Continuity of preferential flow paths as first order control of event scale solute travel distance

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Introduction

- Column scale: macropore length and continuity is an important controlling factor[2,8] (fig. 1).
- Field scale: rarely observed, not taken into account in models[3,4].
- Importance for response (solute leaching) within critical space-time scales?

--> Virtual experiments:

  - Flow path geometry versus initial conditions at the column scale?
  - How does this control translate to the field scale and different forcing?

Column scale - methods

- Infiltration into single vertical macropore, column depth 1m, 24h ponding.
- 3 levels of antecedent moisture: suction heads of 100m (dry), 1m (moist) and 0.1m (wet).
- 3 levels of macropore length: 100cm, 80cm and 45cm.
- 2 pseudo-3D models: HYDRUS[6] (radial flow and transport), CATFLOW[9] (water flow only).

Field scale – methods (media generation)

- Field site represented by gently sloping 2D-trench of 40m (length) by 4m (depth).
- Heterogeneous matrix generated by 2D-Turning Bands[1]: perturbation of k_s, θ_s with spherical variogramm, range of 1m (k_s) and 10m (θ_s); see table 1 for average values.
- Macropores generated by Poisson process (number/location) and normal process (depth).
- 3 levels of macropore density with 0, 20 and 40 burrows/m²; depth: 1.2m ± 0.25m.
- Calculate number of connective flow paths defined as k_s above 90th percentile.

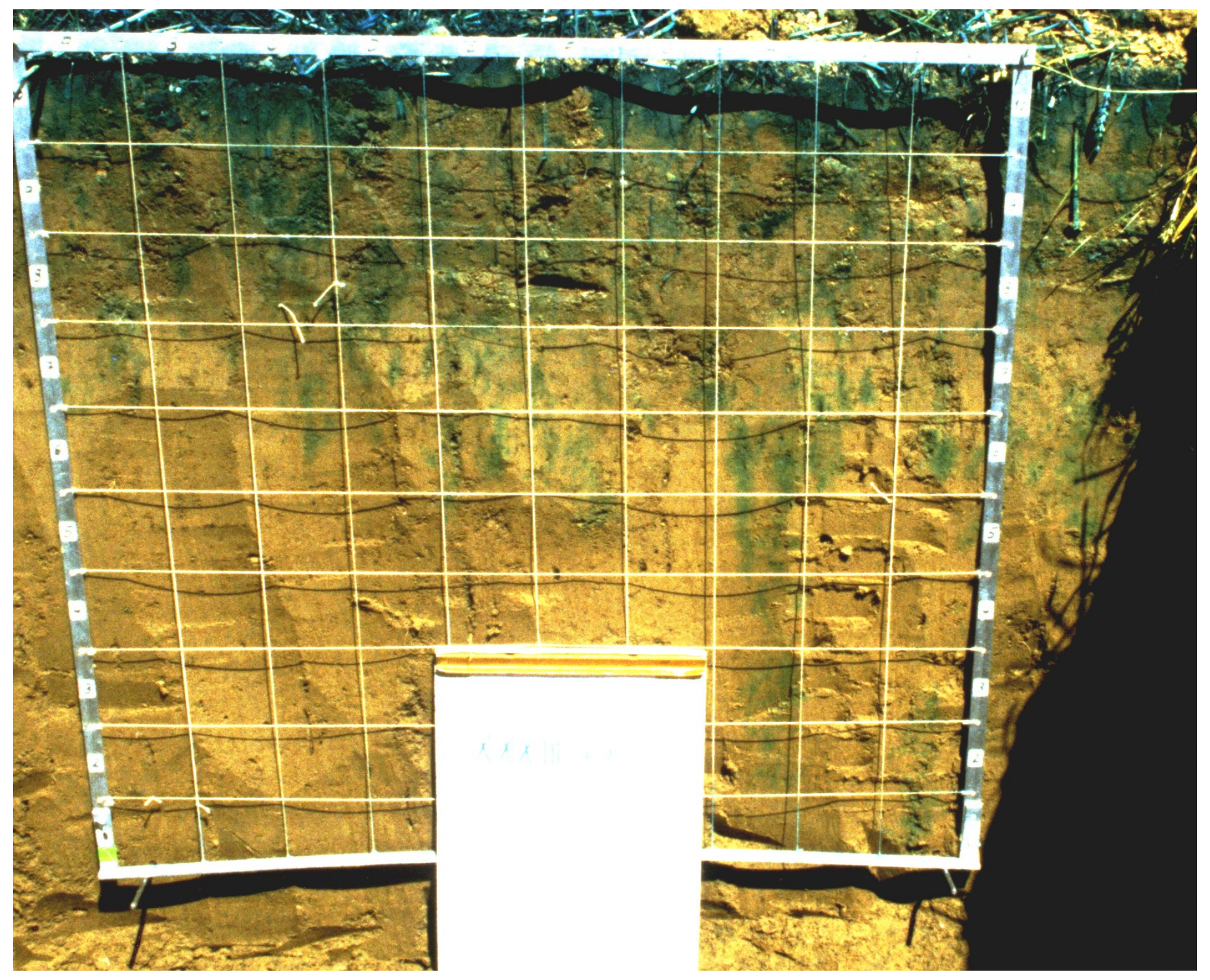

Figure 1. Preferential flow pattern of the dye-tracer Brilliant Blue in a weakly structured loamy soil after irrigation of about 20mm within two hours. (Weiherbach catchment.)

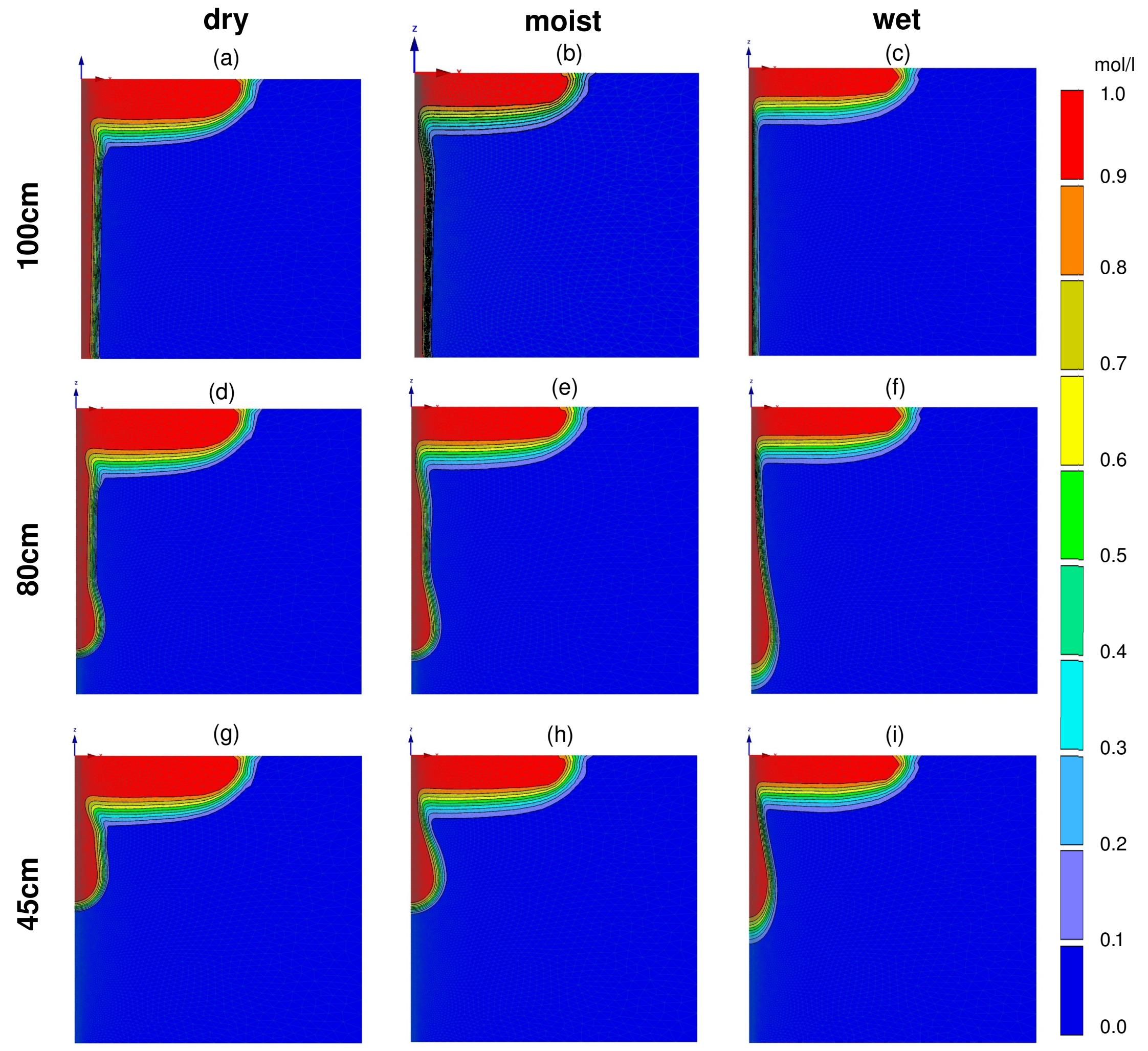

Figure 2. Pattern of solute concentration in soil water after six hours of ponding for three different macropore lengths and antecedent moisture states. Center of axisymmetrical flow domain (domain depth 1m, radius 1m) with vertical macropore at the left of the figure. Input concentration 1 mol/l, advection only. Simulated using HYDRUS.

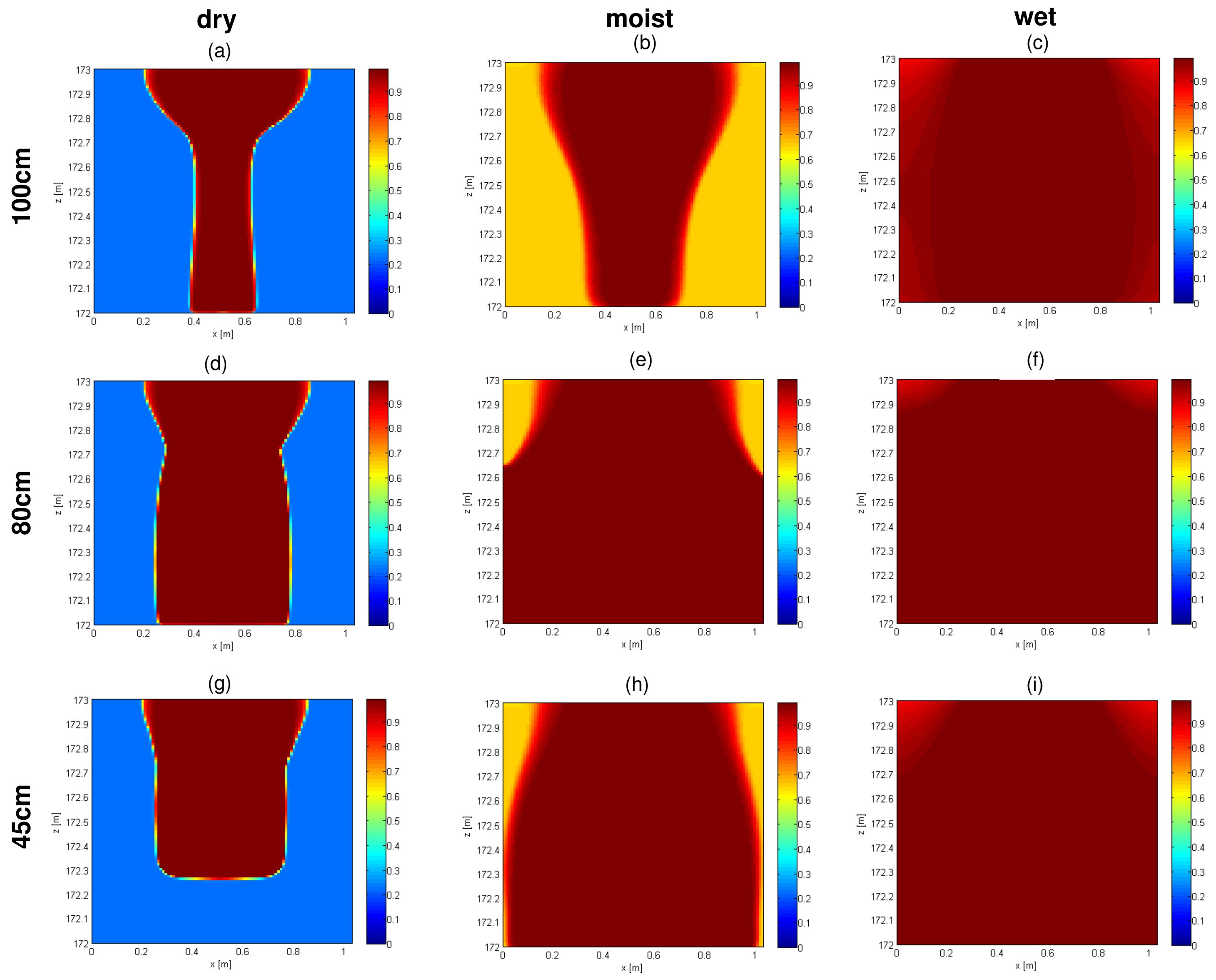

Figure 3. Pattern of relative saturation after six hours of ponding for three different macropore lengths and antecedent moisture states. Pseudo-3D-flow domain (depth, width and length 1m each) with single macropore. Simulated using CATFLOW.

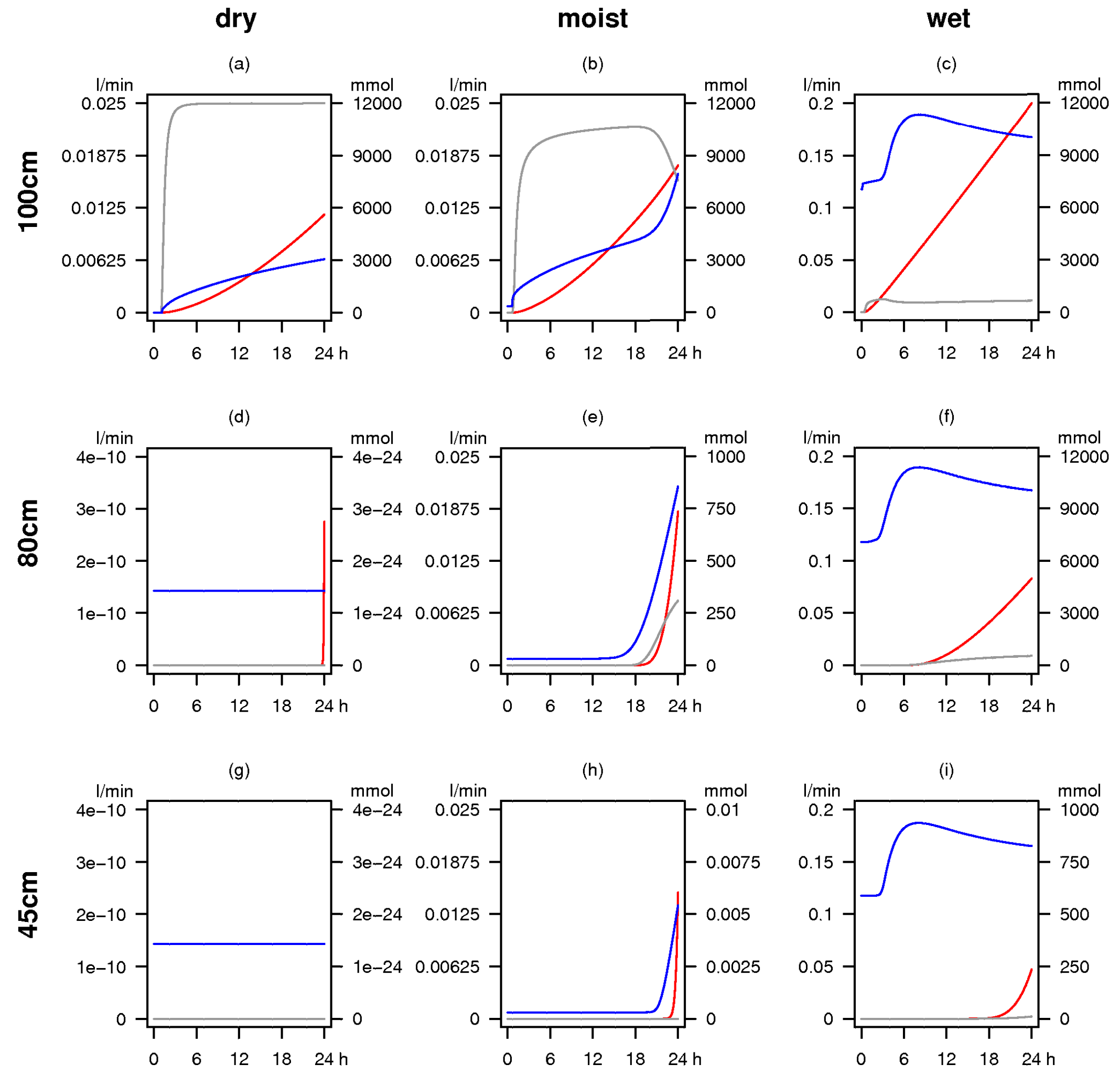

Figure 4. Discharge from column (blue, left axis), cumulative solute leaching (red, right axis) and relative concentration (grey) with time elapsed for three different macropore lengths and antecedent moisture states. Axisymmetrical flow domain (depth 1m, radius 1m) with single macropore. Input concentration 1mol/l, advection only. Simulated using HYDRUS. Mind the different scales!

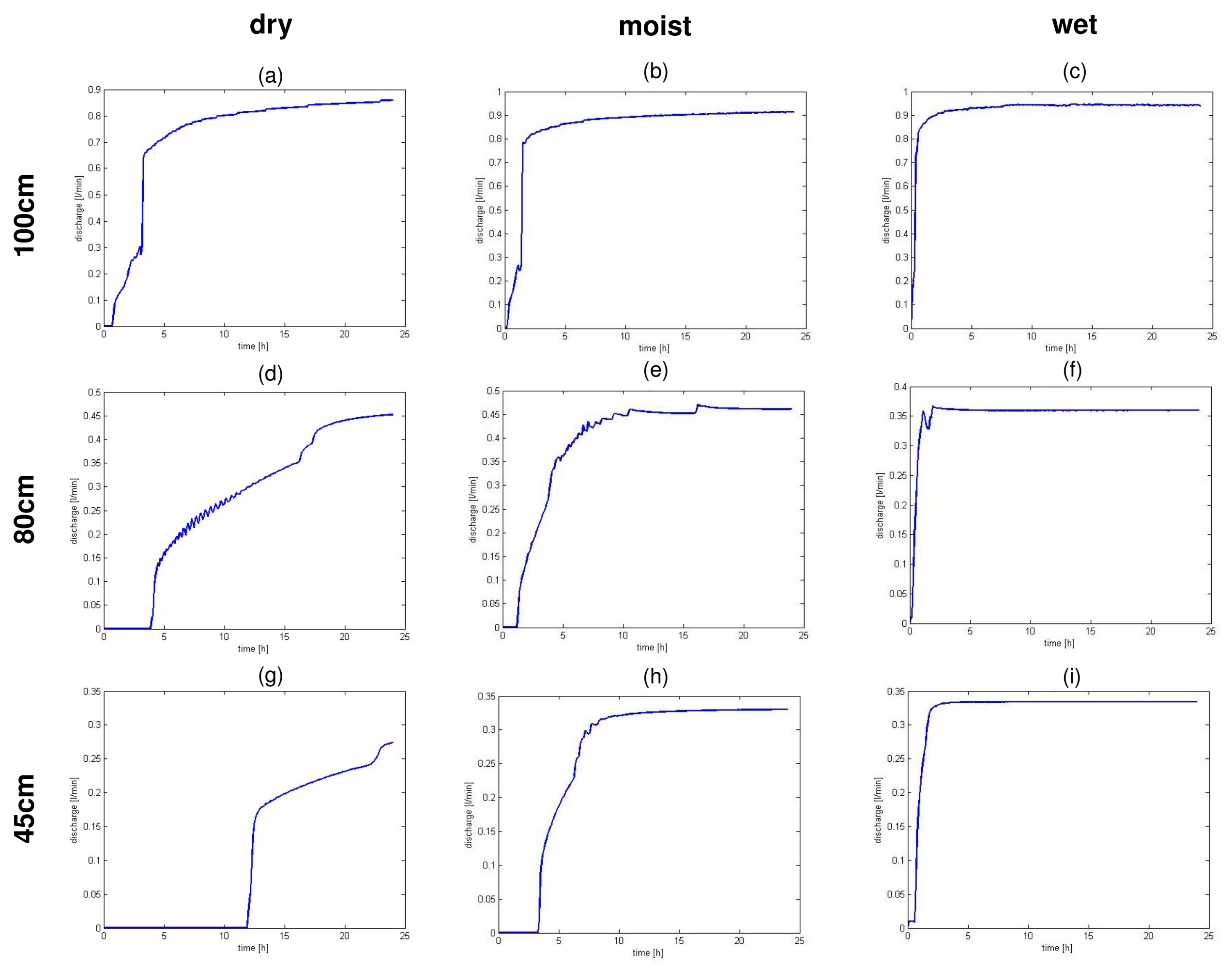

Figure 5. Discharge from column with time elapsed for three different macropore lengths and antecedent moisture states. Pseudo-3D-flow domain (depth, width and length 1m each) with single macropore. Simulated using CATFLOW. Mind the different scales!

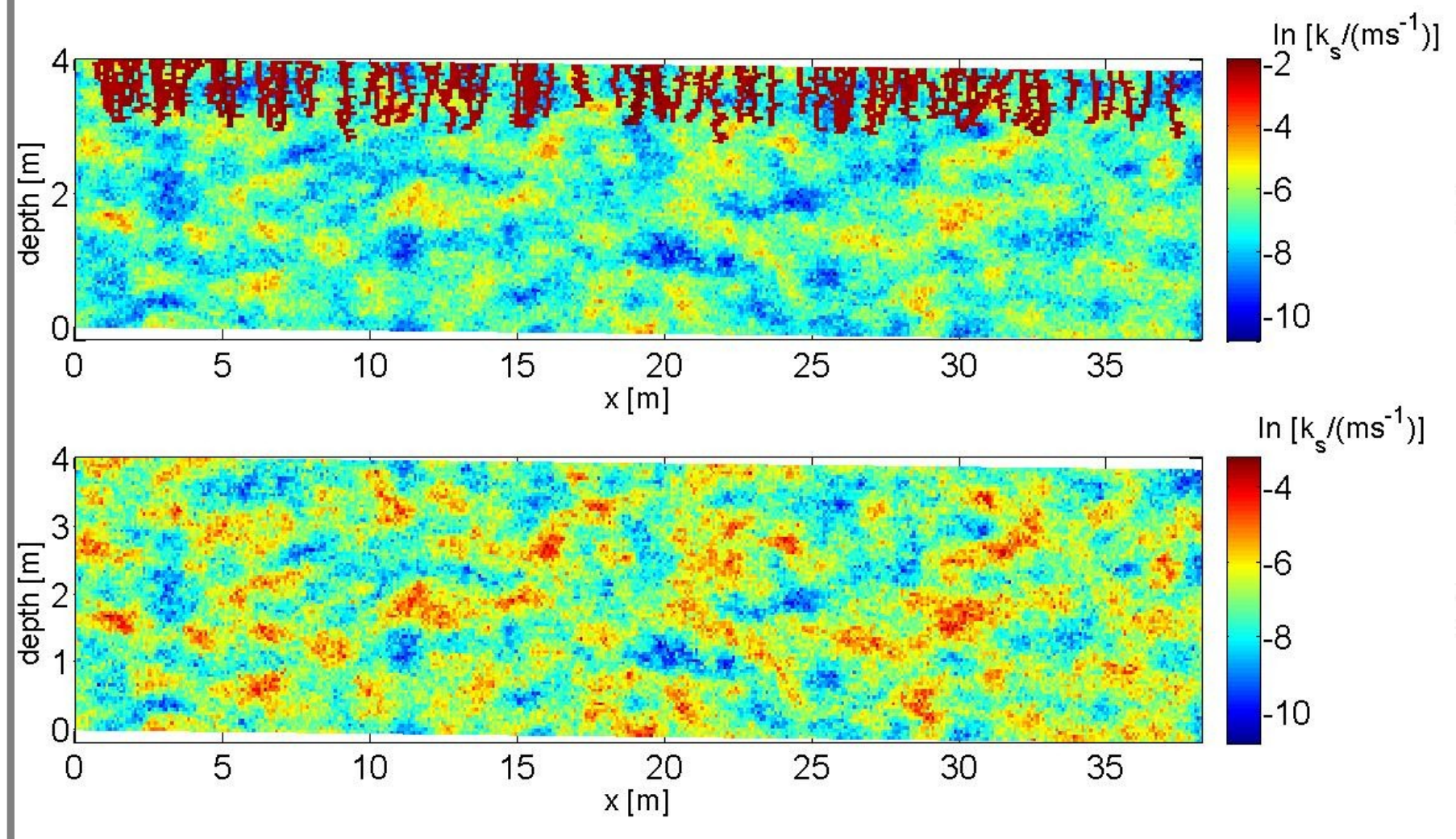

Figure 6: log(k_s) of soil medium with (upper panel) and without (lower panel) population of 40 worm burrows/m², length is on average 1.2 m.

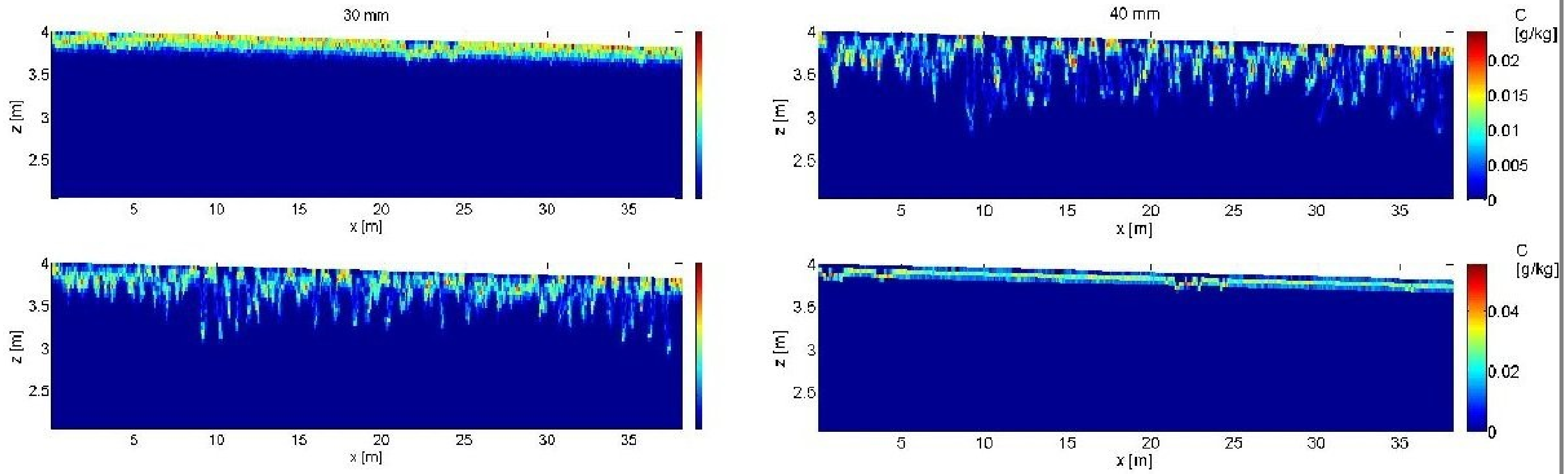

Figure 7: Concentration patterns for pure matrix case and for the medium with burrow density of 40/m² for 30mm (left panels) and 40mm (right panels) rainfall totals. (Guess which patterns belong to which medium in figure 1 ☺)

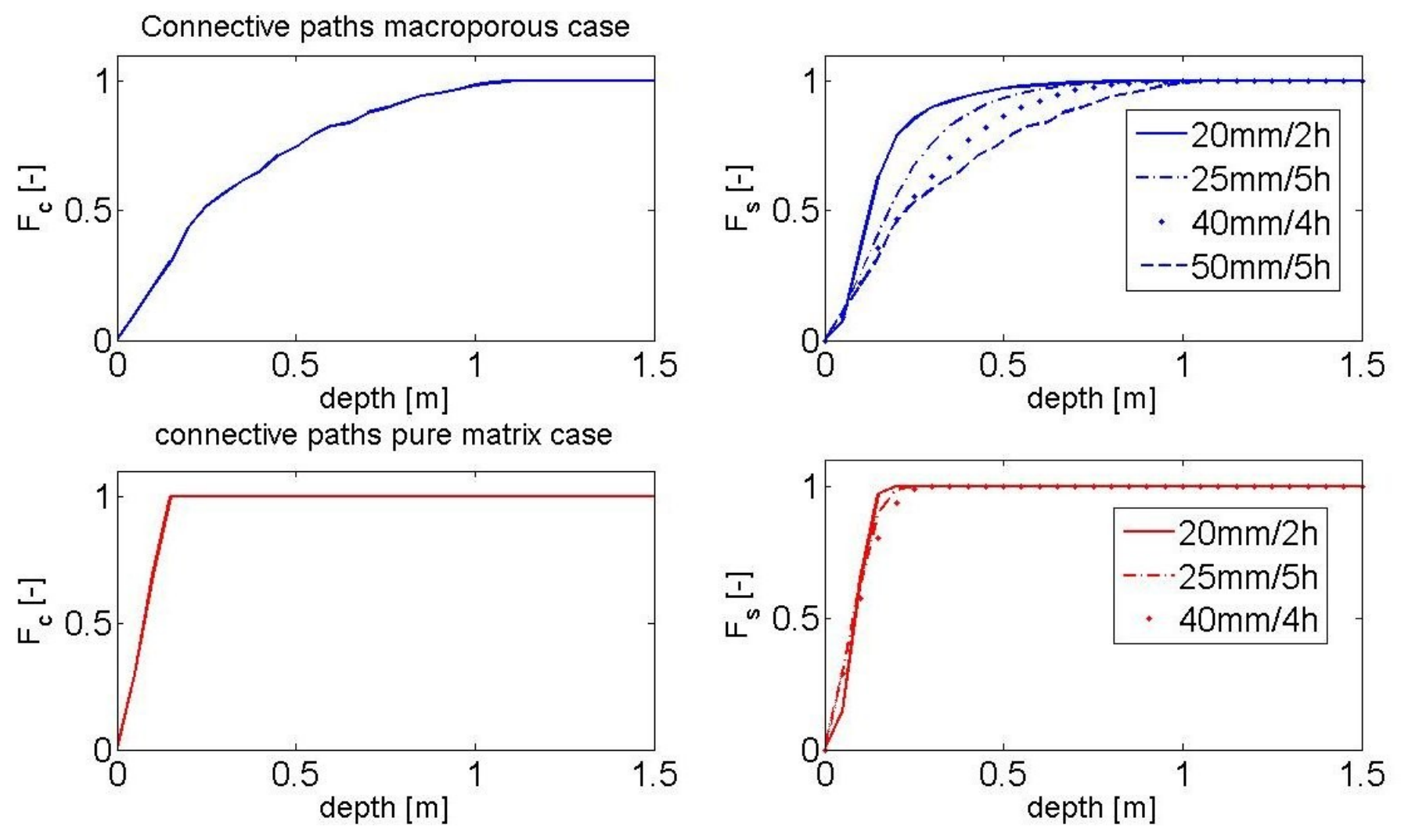

Figure 8: CDF of connect flow paths (left panels) and cumulated probability density of travel distances (right panels) for 40 burrows/m² with 1.2 m average length (upper panels) and the pure matrix case (lower panels).

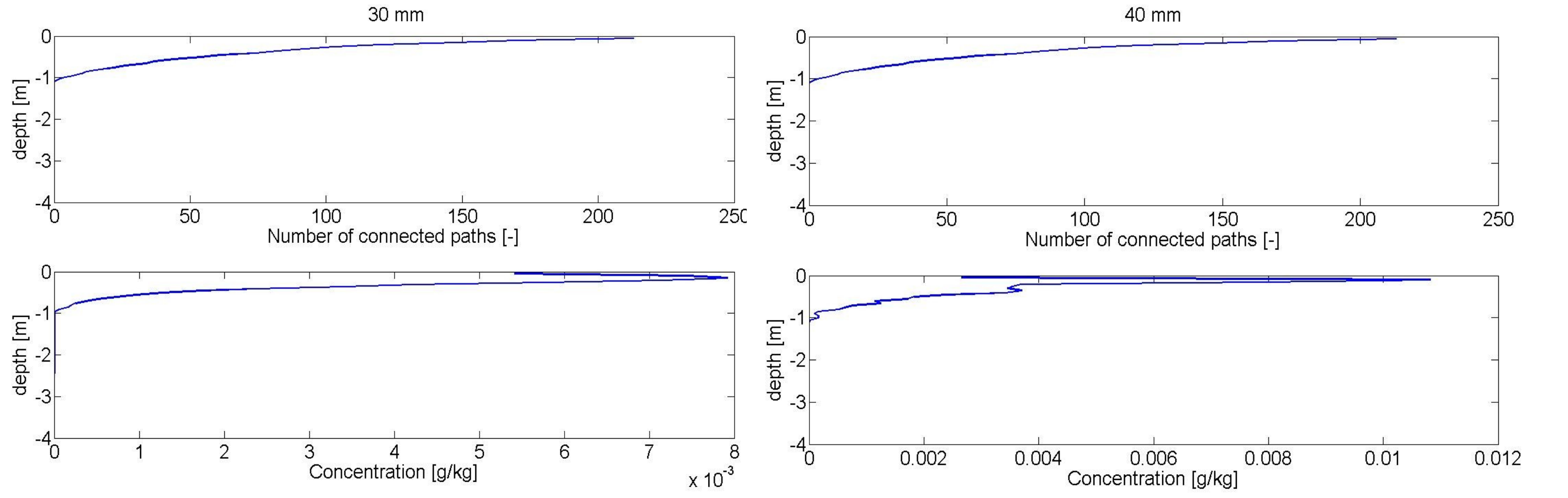

Figure 9: Number of connected flow paths as function of depths (upper panels) and concentration profiles (lower panels) for 30mm (left panels) and 40mm (right panels) rainfall. 40 burrows/m² with 1.2m average length.

Field Scale – methods (continued, simulation)

- Simulation of water flow and solute transport with CATFLOW.
- Dynamic initialization with observed atmospheric boundary conditions from the Weiherbach catchment.
- Initial concentration 0.05g/kg Br in the top 5 cm.
- 5 blocks rains: 20, 30, 40 and 50mm total precipitation with intensity of 10mm/h; 25mm total precipitation with intensity of 5mm/h.

Table1: Soil hydraulic properties determined for the field site.

k_s [m/s]	θ_s [m³/m³]	θ_r [m³/m³]	a [1/m]	n [-]
1.7 10^{-6}	0.40	0.04	1.9	1.25

Column scale - results

- Macropore length controls fast solute transport, significant transport below pore length requires near saturated conditions (fig. 2).
- Macropore length strongly influences the redistribution of infiltrating water within the profile (fig. 3).
- For dry and moist initial conditions, macropore length co-controls discharge (fig. 4 a-b, d-e, g-h; 5 a-b, d-e, g-h).
- For dry and moist initial conditions, non-continuous macropores delay solute breakthrough by orders of magnitude (fig. 4 a-b, d-e, g-h).
- For all antecedent moisture states, non-continuous macropores reduce the amount of solute leached by orders of magnitude (fig. 4).
- Qualitative results are independent of model choice (fig. 4-5); they also hold for distributed material properties and different parametrization (not shown).

Field scale – results

- Concentration patterns reflect the spatial distribution of macropores (fig. 6 and 7).
- Depth distribution of connected flow paths is first order control for travel distance distribution for all forcings (fig. 8 and 9).
- Is the asymptote of the travel distance pdf at high high worm burrows densities (fig. 8 and 9).
- Has to be scaled with drainable area fraction in case of low worm burrows densities & the absence of surface runoff (not shown).

Discussion and outlook

- Length of preferential flow paths limits event scale travel distance even for extreme forcing.
- Appears to hold for the column as well as for the field scale.
- Macropore depth distribution might present an observable to characterize relevant structures determining system response at the scale of interest for risk-assessment of solute leaching with respect to the critical space-time-scales at least in some landscapes.
- It can be measured[8] and hopefully be predicted based on species distribution models (SDMs)[5].
- Explicit inclusion of observables as "structure" into our models instead of focusing solely on parametrization of "texture"[7] might enhance predictive power and our ability to evaluate their performance.
- Possibly, much simpler models could be built around such observables for use at larger scales: they might serve as one input to derivations of
- transfer functions.
- The relevance of our findings for less extreme forcing remains to be explored.
- Suitability of HYDRUS (numerical difficulties close to saturation, no redistribution of surface run-off) and CATFLOW (slow computation in the very dry range) for complementary purposes.

References

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