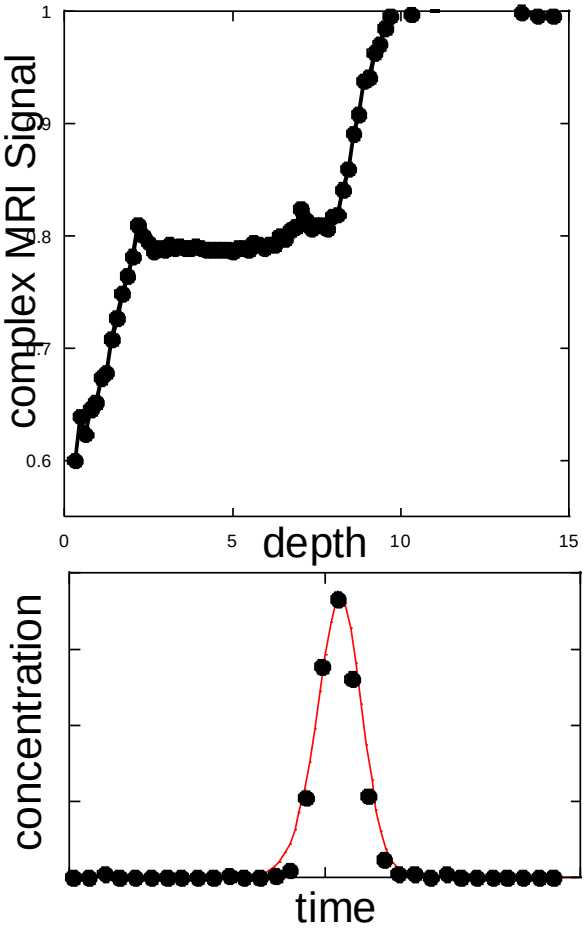

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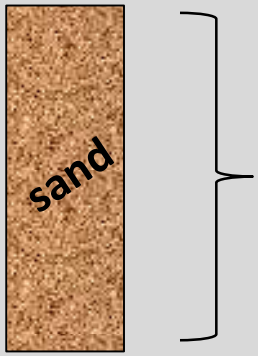

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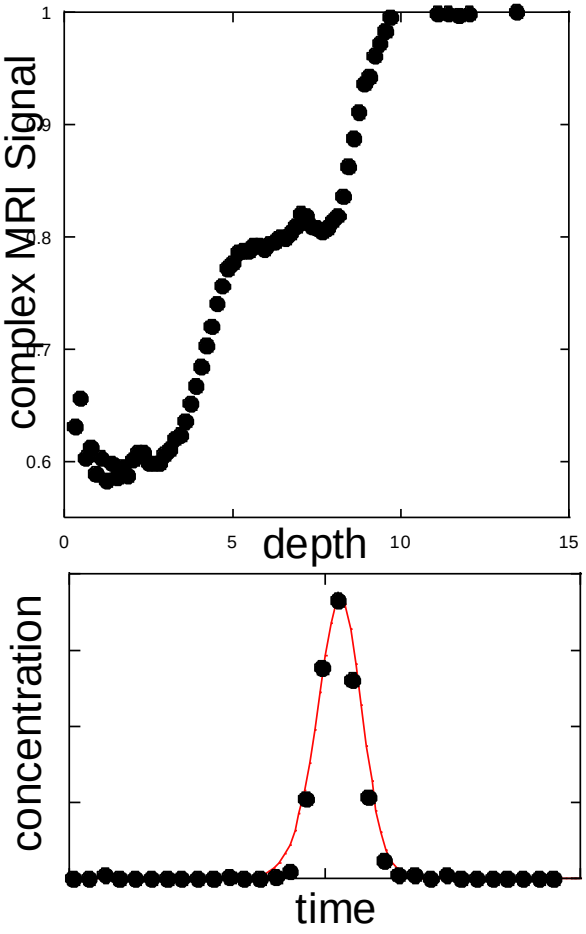

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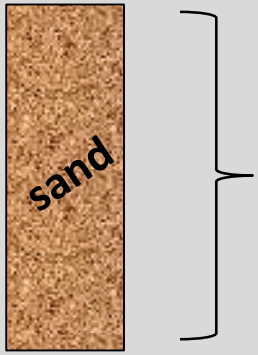

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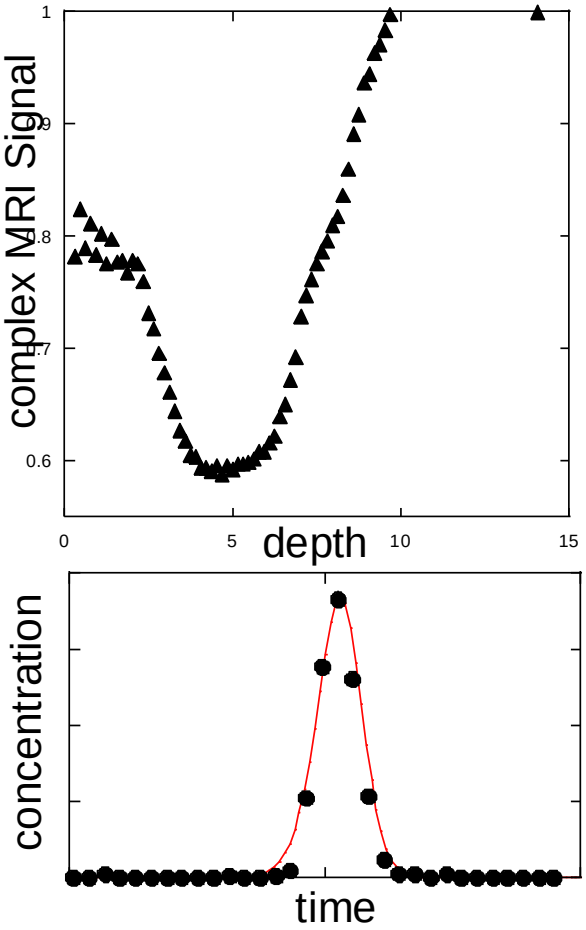

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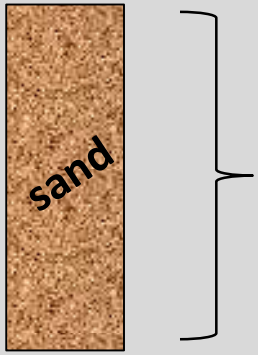

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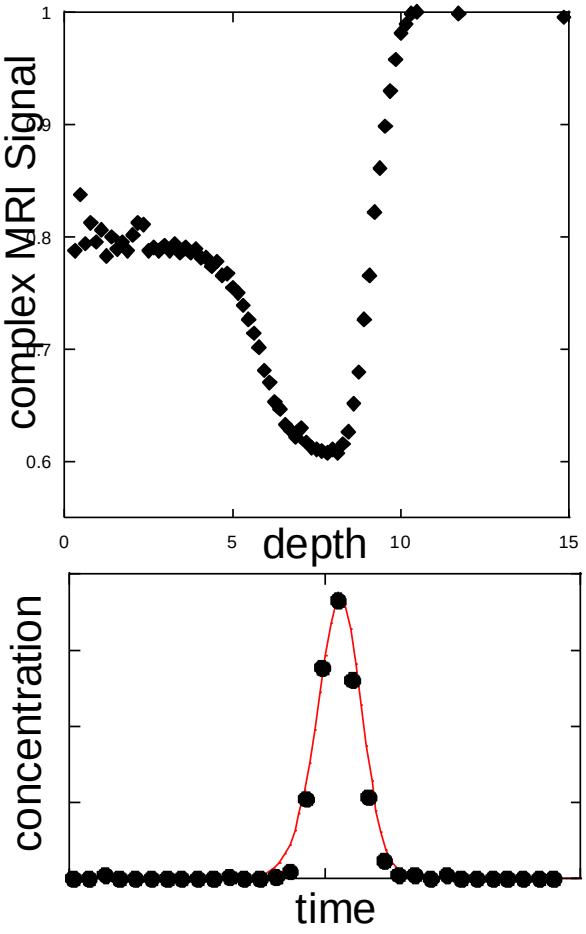

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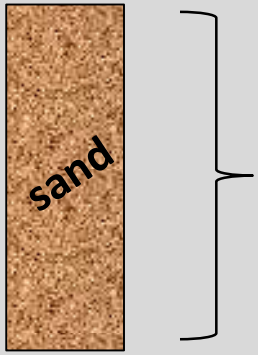

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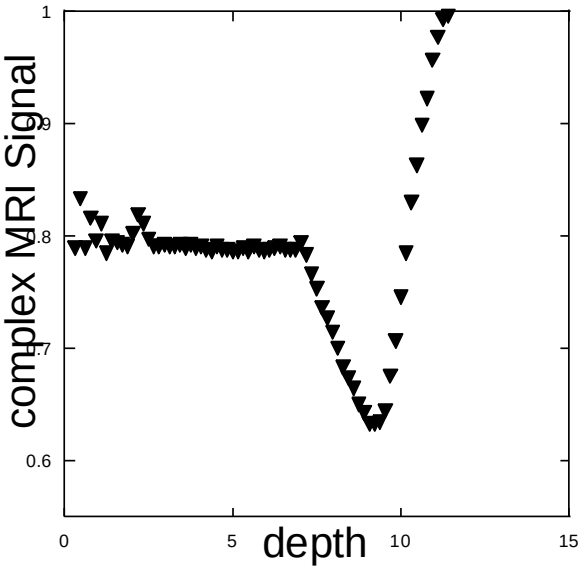

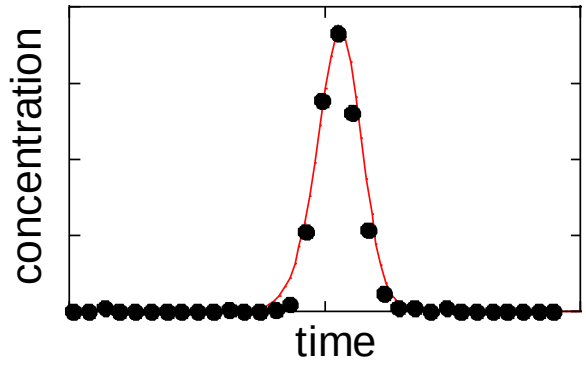

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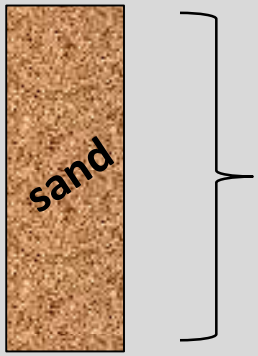

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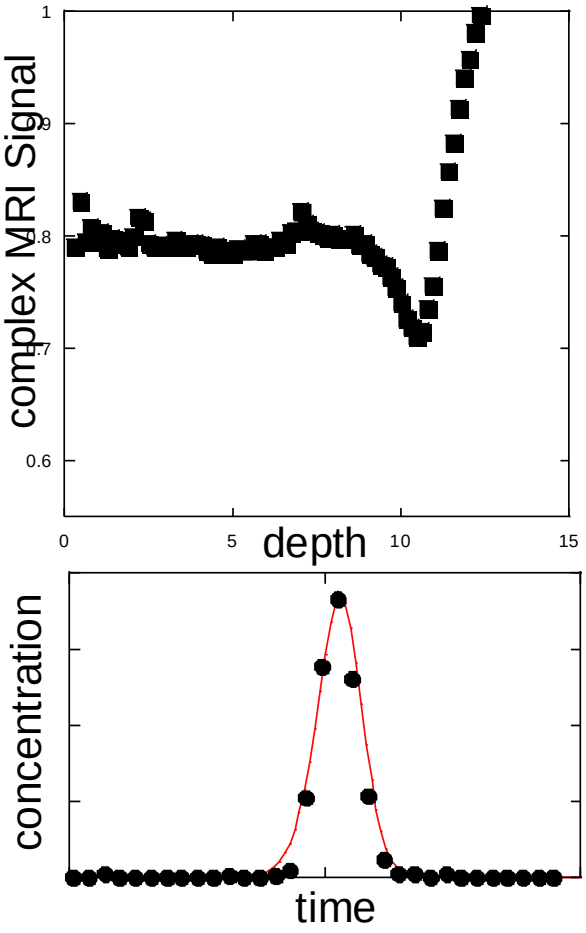

colloid transport model

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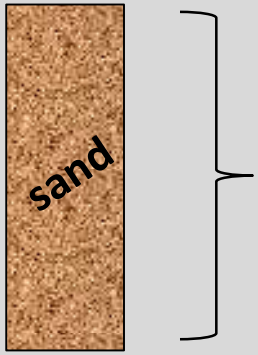
Lehoux et al. *Water Research,* **2017**,123, 12-20

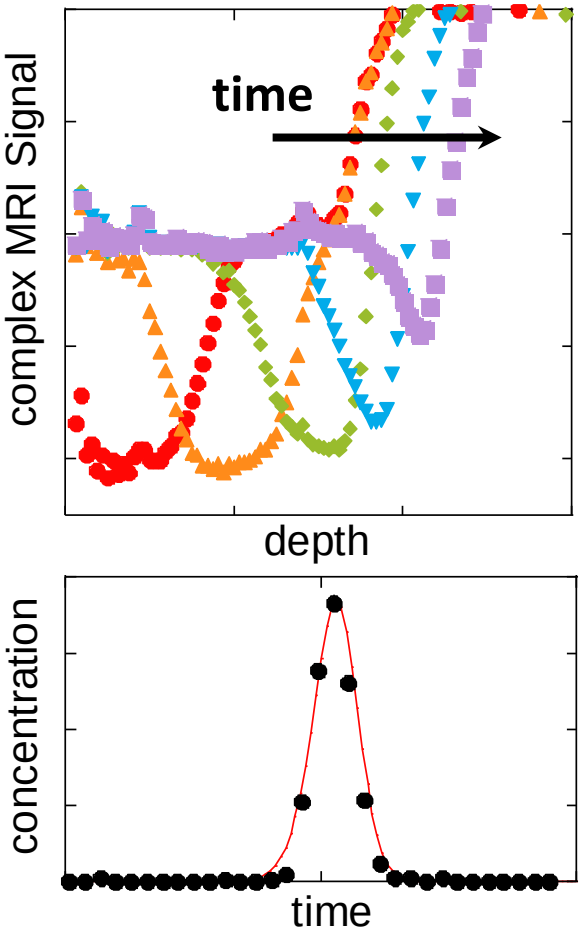
colloid suspension



Complex MRI Signal profiles →

breakthrough curve →

experiment



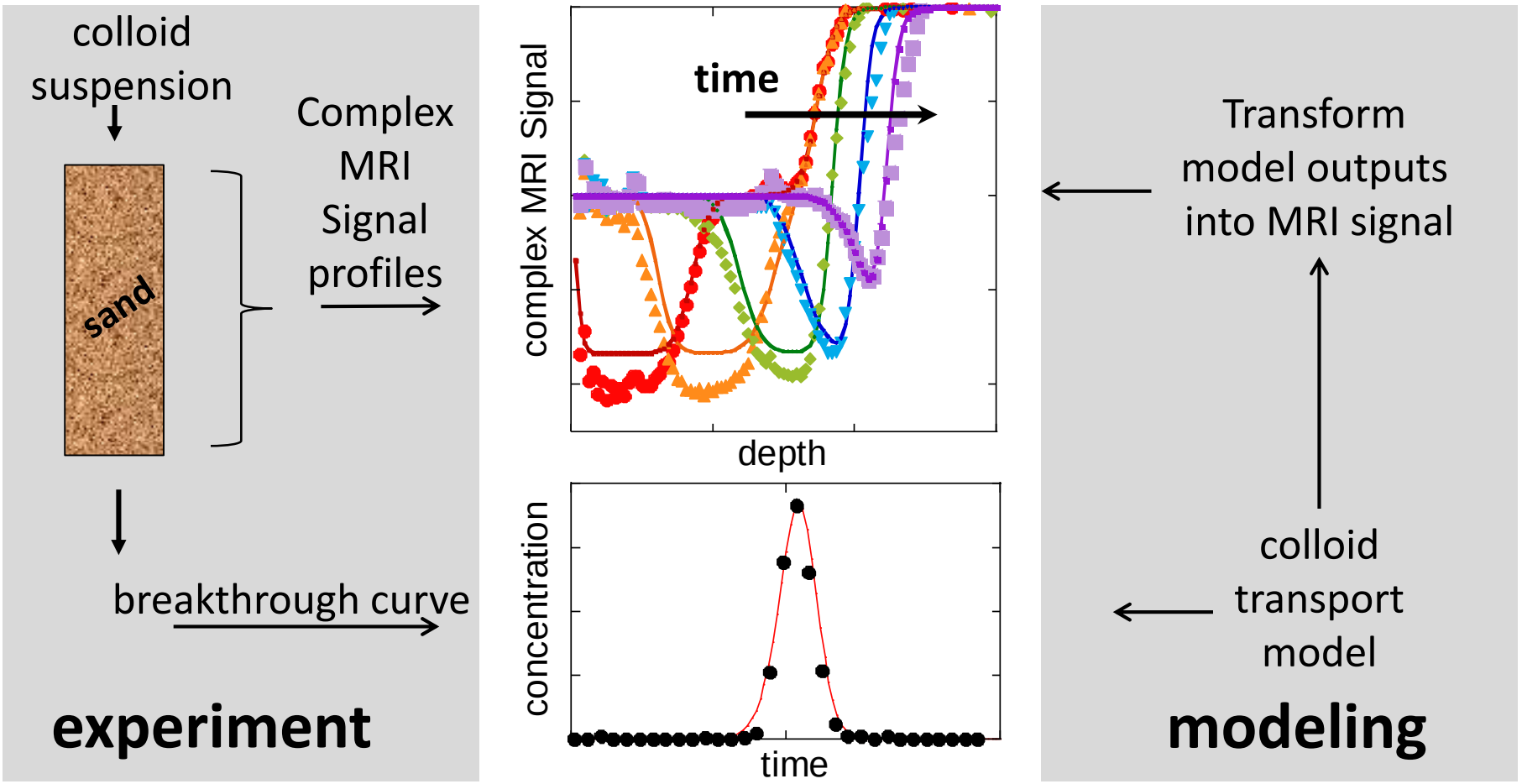
← colloid transport model

modeling

Open the black box !

Transport of colloids monitored by MRI

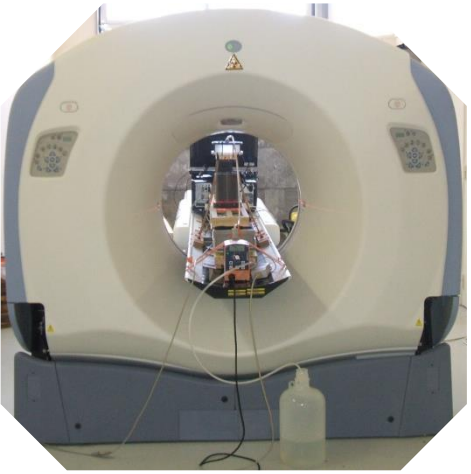
Lehoux et al. *Water Research,* **2017**,123, 12-20



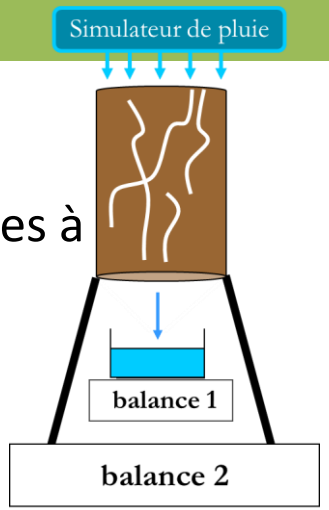
Model permits a quantitative use of the MRI profiles

Abundant time-lapse MRI profiles permit to test the models to their very limits !

Outline

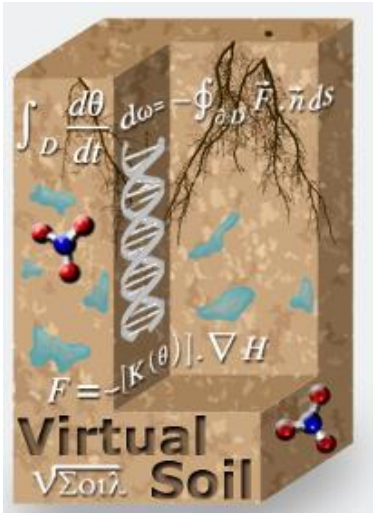


Expériences
transport d'eau de solutés de colloïdes à l'échelle de la colonne de sol non perturbée



Imagerie fonctionnelle:
obtenir des **informations** qualitative et **quantitatives** à l'intérieur du sol **au cours de processus dynamiques**

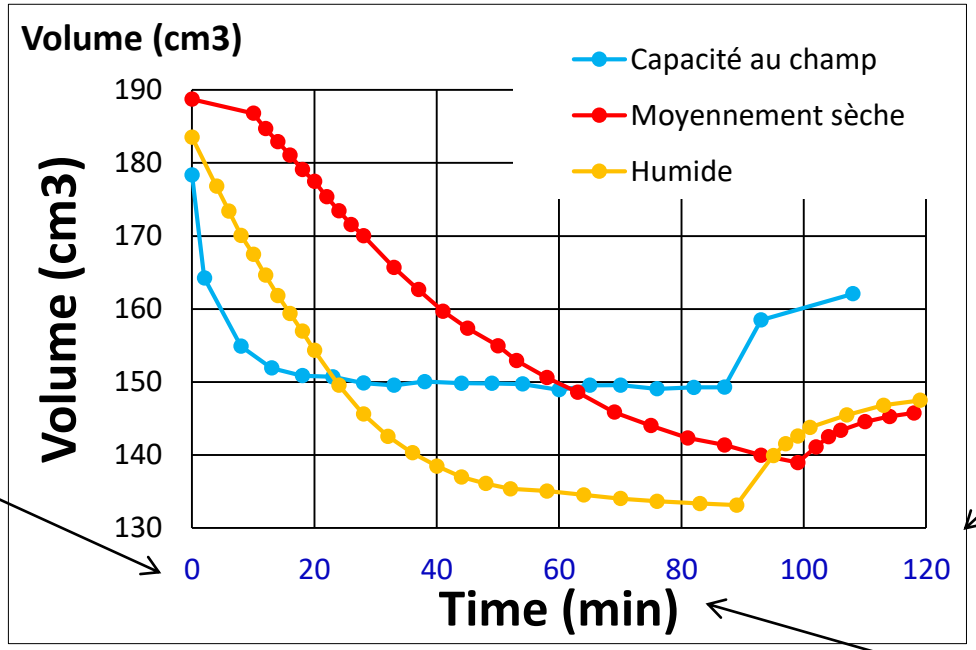
- **Mécanismes**
- **Conception et utilisation de modèles couplés**



Perspectives : [1] macropore flow

Does water flow impact macropore structure ?

t=0



t=120 min

t=80min

Gonflement des parois des macropores
au passage de l'eau ?

Perspectives [2] Transport de solutés et IRM

Substances perfluorées : PFAS

Les substances perfluoro –alkyles, C_nF_{2n+1}–X ….

1- … sont utilisées dans une nombre important de procesus y produits …

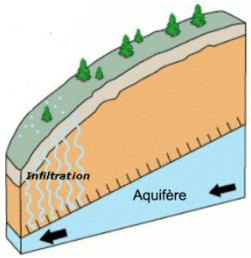




2-…et sont

persistentes **bioacumulables** **toxiques….**

3- … elles sont présentes dans tous les compartiments environnementaux

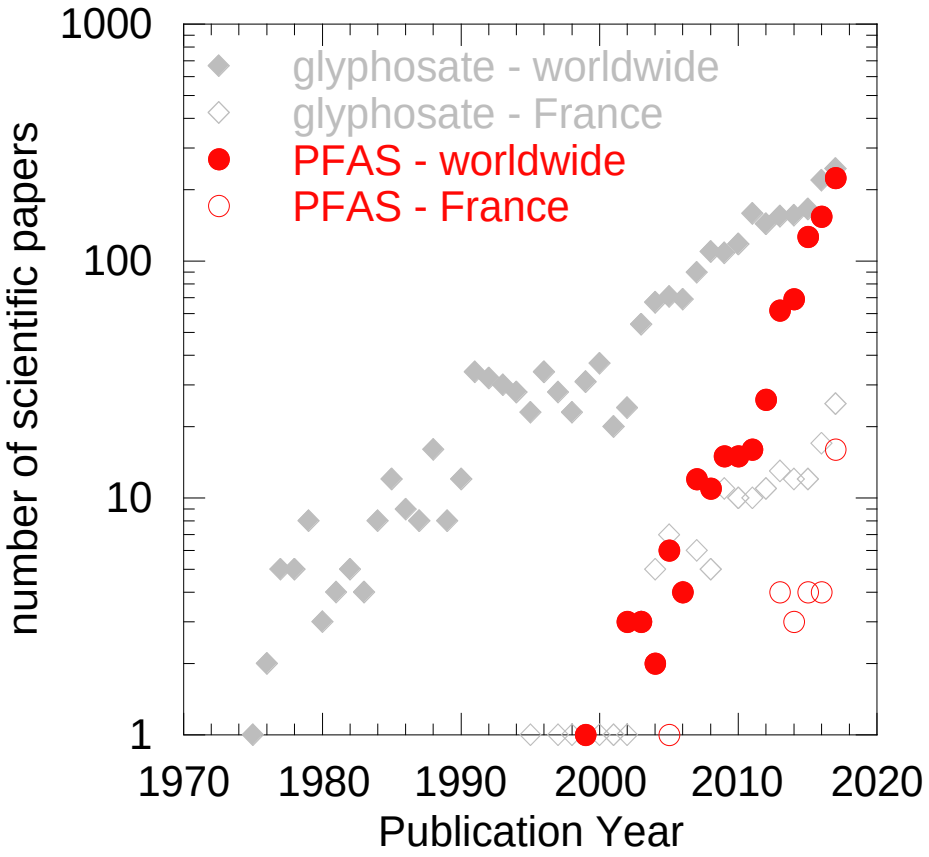






Perspectives [2] Transport de solutés et IRM

Substances perfluorées : PFAS

nombre d'entrées dans le WebOfScience pour la recherche (PFAS ou "perfluoroalkyl substance*"; rouge), ou glyphosate (gris) dans les catégories environmental sciences ou engineering environmental ou toxicology ou public environmental occupational health ou water resources ou agriculture multidisciplinary

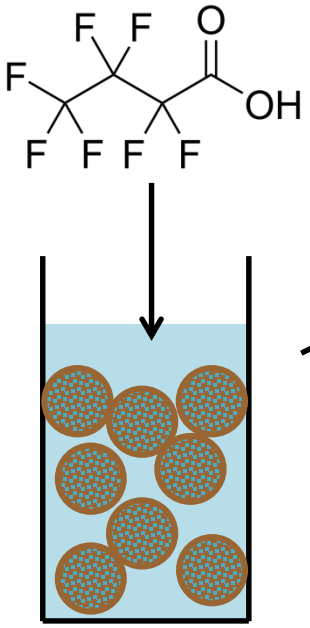


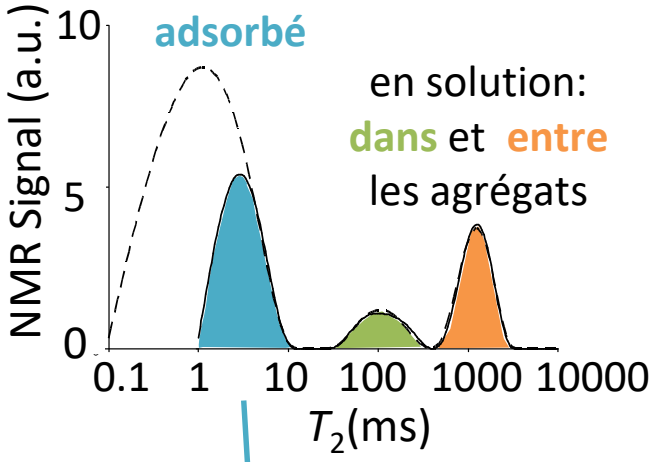
Nécessité de prévoir l'internalisation par les plantes des PFAS, leur devenir dans le sol, les interaction PFAS-sol

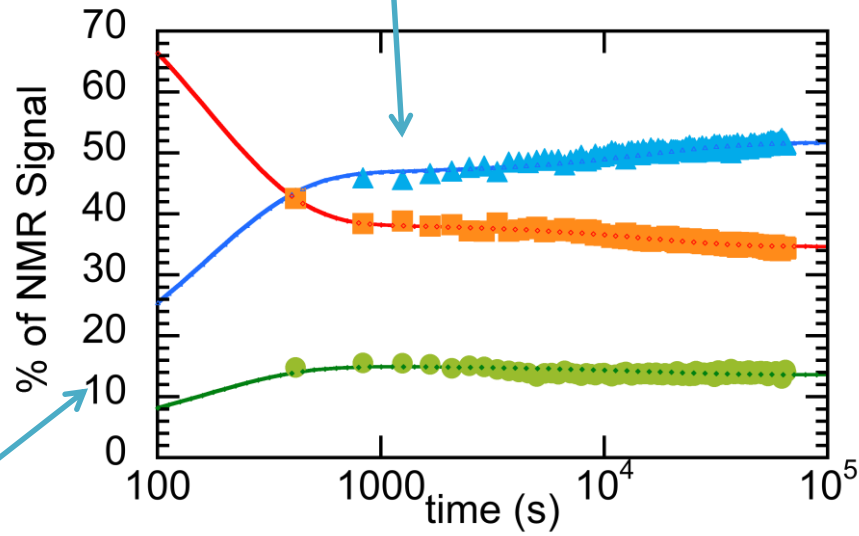
Perspectives [2] Transport de solutés et IRM

Interaction sol – PFAS non comprise complètement

familles des PFAS







Modèle:
(1) difusion dans les agrégats
(2) Adsorption cinétique sur deux sites différents

Interaction hydrophobes et electrostatiques

Interaction Sol – Eau - Contaminant

Déposition de colloides lors de cycles mouillage/séchage

van den Bogaert et al. *Geoderma*. **2016,** 275, 40-47.