How Darcy-scale daemons lead theory developments for soil-water dynamics astray

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What is the Darcy-scale and why is it an issue?

The Darcy experiments on water flow through a saturated filter sands led to his famous **linear flow equation**, stating that the flow rate (q) depends on the hydraulic pressure gradient (∇H) and the invert of the bulk resistance (K, hydraulic conductivity): $\mathbf{q = K \cdot \nabla H}$

This linear model is valid for **laminar flow** conditions dominated by **viscous forces** and small Reynolds numbers. Moreover, it is a **macroscale** description, which requires the **definition** of a representative elementary volume (**REV**) for its application. The properties of this model are inherited by descendant models such as the Richards equation.

While this concept of depletion of a hydraulic gradient against a resistance is highly relevant in general, its embedded scale and bulk property simplification mismatch with most soil water issues. Dynamic connectivity, film flow, local turbulence, inertia, scale transitions, and complex fluid-surface interactions dominate the behaviour of partially saturated soil water dynamics.

For more details about the Darcy model, see my recent publication in the Reference Module in Earth Systems and Environmental Sciences https://doi.org/10.1016/b978-0-12-822974-3.00150-6

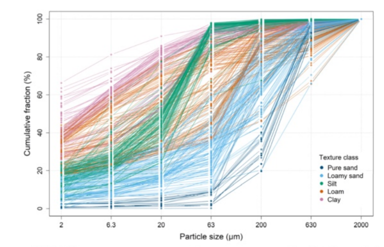
What are Darcy-scale daemons?

The Darcy equation can be seen as the foundation of soil physics and hydrology. As such it is embedded in many levels of analysis: From measurements of soil properties in ring samples to landscape scale model applications. This includes the derivation of parameters for soil hydraulic models (e.g. Kosugi, van Genuchten) to propagate the highly non-linear interaction of matric potential, wetted surfaces (soil moisture) and state-dependent hydraulic conductivity as a unique, derivable function. Any deviation from this function is attributed to hysteresis or heterogeneity.

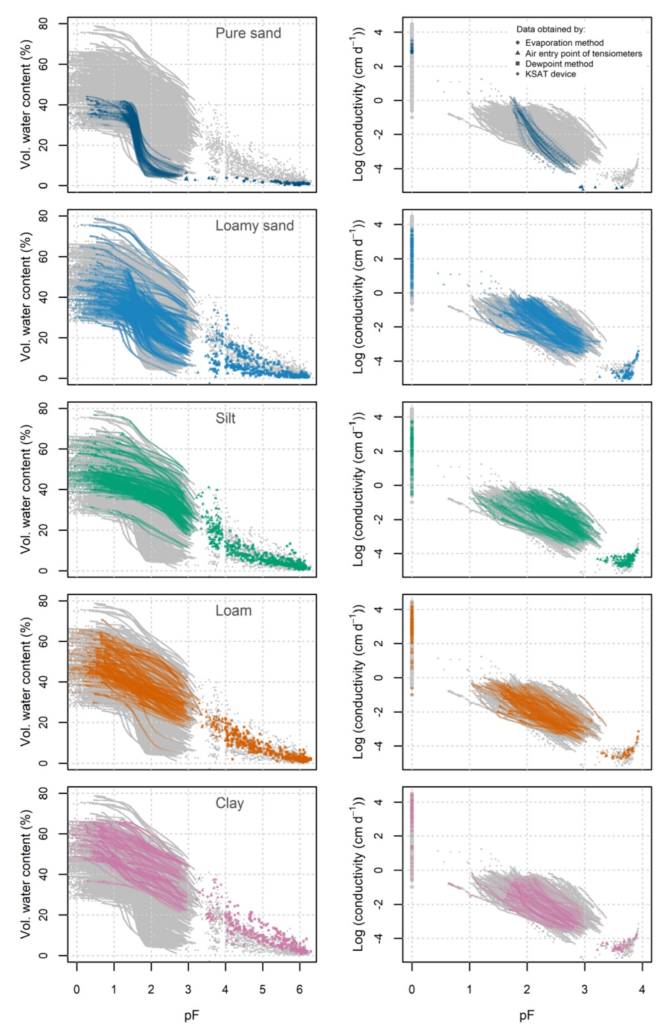
This practice implicitly assumes scale invariance (using ring sample parameters for landscape scale applications) and contradicts scientific standards of falsifiability (when deviations are attributed to external variance rather than systematic problems). Because these problems are deep-rooted and neither intentional nor easy to avoid, we call them daemons.

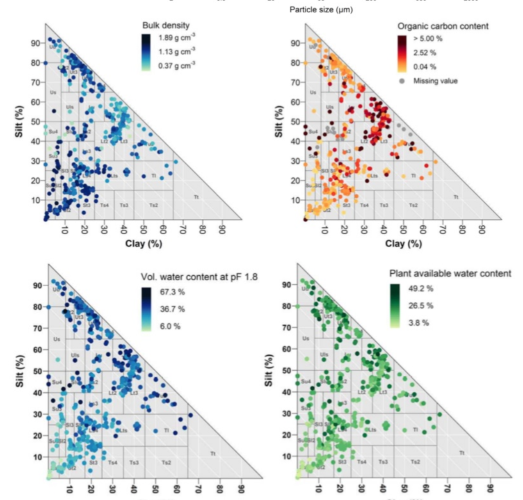
Examples at the lab-scale: Ring samples and measured soil water curves

We analysed **soil water retention capacity** and **hydraulic conductivity** of unsaturated soils in 572 **undisturbed** ring **samples** covering a wide range of soil texture, bulk density and organic carbon content.



Texture appears as rather **weak predictor** for soil hydraulic properties and soil water references. Many drying curves overlay or intersect.



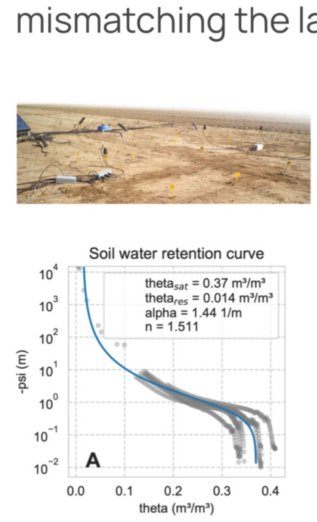


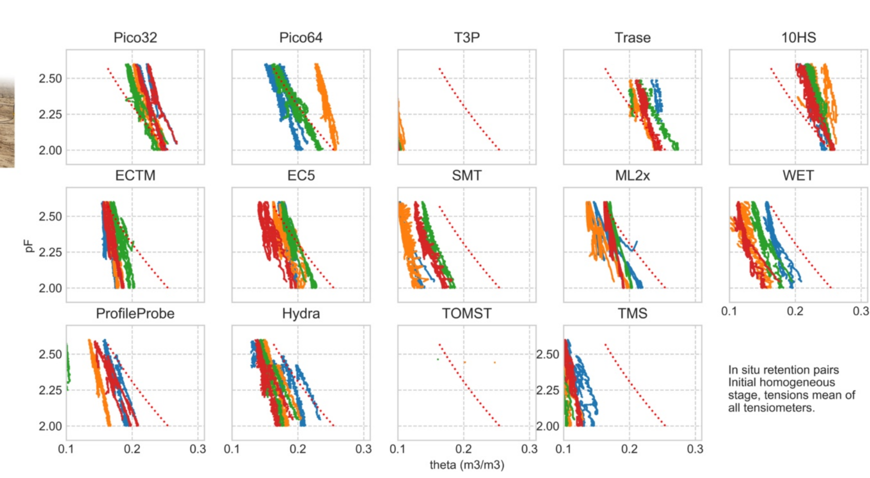
Our Darcy-based models require **macroscale** property **parameters**, which do **not** appear to be so **easy to determine** - even in the absence of hysteresis and scale transfer.

For more details about this study and the data, see our recent publication in Earth System Science Data https://doi.org/10.5194/essd-2023-74

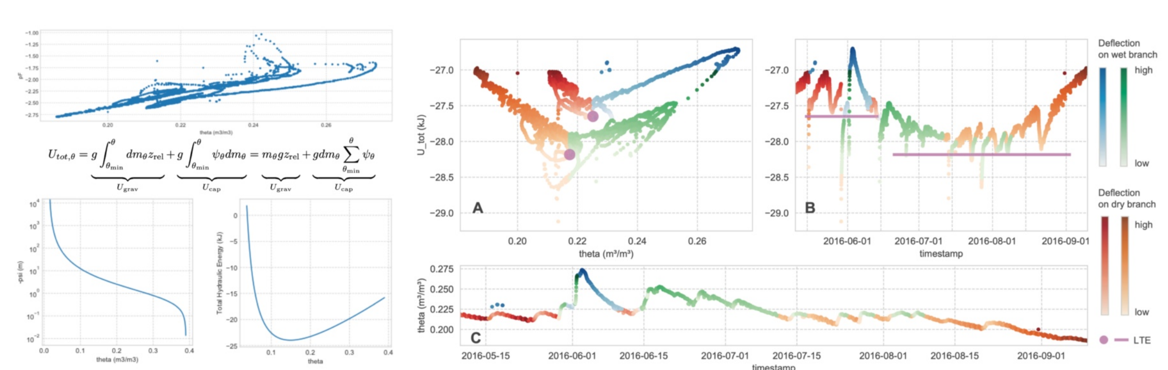
Examples at the plot-scale: Observed soil water curves in the field

We conducted a field trial of many sensors for soil moisture and matric potential. As a side-product we derive in-situ retention curves – mismatching the lab reference measurements.



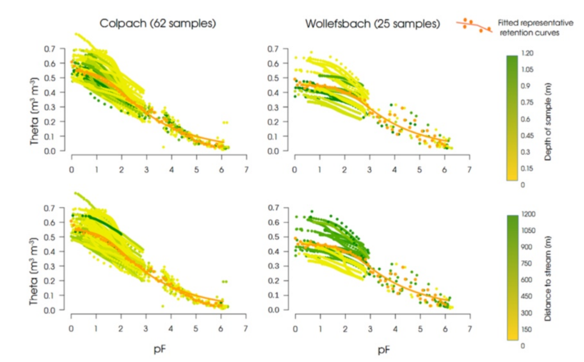


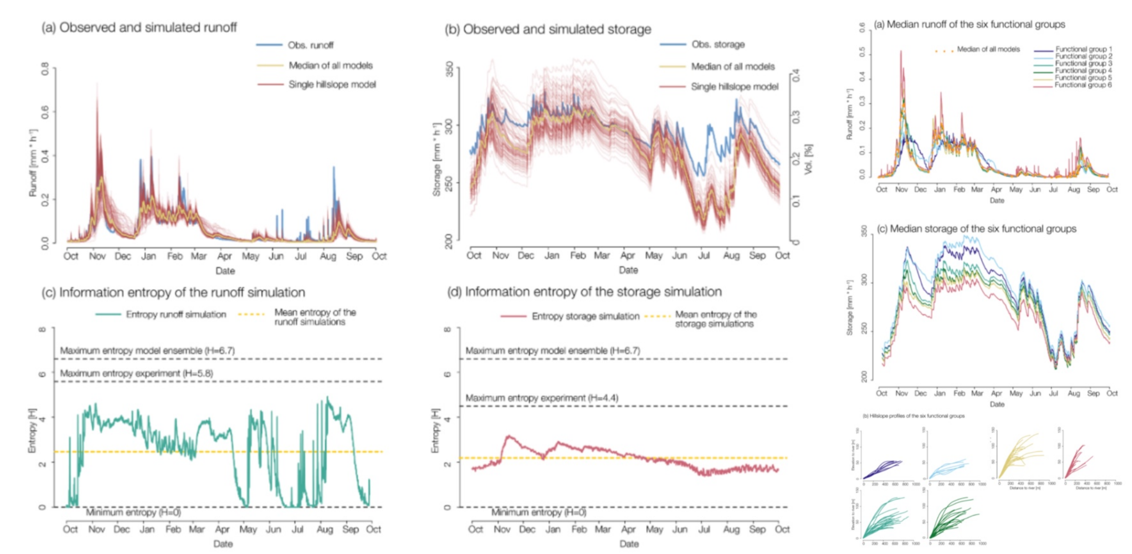
Moreover, the retention time series reveal system **state dynamics after conversion from the Darcyian Θ/ψ relation** to an energy perspective.



Examples at the hillslope-scale: Are soil retention data relevant at all?

We aggregated soil retention data from several samples into one **functional soil water curve** for a catchment. And we analysed how many different hillslopes were necessary to **inform** the observed **runoff** and **soil water dynamics**.





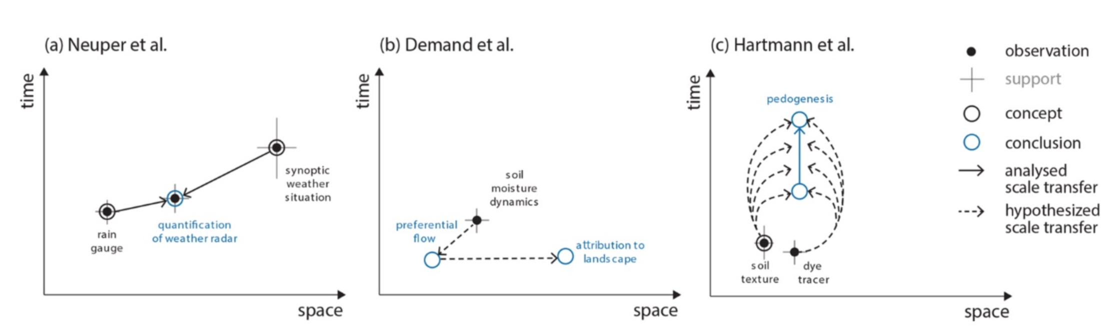
In average about 5 (out of 105) hillslopes with highly **aggregated** soil retention **data** were **sufficient**. The entropy of runoff is higher than the entropy of soil moisture.

For more details about this study and the data, see our publications in HESS https://doi.org/10.5194/hess-21-1225-2017 and https://doi.org/10.5194/hess-22-3663-2018

Examples for scaling in soil landscape studies: How can we align concepts, measurements and conclusions?

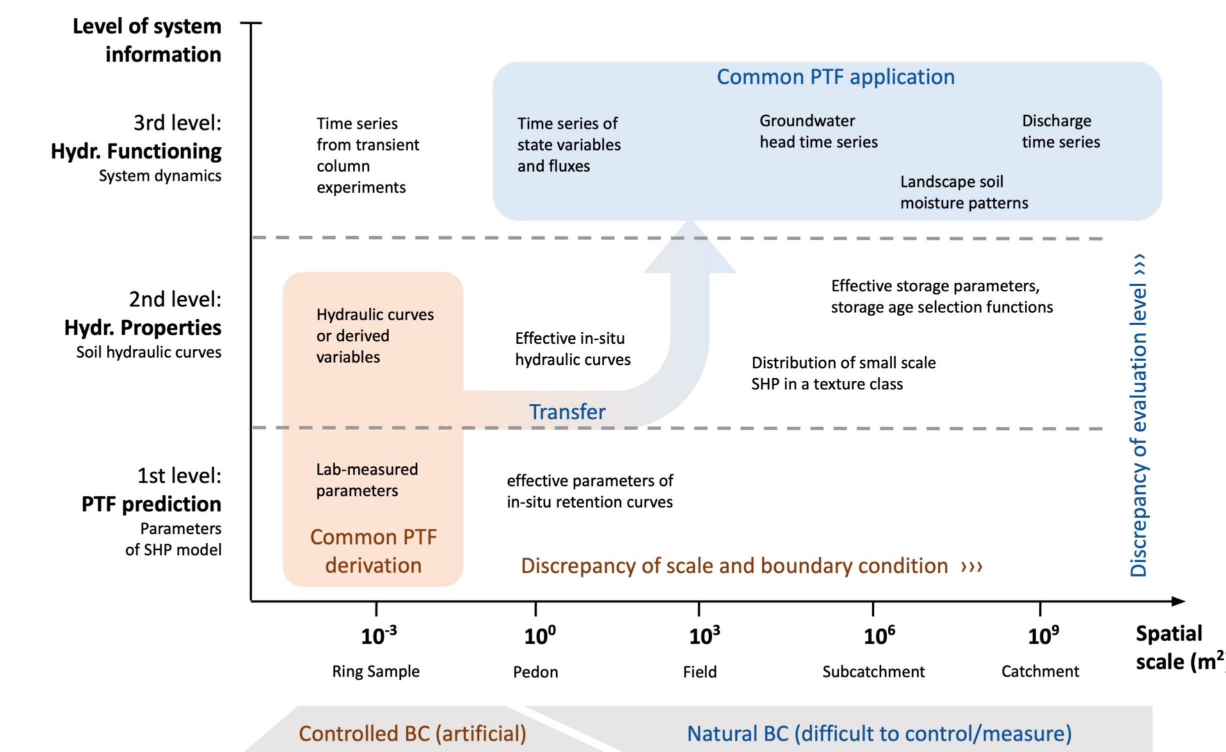
We analysed how different studies dealt with the issue of scales and scaling to infer on landscape properties. In most cases scale transfer remains hypothesized and outside the scope of analyses.

For more details about this study, see our preface to a special issue in HESS and ESSD https://doi.org/10.5194/hess-25-5277-2021



How can we raise awareness to information and scaling in our analyses?

We propose a **scale- and information aware evaluation concept** for pedotransfer function derivation and application. This concept **links** the issue of **information** content with **scale** and **boundary conditions**.



By evaluating the different elements of a study in this concept, **scale transfers become apparent** – and can be addressed or avoided. It also clarifies on the **level of information** required for **evaluation**. This helps to avoid possible mismatching linkages between different levels of system information.

Proposal for a standardised pedon-scale experiment

On the one hand, scale transfer is difficult. On the other hand we require soil functional data above mere retention properties. We propose to convey our lab-scale experiences into the field with a smart, standardised and repeatable field experiment at the pedon scale.

- the pedon-scale might be sufficiently close to the scale of application
- we can observe boundary fluxes, internal reconfiguration, gradients and recovery of equilibrium states
- we could run standardised series of irrigation and evaporation