https://doi.org/10.5194/egusphere-2026-1738
Preprint. Discussion started: 13 April 2026

On the validity of Richards' equation under dynamic flow conditions

Efstathios Diamantopoulos[1*], Sascha Christian Iden[2]

[1] University of Bayreuth, Chair of Soil Physics

[2] Technische Universität Braunschweig, Institute of Geoecology, Division of Soil Science

[*] Corresponding author information: Universität Bayreuth, Fakultät Biologie, Chemie, Geowissenschaften, 95440 Bayreuth, Germany, Email: Efstathios.Diamantopoulos@uni-bayreuth.de

Abstract

Richards' equation is currently applied to simulate water flow in soils over a wide range of spatial scales, from the centimeter to the kilometer scale. A key assumption of Richards' equation is that water content and matric potential are at an equilibrium which is described by the water retention curve. However, numerous observations have called this assumption into question, particularly under conditions of fast water flow. In this mini-review, we present six experiments in which the equilibrium assumption is violated and which therefore cannot be adequately described by Richards' equation: multistep outflow / inflow, continuous outflow / inflow, multistep flux, capillary rise, evaporation and, transpiration. These experiments span a wide range of experimental conditions, from fast to very slow water flow and apply both pressure head and flux boundary conditions. Although it is in most cases unknown which exact physical processes are responsible for these effects, a simple flow model, which extends the Richards equation by a partial decoupling of pressure head and water content under dynamic flow conditions, can

https://doi.org/10.5194/egusphere-2026-1738
Preprint. Discussion started: 13 April 2026

describe the observed relaxation of water content or pressure head well. Notably, this represents the first demonstration of a non-equilibrium model for all six types of non-equilibrium observations. We discuss implications, theoretical limitations, and future perspectives on researching dynamic nonequilibrium in variably-saturated flow in soils, as well as potential improvements of modeling concepts necessary to describe non-equilibrium during variably-saturated flow at different scales and under different boundary conditions.

https://doi.org/10.5194/egusphere-2026-1738
Preprint. Discussion started: 13 April 2026

1 Introduction

Predicting variably saturated water fluxes, soil water content and water potential in soils is considered crucial in the environmental sciences, such as hydrology, ecology, and agricultural science, as the soil's complex biogeochemistry, solute transport, and heat flow are all influenced by water fluxes and water content. Different theories have been proposed to model water flow in soils, but until today the Richards equation (RE), which is grounded in the local mass balance of soil water and the Buckingham-Darcy law for unsaturated flow, remains undoubtedly the most popular (Nimmo, 2020). The Richards equation is based on continuum theory and requires averaging of pore scale variables to macroscopic state variables such as water content and water potential (Bear, 1972). For the solution of RE, the knowledge of the soil hydraulic properties (SHPs) is required. These are the water retention curve, $\theta(h)$, relating volumetric water content θ [m^3 m^{-3}] to matric head h [m], and the hydraulic conductivity curve $K(h)$ [m s^{-1}]. Although RE has been applied and is currently applied from the cm (Weller et al., 2011) scale up to kilometer (Ashby and Falgout, 1996; Kuffour et al., 2020) scale, there is still a lack of understanding on the relationship between SHPs determined in the laboratory and estimated from field measurements. Due to structural heterogeneities below the scale of the numerical grid, the hydraulic equilibrium assumption between h and θ in RE can be violated (Vogel, 2019). For this reason, the simulation of processes like infiltration and drainage in field soils and large field lysimeters often do not yield results which are in close enough agreement with measurements (Vogel, 2019), in particular when soil hydraulic properties measured in the laboratory are used as material functions, or the effective SHPs obtained from field data are compared against the ones determined in controlled experiments in the laboratory.

https://doi.org/10.5194/egusphere-2026-1738
Preprint. Discussion started: 13 April 2026

One of the reasons for the systematic discrepancy between SHPs (Hannes et al., 2016), estimated under field and lab conditions is the phenomenon of capillary hysteresis (Poulovassilis and Childs, 1971; Pham et al., 2005). It refers to the non-uniqueness of the $\theta(h)$ and its dependence upon the history of soil wetting and drying and has three causes on the pore scale, (i) the ink bottle effect caused by irregular pore shape (Haines, 1930), (ii) contact angle hysteresis (Bachmann et al. 2009; Diamantopoulos et al., 2013) and (iii) shrinkage/swelling effects (Hillel et al., 2007; Pham et al., 2005). Although hysteresis is recognized as an important process in variably-saturated flow, it is very rarely considered for larger scale simulation (field and larger), because it requires long and complicated experiments to adequately parametrize the numerous wetting and drying curves. Furthermore, given the complexity of real soils (heterogeneity, soil structure variability, etc.), it is questionable whether incorporating hysteresis leads to decisive improvements in water flow simulations (Vogel and Roth, 2003).

Studying capillary hysteresis and conducting laboratory experiments in general can be challenging due to the co-occurrence of an additional phenomenon that is difficult to disentangle from hysteresis (Diamantopoulos et al., 2015; Hannes et al., 2016). Central assumption to RE, among many others (Diamantopoulos and Durner, 2012), is that water content and matric potential are tightly coupled through $\theta(h)$ (or any wetting/drying scanning curve), independently of whether water does flow or not. This is called the local equilibrium assumption. The water retention curve is a soil property that reflects the effective pore-size distribution of the soil and intrinsically accounts for various effects, water properties, and processes which influence the spatial distribution of water and air in soils. These encompass (i) surface tension, (ii) the presence of fluid-fluid interfaces, (iii) wettability of solid surfaces, (iv) the particle size distribution, and (v) micro and macro heterogeneities. Similarly, the unsaturated hydraulic conductivity function $K(h)$ or $K(\theta)$ is

https://doi.org/10.5194/egusphere-2026-1738
Preprint. Discussion started: 13 April 2026

influenced by water content, the spatial distribution of air-water interfaces, specific surface area, roughness of solids, pore tortuosity, and the shape and degree of interconnection of the water-conducting pores. When using equilibrium $\theta(h)$ in RE, we assume that all of these influencing factors have the same effect, regardless of whether water is moving or not. For $K(h)$ or $K(\theta)$, it is usually assumed that hydraulic conductivity is the same for both transient and steady-state water flow. Summing up, it is generally assumed that both soil hydraulic properties are invariant with respect to flow dynamics and therefore identical for static, steady-state, and transient flow.

Starting from the 1960s, many scientists have tested this assumption for various experimental conditions. Results of those studies show that $\theta(h)$, and $K(h)$ in a lesser degree, are different between transient and equilibrium conditions (Topp et al., 1967; Hassanizadeh et al., 1990; Hassanizadeh et al., 2002). This phenomenon is loosely called "dynamic effects" or "non-equilibrium water flow". In the following, we will use the acronym DNE. DNE has been observed in numerous laboratory experiments designed to validate RE or estimate SHPs: constant flux irrigation wetting/drying experiments (Stonestrom and Aksin, 1994; Weller et al., 2011; DiCarlo, 2005; 2007), pressure head drainage and imbibition experiments (Topp et al., 1967; Schultze et al., 1999; O'Carroll, et al., 2005;2010), and many others (Hassanizadeh et al., 2002; Diamantopoulos and Durner, 2012; Yan et al., 2022). In the field, preferential water flow can be considered as a larger scale manifestation of DNE (Jarvis, 2007; Ross and Smettem, 2000) which occurs during infiltration or more generally, during wetting conditions. The occurrence of DNE during drying is less well researched and it is currently not known if DNE is relevant for drying conditions. Many different pore-scale processes have also been identified in the literature as being responsible for DNE. Very briefly, immiscible two-phase interface configuration (Barenblatt, 1991; Sakaki et al., 2010) dynamic contact angle (Hofmann, 1974; Friedman,

https://doi.org/10.5194/egusphere-2026-1738
Preprint. Discussion started: 13 April 2026

1999), air entry effects (Diamantopoulos and Durner, 2012), air (Smiles et al., 1971; Camps-Roach et al., 2010), and water entrapment (Poulovassilis, 1974;Wildenschild et al., 2001) and/or blockage (Weller et al., 2011), time-dependent water repellency /hydrophobicity (Reszkowska et al., 2014), fluid properties (Das et al., 2007; Goel and O'Caroll, 2011) and micro (Mirzaei and Das, 2007) and macroscale heterogeneities (Manthey et al., 2005). It is important to note, that even if there is hydraulic equilibrium at the pore scale, spatial averaging may result in DNE at the REV scale (Hassanizadeh et al., 2002). There is currently no methodology for identifying the dominant cause of DNE for a specific experiment. Moreover, Wildenschild et a., (2001) suggested that more than one process can cause DNE for a specific experiment. Summing up, it is difficult to distinguish which specific processes and causes are responsible for appearances of DNE.

Different models to describe DNE have been proposed in the past years. Some of those are empirical (Barenblat, 1971; Ross and Smettem, 2000; Diamantopoulos et al., 2012), while others are based on thermodynamic considerations (Hassanizadeh et al., 2002). For all models, data-model comparison studies exist, showing that the models are capable of describing DNE observations (DiCarlo, 2005; O'Carroll et al., 2010; Camps-Roach et al., 2010). However, model applications are often limited to a single boundary-condition type and a single porous medium. Although there are some similarities between the different models, it is currently unclear if those models can describe all or only a subsample of DNE observations. Moreover, even for the models based on thermodynamic principles, non-equilibrium parameters can be only estimated through inverse modelling using measured data with sufficient information content. One special case is provided by the models of Barenblatt (1971) and Hassanizadeh and Gray (1990) which assume that the faster the water saturation changes, the more pronounced the DNE becomes.

https://doi.org/10.5194/egusphere-2026-1738
Preprint. Discussion started: 13 April 2026

In this contribution, we present experimental results for six different laboratory observations, and show that RE, with the inherent assumption of hydraulic equilibrium between h and θ, cannot describe the observed relaxation between water content and the matric potential. Notably, we also show that this is not only the case for fast water flow conditions, for which the existence of DNE is currently acknowledged, but that DNE occurs under slow experiments, too. Despite the different pore scale processes responsible for the mismatch between RE and the data, we illustrate that a parsimonious effective model that decouples *h* from θ under dynamics conditions and includes RE as core component, can qualitatively describe all experimental data. To the best of our knowledge, this ability has not been demonstrated by any of the published non-equilibrium models. We conclude this article with a brief discussion on the relevance of DNE at the field scale, along with the theoretical limitations and prospects for future research.

2 Materials and Methods

2.1 Theory

2.1.1 Richards equation

Water flow in unsaturated porous media is described by the RE (Riuchards, 1931), which in one dimension and without any sink/source terms has the form:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left(K(h)\left(\frac{\partial h}{\partial z} + 1\right)\right) \tag{1}$$

where θ $[\mathrm{L}^3\mathrm{L}^{-3}]$ is the volumetric water content, t $[\mathrm{T}]$ is time, z $[\mathrm{L}]$ is the vertical spatial coordinate (positive upwards), h $[\mathrm{L}]$ is the pressure head, and $K(h)$ $[\mathrm{L\,T}^{-1}]$ is the hydraulic conductivity function. The numerical solution of Eq. (1) requires the definition of $\theta(h)$ and

https://doi.org/10.5194/egusphere-2026-1738
Preprint. Discussion started: 13 April 2026

149 $K(h)$. For all the simulations in this article, the van Genuchten-Mualem model (van
150 Genuchten, 1980) is used to parametrize the soil hydraulic properties:

$$S(h) = (1 + |\alpha h|^n)^{-m} \tag{2}$$

$$\theta(h) = \begin{cases} \theta_r + (\theta_s - \theta_r)S(h) & h < 0 \\ \theta_s & h \geq 0 \end{cases} \tag{3}$$

$$K(S) = K_s S^l \left[1 - \left(1 - S^{1/m}\right)^m\right]^2 \tag{4}$$

151 where S [-] is the effective saturation, θ_s [L^3L^{-3}] and θ_r [L^3L^{-3}] are the saturated and
152 residual water contents, respectively, α [L^{-1}], $n > 1$ [$-$], $m = 1 - 1/n$ [$-$], and l [$-$] are
153 shape parameters.

154 **2.1.2 Dual Domain Dynamic Non-Equilibrium model (DUAL-NE)**

155 The DualNE model of Diamantopoulos et al. (2012;2015) assumes that the soil water can
156 be divided into two distinct fractions or domains. For the first fraction, instantaneous
157 equilibration between water content and local pressure head is assumed and the soil water
158 retention curve defines the equilibrium relationship between the two state variables. The
159 dynamics of unsaturated water flow in this domain are described by RE (Eq. 5). In the
160 second fraction, some time is required for the equilibration between the water content and
161 pressure head. This time dependence of the equilibration is described by the non-
162 equilibrium model of Ross and Smettem (2000). The DualNE model predicts that if the
163 system has sufficient time to equilibrate, both domains will reach the same equilibrium
164 state, described by the water retention curve. Assuming that equilibration of the pressure
165 head between the two domains is relatively fast, the equation of Diamantopoulos et al
166 (2012) is:

https://doi.org/10.5194/egusphere-2026-1738
Preprint. Discussion started: 13 April 2026

$$(1-f_{\mathrm{ne}})\frac{\partial\theta_{\mathrm{eq}}}{\partial t}+f_{\mathrm{ne}}\frac{\partial\theta_{\mathrm{ne}}}{\partial t}=\frac{\partial}{\partial z}\left(K(\theta)\left(\frac{\partial h}{\partial z}+1\right)\right) \quad (5)$$

where θ_{eq} $[\mathrm{L}^3\mathrm{L}^{-3}]$ and θ_{neq} $[\mathrm{L}^3\mathrm{L}^{-3}]$ are the equilibrium and non-equilibrium volumetric water contents, respectively, and f_{ne} [-] is a partitioning parameter having a value between 0 and 1 In the limit of $f_{\mathrm{ne}}=0$, Eq. (7) is identical to RE (Eq. 1) and for $f_{\mathrm{ne}}=1$, Eq. (5) is identical to the Ross and Smettem[Error! Bookmark not defined.] approach. For the non-equilibrium domain, we assume that $\frac{\partial\theta_{\mathrm{ne}}}{\partial t}\cong\frac{\theta^*_{\mathrm{eq}}-\theta_{\mathrm{ne}}}{\tau}$, where θ^*_{eq} is the equilibrium water content, given by the equilibrium retention curve and τ [T] describes how fast equilibrium is reached (Ross and Smettem, 2000). As parameter τ approaches 0, Eq. 5 converges to RE (Eq. 1). The model of Diamantopoulos et al. (2012) requires two more parameters than RE, namely f_{ne} and τ. As previously stated, DualNE is a phenomenological model and the parameter f_{ne} and τ, can be only estimated through model calibration, contrary to the non-equilibrium parameter τ_{h} in the model of Hassanisadeh and Gray (1990), which, at least theoretically, can be estimated from other physical properties (Stauffer, 1978). Both models, have been implemented in Hydrus 1D (Simunek et al., 1998).

2.2 Experimental setups

We tested RE and Dual-NE model against experimental observations from the literature. The data sets represent six different types of experiments with different boundary conditions. Table 1 shows the name and type of each experiment, the boundary conditions, and a reference to the published data. A short description of the experiments is presented in the results section.

3 Evidence of dynamic non-equilibrium und simulations with DUAL-NE model

Multistep Outflow/Inflow (MSO/MSI) experiments

https://doi.org/10.5194/egusphere-2026-1738
Preprint. Discussion started: 13 April 2026

MSO/MSI experiments are routinely used for the estimation of SHPs in the lab. A soil column is equipped with one or two tensiometers (Fig 1). At the bottom of the soil column, a pressure head is applied in an increasing (or decreasing) stepwise manner. The experiment is simulated with the RE and the SHP of the studied soil are determined by inverse modeling using a parametric representation of the SHP (Hopmanns et al., 2002). Nonparametric nonlinear regression has also been applied successfully in the context of MSO experiments (Bitterlich et al., 2004; Iden and Durner, 2007). After a sudden change in pressure head at the lower boundary, the pressure head in the soil reaches its equilibrium (hydrostatic) value quickly whereas the outflow across the bottom shows two stages (Fig 1a&b). After the pressure change at the bottom boundary, a fraction of water leaves the soil sample quickly while the pressure head changes (first stage). Afterwards, while the pressure head in the soil is already constant indicating an apparent hydraulic equilibrium, a relatively slow drainage of water takes place (second stage, Fig 1a). Similar dynamics are observed during wetting conditions (Fig 1b) when the pressure head at the bottom boundary is increased. The dynamics during the second stage cannot be captured by RE, as it assumes instantaneous local equilibrium between water content and pressure head. In contrast, the Dual-NE model, as depicted in Fig. 1, accurately represents the pressure head and cumulative outflow data. Furthermore, it is able to describe an outflow of water even when the pressure head distribution in the soil column is already in apparent hydrostatic equilibrium.

Continuous outflow/inflow experiments

A laboratory experiment similar to MSO/MSI uses a smooth, quasi-continuous change of the pressure head at the lower boundary. This avoids unnatural, abrupt changes in pressure head and is therefore closer to real field conditions. In the example shown in

https://doi.org/10.5194/egusphere-2026-1738
Preprint. Discussion started: 13 April 2026

Fig. 2, a soil column is continuously drained from 10.2 cm to -60 cm in 192 h and in 3 h, respectively (Fig 2a). Tensiometers and TDR sensors are installed at the same depth to measure pressure head and volumetric water content. By pairing the measured data, an experimental (in-situ) soil water retention curve is obtained. It is obvious that the in-situ retention curves obtained for the slow and for the fast drainage process differ markedly (Fig 2c). Based on the $\theta(h)$ function fitted to the measured outflow and pressure head data obtained from the slow drainage experiment, both experiments were simulated with RE. While RE describes the slow (192h) experiment (Fig. 2b) and the slow in situ retention curve (triangles in Fig 2c), it fails to describe the in-situ retention curve determined under fast flow conditions (Fig 2c, circles), because there is no difference between fast and slow drainage for the RE. The Dual-NE model can describe both experiments, with the same (equilibrium) SHPs and non-equilibrium parameters. This shows that for some part of the soil water, time is needed to reach equilibrium.

Multistep Flux experiment (MSFd/MSFi)

In MSF experiments, a water flux is applied across the top of soil column. This flux is either decreased (MSFd for “drainage”) or increased (MSFi for “imbibition”) in a stepwise manner. A tensiometer measures the pressure head near the top of the column and the same pressure head is applied at the bottom of the soil column (Fig 3). By this experimental design, the column is forced to reach a unit gradient in hydraulic head, in which case the flux density equals the hydraulic conductivity of the soil $K(h)$. An independent second tensiometer measures the pressure head at the center height of the soil column. Results show that after a reduction in the applied upper flux (MSFd), the pressure head drops initially as expected. However, shortly thereafter, it increases although the water content remains macroscopically constant under the realized steady-

https://doi.org/10.5194/egusphere-2026-1738
Preprint. Discussion started: 13 April 2026

state flow conditions. Conversely, a matric potential undershoot is observed for the imbibition experiment (Fig 3b). While the pressure head dynamics in both cases cannot be described by RE (Fig 3a: drainage, Fig 3b: imbibition), the Dual-NE model is able to describe both the overshoot and undershoot occurring under steady-state flow conditions.

Capillary rise experiments

DNE has also been observed in capillary rise experiments using a constant pressure head boundary condition at the bottom (Fig 4). In these experiments (Reszkowska, et al., 2014), soil water flow dynamics are very slow and occur against gravity. A soil column is filled with dry soil, and it is brought in contact with water at the bottom. The soil column is equipped with a TDR sensor at a specific height above the water level, and between two tensiometers (Fig 4a). Tensiometer measurements show that the pressure heads reach equilibrium with the water table fast (hydrostatic conditions), but water content still increased for more than 2000 h (Fig 4a). Obviously, the decoupling of water content and pressure head cannot be described by RE. Once matric potential is at hydrostatic equilibrium, the RE predicts zero water flow. When the natural soil is mixed with artificially hydrophobized particles, the effect is more pronounced (Reszkowska et al., 2014) (Fig 4b). Dual-NE can describe the fast equilibration of the matric potential recorded by the two tensiometer and the slow increase of the water content for both experiments.

Transpiration experiments

For investigating DNE for the case of slow drying experiments, a simple transpiration experiment is conducted (Fig 5a). A plant is grown in a soil column and the top of the soil is covered to minimize evaporation. The column is instrumented with 2 tensiometers, installed in two different depths. During transpiration, the pressure heads in both depths have similar values reflecting root water uptake of similar intensity (Fig 5b). Once the

https://doi.org/10.5194/egusphere-2026-1738
Preprint. Discussion started: 13 April 2026

transpiration flux is stopped, both tensiometers show an increase in pressure head, even when the total water content of the soil column does not change (Fig 5b, green line). Similar effects occur if transpiration is reduced, and not fully stopped (not shown). Due to the absence of a water sink, the pressure heads converge to different values reflecting a hydrostatic distribution. The RE with a root water uptake term which is constant in space cannot describe the increase of pressure head at both depths. Once transpiration stops, vertical redistribution of water leads to a decrease at the lower position and an increase at the upper position, but not to an increase in both depths. On the contrary, the Dual-NE model describes the relaxation of the matric potentials qualitatively, similar to what was observed in the case of the MSF experiments.

Evaporation experiments

Another observation of DNE during slow water dynamics can be made in soil evaporation experiments. A nearly water-saturated soil column is equipped with 2 tensiometers, and the column is open to the atmosphere at the top. The entire setup is placed on a balance to monitor water loss and to determine the evaporation rate and the column-averaged water content (Fig 6). For relatively wet soil profiles (almost linear distribution of matric potential with depth), a relaxation of all the tensiometer data is observed when the evaporation flux is stopped. While vertical redistribution of soil water towards hydrostatic equilibrium would lead to an increase of pressure head at one height and a decrease in another, the simultaneous increase of pressure head at both heights cannot be described by RE (Fig 6). During the interruption of evaporation, the soil temperature increases from 15 to 20 °C, following the stop of the latent heat flux and the thermal equilibration with the surroundings. Although an increase in soil temperature leads to an increase in pressure head, the magnitude of the temperature effect on pressure head is not large enough to

https://doi.org/10.5194/egusphere-2026-1738
Preprint. Discussion started: 13 April 2026

explain the observed increase during the evaporation interruption. As a result of the observed dynamics, the apparent WRC is “shifting” to the left during the interruption, indicating that more water is retained by the soil if water flows (Fig 3b). The Dual-NE model describes the relaxation of the two tensiometer very well. Most importantly, it describes the dynamics of the evaporation experiment with the equilibrium water retention curve (Fig 3b).

4 Discussion

The phenomenon of DNE describes the decoupling of water content and pressure head during transient and sometimes even during steady-state flow. The phenomenon contradicts the local equilibrium assumptions which is the basis for simulating variably-saturated flow with the RE. As a result, the RE often fails to describe flow experiments in which pressure head and water content are monitored.

One result of DNE is the flow-rate dependence of soil hydraulic properties. Examples for the dependency of the water retention curve on flow conditions have been presented in chapter 3. Even in well-sorted and packed soil materials, the identified retention curve $\theta(h)$ depends on whether it is determined under static, slow or fast dynamic flow conditions. In the case of dynamic drainage, more water is withheld by the soil at the same pressure head compared to the static case. The opposite is observed for imbibition experiments. This has not only been observed for fast water flow, as it was previously believed, but also for relatively slow water dynamics occurring during evaporation, transpiration, and capillary rise.

It is noteworthy that the physical mechanisms accountable for DNE in the six distinct experiments outlined in chapter 3 differ from one another. For example, water entrapment may explain DNE in MSO and MSF type of experiments but not in the capillary rise

https://doi.org/10.5194/egusphere-2026-1738
Preprint. Discussion started: 13 April 2026

experiments. To explain the occurrence of DNE in slow experiments such as evaporation, transpiration, and capillary rise, it seems reasonable to consider the influence of sub-REV scale heterogeneities in surface energy and wettability. This is because the faster dynamics, required for phase entrapment, or dynamic contact angle are not relevant for these slow processes. As pointed out by other researchers (Wildenschild et al., 2001), it is possible that DNE may arise from more than one physical process, which complicates the design of experiments to disentangle the exact underlying mechanisms. At a macroscopic level, all six observations presented here can be explained by the following mechanism: certain accessible pore paths are responsible for initiating flow after a change in boundary conditions. However, behind the wetting or drying front, a second stage of (horizontal) equilibration occurs involving a relatively small amount of water between pores of varying sizes within the REV. This secondary stage of equilibration is not instantaneous and is responsible for the time-varying, and thus non-unique, behavior of the water retention curve $\theta(h)$ at the REV scale.

Although multiple factors can simultaneously drive DNE in dynamic flow experiments, which makes it difficult to pinpoint the dominant cause(s), we demonstrated that the DUAL-NE model, which partially decouples water content from pressure head, can describe all observations at the macroscopic scale. We neither suggest to replace the RE by the more general Dual-NE model in all cases, nor argue that research aimed at identifying the precise physical processes responsible for DNE should be abandoned. Rather, and given the complexity of DNE, it is crucial for the soil hydrologic community to acknowledge these effects in laboratory experiments and to consider potential biases when interpreting data. The Dual-NE model can be a valuable tool for quantitatively comparing DNE across various experiments and different materials or evaluating standard laboratory experiments. For example, in the evaporation experiment (Fig 6), the model can be used

https://doi.org/10.5194/egusphere-2026-1738
Preprint. Discussion started: 13 April 2026

to estimate the equilibrium $\theta(h)$ instead of the dynamic one. Of course, this would require simple modifications to the experimental procedure, for instance the inclusion of flow interruptions, an established technique in column breakthrough experiments, at least in the majority of cases in which the non-equilibrium parameters are unknown. Moreover, targeted experiments are necessary to improve our understanding of DNE and to identify potential biases resulting from it. This is very important for studying the combined effect of DNE and hysteresis, since it is expected that there will be a difference between dynamic and equilibrium hysteretic scanning curves. Moreover, it is crucial to investigate how different intensities of boundary condition changes (or saturation changes), different materials (i.e., packed, structured), and different spatial scales (cm, dm, m) affect the non-equilibrium parameters of the Dual-NE model. Can the Dual-NE model describe different experiments conducted at the same system (type, imbibition, drying, etc.) with the same set of SHPs for one material, and the same non-equilibrium parameters? And, if this is not the case, how do these parameters differ for the different boundary conditions, and for different water contents or pressure heads. Recent advances in information science suggest that combining the flexibility of a model such as Dual-NE with statistical learning methods may eventually lead to the development of more accurate prediction tools.

Many scientists hold the view that DNE occurs only in (rapid) laboratory experiments and are questioning its relevance for field conditions. However, at the plot scale, preferential water flow can also be regarded as expression of DNE. The Ross and Smettem**Error! Bookmark not defined.** model, which is a special case of the Dual-NE model if f_{ne}=1, was originally developed to effectively describe fast, preferential water flow through soils. For this model, it is essential to use $K(h)$ rather than the $K(\theta)$ formulation currently used in Dual-NE (Eq. 5). This means that a reevaluation of the conductivity function is necessary

https://doi.org/10.5194/egusphere-2026-1738
Preprint. Discussion started: 13 April 2026

to extend Dual-NE for describing preferential water flow. While there are some initial ideas on this topic (Vogel et al., 2022), further testing of all the experiments mentioned above is necessary to demonstrate the generalizability of any new approach. It is also worth noting that even when the RE is applied at the hectometer or kilometer scale, its parametrization typically relies indirectly on laboratory experiments, because pedotransfer functions (Van Looy et al., 2017; Weber et al., 2024) are based on lab data. This means that DNE occurring in lab experiments may indirectly affect large scale simulations. In contrast to DNE during infiltration, the relevance of DNE at the plot scale under drainage conditions remains to be explored. For field drainage, flux densities similar to those encountered in the reported evaporation (0.12 mm/h) and transpiration experiments (1.9 mm/h) are expected. This calls again for multiscale experiments on DNE, that include drying and wetting conditions.

5 Conclusion

In this mini-review, we presented evidence of dynamic non-equilibrium (DNE) effects in six types of laboratory experiments covering a wide range of boundary conditions and flow rates. The results demonstrate that the decoupling of water content and pressure head is not restricted to fast water flow conditions, as previously believed, but also occurs under slow dynamics such as evaporation, transpiration, and capillary rise. The RE, with its inherent local equilibrium assumption, systematically fails to describe these observations. A simple extension of the RE, the Dual-NE model, which decouples water content from pressure head in a subdomain of the soil, was able to qualitatively reproduce all six experiments. This suggests that a single and relatively simple modeling approach might be capable of describing DNE in a consistent manner. While we do not advocate replacing the Richards equation in all applications, these findings highlight the need for the soil

https://doi.org/10.5194/egusphere-2026-1738
Preprint. Discussion started: 13 April 2026

hydrology community to acknowledge DNE effects when designing and interpreting laboratory experiments. Future work should focus on multi-scale experiments under both wetting and drying conditions, the interplay between DNE and hysteresis, work towards a unified DNE framework that can additionally simulate preferential water flow, and the potential use of statistical learning methods to improve the predictive capability of non-equilibrium models.

Code Availability

The code for this work will be made available upon acceptance of the manuscript.

Data Availability

The data for this work will be made available upon acceptance of the manuscript.

Acknowledgments

The authors acknowledge using ChatGPT (https://chatgpt.com/) to review language usage and enhance readability. After using this tool, the authors reviewed and edited the manuscript, and take full responsibility for its content. This work was carried out in the framework of the project „DynSoilWater“ funded by the German Research Fundation (DFG) under grants DI2146/3-1 and ID 75/2-1.

https://doi.org/10.5194/egusphere-2026-1738
Preprint. Discussion started: 13 April 2026

References

Ashby, S. F. and Falgout, R. D.: A Parallel Multigrid Preconditioned Conjugate Gradient Algorithm for Groundwater Flow Simulations, Nucl. Sci. Eng., 124, 145–159, 1996.

Bachmann, J., Woche, S.K., Goebel, M.O., Kirkham, M.B., Horton, R., 2003. Extended methodology for determining wetting properties of porous media. Water Resour. Res. 39, 1353–1365. Barari, A., Omidvar, M., Ghotbi, A.R., and D.D. Ganji, (2009), Numerical analysis of Richards problem for water penetration in unsaturated soils, Hydrology and Earth System Sciences, https://doi.org/10.5194/hessd-6-6359-2009

Barenblat , G.I. 1971. Filtration of two nonmixing fluids in a homogeneous porous medium. Fluid Dyn. 6:857–864.

Barenblatt, G.I., 1971. Filtration of two mixing fluids in a homogeneous porous medium, Fluid. Dyn. 6:857-864

Bear, J. 1972. Dynamics of fluids in porous media. American Elsevier, New York.

Bitterlich, S., Durner, W., Iden, S.C. and Knabner, P. (2004), Inverse Estimation of the Unsaturated Soil Hydraulic Properties from Column Outflow Experiments Using Free-Form Parameterizations. Vadose Zone Journal, 3: 971-981. https://doi.org/10.2136/vzj2004.0971

Camps-Roach, G., D.M. O'Carroll, T.A. Newson, T. Sakaki, and T.H. Illangasekare. 2010. Experimental investigation of dynamic effects in capillary pressure: Grain size dependency and upscaling. Water Resour. Res. 46:W08544. doi:10.1029/2009WR008881

https://doi.org/10.5194/egusphere-2026-1738
Preprint. Discussion started: 13 April 2026

Das, B.D., Gauldie, R., Mirzaei, M., 2007. Dynamic effects for two-phase flow in porous media: fluid property effects. AIChE J. 53 (10), 2505–2520.

Diamantopoulos, E., and W. Durner, 2012. Dynamic nonequilibrium of water flow in porous media: A review, Vadose Zone J., doi:10.2136/vzj2011.0197

Diamantopoulos, E., and W. Durner, 2012. Dynamic nonequilibrium of water flow in porous media: A review, Vadose Zone J., doi:10.2136/vzj2011.0197

Diamantopoulos, E., Durner, W., Reszkowska, A. and Bachmann, J., 2013. Effect of soil water repellency on soil hydraulic properties estimated under dynamic conditions, Journal of Hydrology, 10.1016/j.jhydrol.2013.01.020

Diamantopoulos, E., I.C. Iden, and W. Durner. 2012. Inverse modeling of dynamic non-equilibrium in water flow with an eff ective approach. Water Resour. Res. 48:W03503. doi:10.1029/2011WR010717

Diamantopoulos, E., W. Durner, S. Iden, U. Weller, and H.-J. Vogel. 2015. Modeling dynamic non-equilibrium water flow observations under various boundary conditions. J. Hydrol. 529:1851–1858. doi:10.1016/j.jhydrol.2015.07.032

DiCarlo, D.A. 2005. Modeling observed saturation overshoot with continuum additions to standard unsaturated theory. Adv. Water Resour. 28:1021–1027. doi:10.1016/j.advwatres.2004.12.003

DiCarlo, D.A. 2007. Capillary pressure overshoot as a function of imbibition flux and initial water content. Water Resour. Res. 43:W08402. doi:10.1029/2006WR005550

Friedman, S.P. 1999. Dynamic contact angle explanation of flow rate-dependent saturation–pressure relationships during transient liquid flow in unsaturated porous

https://doi.org/10.5194/egusphere-2026-1738
Preprint. Discussion started: 13 April 2026

media. J. Adhes. Sci. Technol. 13: 1495– 1518. https://doi.org/10.1163/156856199X00613

Goel, G., and D.M. O'Carroll. 2011. Experimental investigate on of nonequilibrium capillarity effects: Fluid viscosity effects. Water Resour. Res. 47:W09507. doi:10.1029/2010WR009861

Haines, W. B. (1930), Studies in the physical properties of soil. V. The hysteresis effect in capillary properties, and the modes of moisture distribution associated therewith, J. Agric. Sci., 20, 97– 116, doi:10.1017/S002185960008864X.

Hannes, M., Wolschlaeger, U., Woehling, T., and H.-Vogel, 2016. Revisiting hydraulic hysteresis based on long-term monitoring of hydraulic states in lysimeters, Water Resour. Res., https://doi.org/10.1002/2015WR018319

Hassanizadeh, S.M., and W.G. Gray. 1990. Mechanics and thermodynamics of multiphase flow in porous media including interphase boundaries. Adv. Water Resour. 13:169–186. doi:10.1016/0309-1708(90)90040-B

Hassanizadeh, S.M., M.A. Celia, and H.K. Dahle. 2002. Dynamic effects in capillary pressure–saturation relationships and its impact on unsaturated flow. Vadose Zone J. 1:38–57

Hillel, 1998. Environmental Soil Physics Academic Press, San Diego (1998), 7771 pp

Hillel, D., Pham HQ, Fredlund DG, Barbour SL. 2005. A study of hysteresis model for soil-water characteristic curves. Canadian Geotechnical Journal 42: 1548–1568.

Hoffman, R.L. 1975. Study of advancing interface: 1. Interface shape in liquid–gas systems. J. Colloid Interface Sci. 50: 228– 241. https://doi.org/10.1016/0021-9797(75)90225-8

https://doi.org/10.5194/egusphere-2026-1738
Preprint. Discussion started: 13 April 2026

Hopmans, J.W., Simunek, J., Romano, N., Durner, W., 2002. Simultaneousdetermination of water transmission and retention properties – inversemethods. In: Dane, J.H., Topp, G.C. (Eds.), Methods of Soil Analysis, Part 4.SSSA Book Ser. 5. SSSA, Madison, WI, pp. 963–1008.

Iden S.C., and W. Durner (2007): Free-Form estimation of the unsaturated soil hydraulic properties by inverse modelling using global optimization, Water Resources Research, doi:10.1029/2006WR005845

Jarvis, N.J., 2007. A review of non-equilibrium water flow and solute transport in soil macropores: Principles, controlling factors and consequences for water quality. Eur. J. Soil Sci., 58:523-546. Doil:10.111/j.1365-2389.2007.00915.x

Kuffour B.N.O., Engdahl, N.B., Woodward, C.S., Condon, L.E., Kollet, S., R. M. Maxwell, 2020. Simulating coupled surface–subsurface flows with ParFlow v3.5.0: capabilities, applications, and ongoing development of an open-source, massively parallel, integrated hydrologic model, Geosci. Model Dev., 13, 1373–1397, 2020, https://doi.org/10.5194/gmd-13-1373-2020

Manthey, S., S.M. Hassanizadeh, and R. Helmig. 2005. Macro-scale dynamic effects in homogeneous and heterogeneous porous media. Transp. Porous Media 58:121–145. doi:10.1007/s11242-004-5472-6

Mirzaei, M., and B.S. Das. 2007. Dynamic effects in capillary pressure saturation relationships for two-phase flow in 3D porous media: Implication of micro-heterogeneities. Chem. Eng. Sci. 62:1927–1947. doi:10.1016/j.ces.2006.12.039

Nimmo, J.R., (2020), The processes of preferential flow in the unsaturated zone, Soil Science Society of America Journal [Invited Review], doi:10.1002/saj2.20143

https://doi.org/10.5194/egusphere-2026-1738
Preprint. Discussion started: 13 April 2026

490 O'Carroll, D.M., K.G. Mumford, L.M. Abriola, and J.I. Gerhard. 2010. Influence of
491 wettability variations on dynamic effects in capillary pressure. Water Resour. Res.
492 46:W08505. doi:10.1029/2009WR008712

493 O'Carroll, D.M., T.J. Phelan, and L.M. Abriola. 2005. Exploring dynamic effects in
494 capillary pressure in multistep outflow experiments. Water Resour. Res. 41:W11419.
495 doi:10.1029/2005WR004010

496 Pham HQ, Fredlund DG, Barbour SL. 2005. A study of hysteresis model for soil-water
497 characteristic curves. Canadian Geotechnical Journal 42: 1548–1568.

498 Poulovassilis, A. 1974. The uniqueness of the moisture characteristics. Soil Sci. 25:27–
499 33. doi:10.1111/j.1365-2389.1974.tb01099.x

500 Poulovassilis, A., and E. C. Childs (1971), The hysteresis of pore water: The non-
501 independence of domains, Soil Sci., 112(5), 301–312

502 Reszkowska, A.. Bachmann, J., A. Lamparter, Diamantopoulos, E., and W. Durner. 2014.
503 The effect of temperature-induced soil water repellency on transient capillary
504 pressure-water content relations during capillary rise. European Journal of Soil
505 Science, 2014, 64, 369-376, doi: 10.1111/ejss.12139

506 Richards, L.A. 1931. Capillary conduction of liquids through porous media. Physics
507 1:318–333. doi:10.1063/1.1745010

508 Ross, P.J., and K.R.J. Smettem. 2000. A simple treatment of physical nonequilibrium
509 water flow in soils. Soil Sci. Soc. Am. J. 64:1926–1930.
510 doi:10.2136/sssaj2000.6461926x

https://doi.org/10.5194/egusphere-2026-1738
Preprint. Discussion started: 13 April 2026

511 Sakaki, T., D. M., O`Carroll and T.H. Illangasekare, 2010. Direct quantification of dynamic
512 effects in capillary pressure for drainage-wetting cycles. Vadose Zone Journal, 9:424-
513 437, doi:10.2136/vzj2009.0105

514 Schultze, B., O. Ippisch, B. Huwe, and W. Durner. 1999. Dynamic nonequilibrium in
515 unsaturated water flow. In: M.Th. van Genuchten et al., editors, Proceedings of an
516 International Workshop on Characterization and Measurement of the Hydraulic
517 Properties of Unsaturated Porous Media, Riverside, CA. 22–24 Oct. 1997. Univ. of
518 California, Riverside. p. 877–892.

519 Simunek, J., M. Sejna, and M. Th. Van Genuchten, 1998. The Hydrus-1D software
520 package for simulating the one-dimensional movement of water, heat and multiple
521 solutes in variably-saturated media. Version 2.0, IGWMC-TPS-70, International
522 Ground Water Modelling Center, Colorado School of Mines, Golden, CO. 202

523 Smiles, D.E., G. Vachaud, and M. Vauclin. 1971. A test of the uniqueness of the soil
524 moisture characteristic during transient, nonhysteretic flow of water in a rigid soil. Soil
525 Sci. Soc. Am. Proc. 35:534–539. doi:10.2136/sssaj1971.03615995003500040018x

526 Stauffer, F. 1978. Time dependence of the relationships between capillary pressure water
527 content and conductivity during drainage of porous media. In: IAHR Symposium on
528 scale Effects in porous media, Thessaloniki, Grece. 29 Aug-1 Sept 1978.Int. Assoc
529 Hydro-Environ. Eng. Res., Madrid, Spain, p.3.35-3.53.

530 Stonestrom, D.A., and K.C. AksΘ n. 1994. Nonmonotonic matric pressure histories
531 during constant flux infiltration into homogeneous profiles. Water Resour. Res. 30:81–
532 91. doi:10.1029/93WR02476

https://doi.org/10.5194/egusphere-2026-1738
Preprint. Discussion started: 13 April 2026

533 Topp, G.C., A. Klute, and D.B. Peters. 1967. Comparison of water content– pressure
534 head data obtained by equilibrium, steady-state, and un- steady-state methods. Soil
535 Sci. Soc. Am. Proc. 31:312–314. doi:10.2136/ sssaj1967.03615995003100030009x

536 van Genuchten, M.Th. 1980. A closed-form equation for predictinng the hydraulic
537 conductivity of unsaturated soils. Soil Sci. Soc. Am. J. 44:892–898.
538 doi:10.2136/sssaj1980.03615995004400050002x

539 Van Looy, K., Bouma, J., Herbst, M., Koestel, J., Minasny, B., Mishra, U., Montzka, C.,
540 Nemes, A., Pachepsky, Y., Padarian, J., Schaap, M.G., Tóth, B., Verhoef, A.,
541 Vanderborght, J., van der Ploeg, M.J., Weihermüller, L., Zacharias, S., Zhang, Y.,
542 Vereecken, H., 2017. Pedotransfer functions in Earth System Science: Challenges
543 and Perspectives, Review of Geophysics, https://doi.org/10.1002/2017RG000581

544 Vogel, H.J., 2019. Scale issues in soil hydrology. Vadose Zone j.,
545 doi:10.2136/vzj2019.01.0001

546 Vogel, H.J., and K., Roth, 2003. Moving through scales of flow and transport in soil, J.
547 Hydrol., https://doi.org/10.1016/S0022-1694(02)00257-3

548 Vogel, H.J., Gerke, H. H., Mietrach, R., Zahl, R., Wöhling, T., 2022. Soil hydraulic
549 conductivity in the state of nonequilibrium, Vadose Zone Journal, 2023,e20238

550 Weber, KDT et al., 2024, Hydro-pedotransfer functions: a roadmap for future
551 development, https://doi.org/10.5194/hess-28-3391-2024

552 Weller, U., O. Ippisch, J.M. Köhne, and H.J. Vogel. 2011. Direct measurement of
553 unsaturated hydraulic conducϴ vity including nonequilibrium and hyster-esis. Vadose
554 Zone J. 10:654–661. doi:10.2136/vzj2010.0074

https://doi.org/10.5194/egusphere-2026-1738
Preprint. Discussion started: 13 April 2026

555 Wildenschild, D., J.W. Hopmans, and J. Šimůnek. 2001. Flow rate dependence of soil
556 hydraulic characteristics. Soil Sci. Soc. Am. J. 65:35–48.
557 doi:10.2136/sssaj2001.65135x

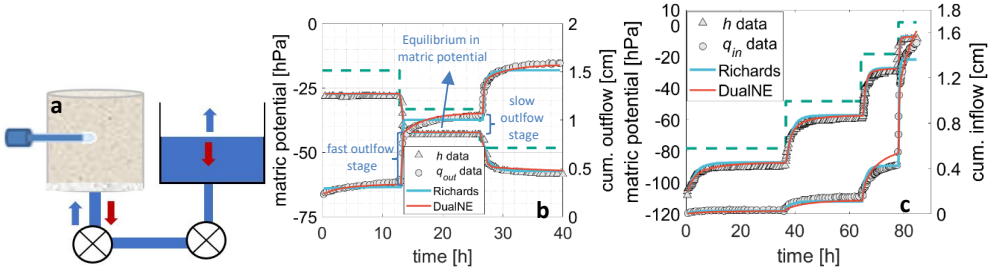
558 Yan, G., Li, Z., Torres, S.A.G., Scheuermann, A., and Li, L., 2022, Transient Two-Phase
559 flow in Porous media: A literature review and Engineering Application in Geotechnichs,
560 Geotechnichs, http://doi.org/10,3390/geotecvhnichs2010003

561

https://doi.org/10.5194/egusphere-2026-1738
Preprint. Discussion started: 13 April 2026

562 **Figures and Tables**

563

564 

565

566 **Figure 1.** Schematic diagram of experimental setup for the multistep outflow and inflow
567 experiments (a). The pressure head at the lower boundary is varied in a stepwise manner (green
568 dashed line in b, c). During drainage, the pressure head reaches equilibrium quickly, but the
569 outflow dynamics show two stages. In the first stage, water outflow is rapid while the pressure
570 head changes. This is followed by a slower equilibration under an apparent hydrostatic pressure
571 distribution (b). Similarly, a two-stage inflow is observed during imbibition experiments (c).
572 Although Richards' equation describes the dynamics and equilibration of the matric potential data,
573 it fails to mimic the dynamics of the cumulative outflow (b) or inflow (c). In contrast, both
574 experiments can be described by the Dual-NE approach, where the water content is divided into
575 two fractions, one which equilibrates quickly with pressure head, and one which lags behind.

576

577

https://doi.org/10.5194/egusphere-2026-1738
Preprint. Discussion started: 13 April 2026

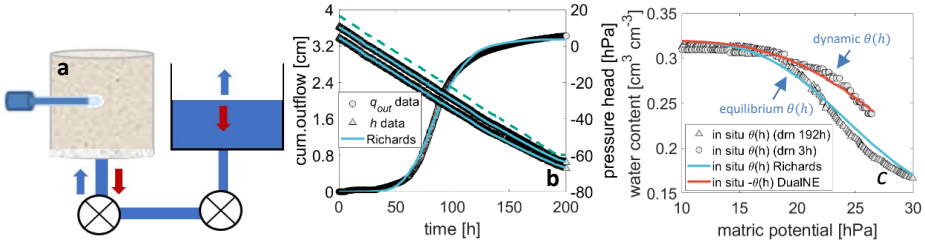
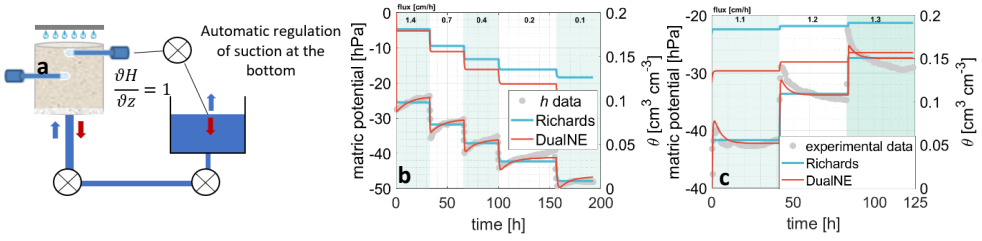


Figure 2. Schematic diagram of the experimental setup for continuous outflow experiments (a). The pressure head at the lower boundary is changed continuously (green line in b) under slow drainage. Richards' equation can adequately describe the pressure head and cumulative outflow data for slow drainage (b), as well as the slow in-situ retention curve (c). However, it fails to describe the retention curve obtained from the fast experiment (circles in c). For fast flow, Richards' equation predicts the same equilibrium curve, regardless of the flow conditions. In contrast, the Dual-NE model can describe both experiments using the same set of soil hydraulic properties and non-equilibrium parameters.

https://doi.org/10.5194/egusphere-2026-1738
Preprint. Discussion started: 13 April 2026



587

588 **Figure 3.** Schematic diagram of the experimental setup for the multistep flux experiment (a). An
589 irrigation flux is either reduced (drainage experiment, b) or increased (wetting experiment, c) at
590 the top of the soil column. A tensiometer is used to measure the pressure head near the soil
591 surface, and the same pressure is applied at the bottom of the soil column, forcing the system to
592 reach unit gradient conditions, as shown in a. For the drainage experiment (MSFd, b), once the
593 flux is reduced, the matric potential measured by an independent tensiometer is also reduced as
594 expected, but then it slowly rises again. The opposite is observed for the wetting experiment (c).
595 This behavior cannot be described by the Richards equation since it predicts constant matric
596 potential and water content throughout the column once steady-state conditions are reached. On
597 the other hand, the Dual-NE model can describe both overshoot (b) and undershoot (c) in
598 pressure head.

https://doi.org/10.5194/egusphere-2026-1738
Preprint. Discussion started: 13 April 2026

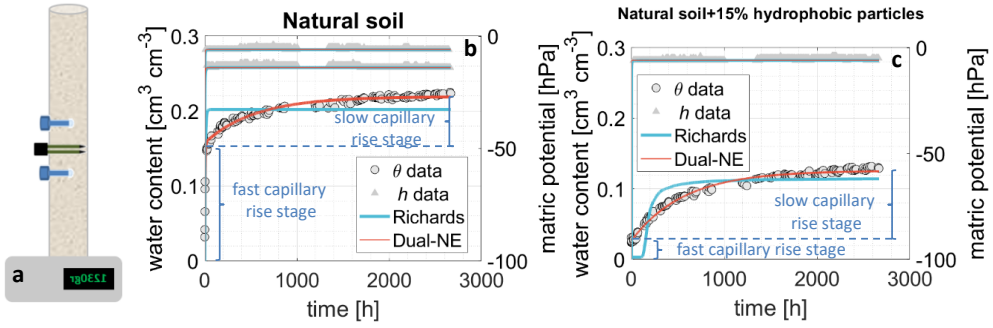
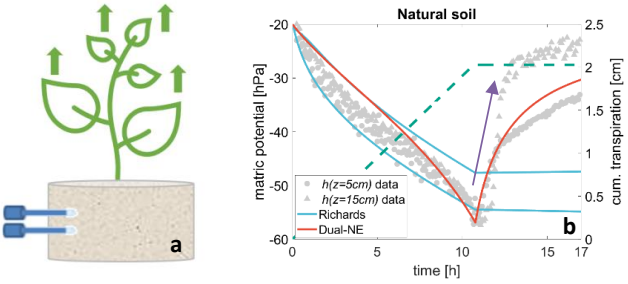


Figure 4. Schematic diagram of the experimental setup for capillary rise experiments (a). An initially dry soil is brought into contact with water, and the water in the column rises against gravity. The soil column is equipped with two tensiometers and one TDR installed between the two tensiometers (a). The data show that the two tensiometers equilibrate very quickly with the water level. However, the water content measured by the TDR keeps increasing, and the soil continues to absorb water for more than 2500 hours or more than 105 days (b). This effect is more pronounced for a mixture of a natural soil with 15% hydrophobic particles, where only one tensiometer is used (c). Richards' equation describes the fast equilibration of the matric potential data but fails to describe the two-stage equilibration of the water content. This is because, once equilibrium in matric potential is reached, Richards' equation predicts equilibrium in water content as well (blue line b, c). In contrast, the Dual-NE model predicts both the matric potential data and the two-stage water content data well (b, c).

https://doi.org/10.5194/egusphere-2026-1738
Preprint. Discussion started: 13 April 2026



613

614 **Figure 5.** Schematic diagram of the experimental setup for the transpiration experiment (a).
615 Initially, a soil column with high water content and two installed tensiometers is allowed to
616 transpire. When the transpiration flux is stopped, both tensiometers show a relaxation towards
617 higher pressure head (purple arrow in b). This cannot be adequately described by Richards'
618 equation (blue lines in b). In contrast, the Dual-NE model can qualitatively describe the relaxation
619 in matric potential (red line in b).

620

https://doi.org/10.5194/egusphere-2026-1738
Preprint. Discussion started: 13 April 2026

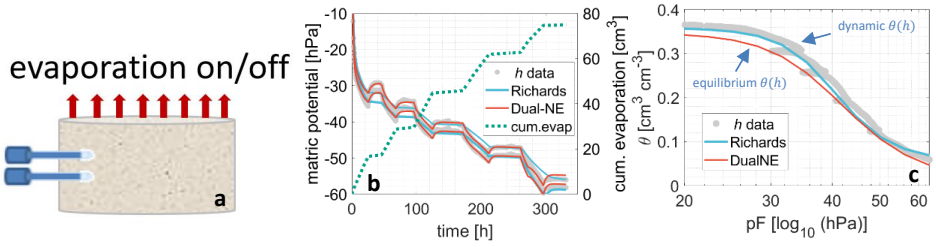


Figure 6. Schematic diagram of the experimental setup for the evaporation experiment (a). An initially wet soil column, equipped with two tensiometers, evaporates across the top boundary. The evaporation is stopped repeatedly by covering the soil surface. The recorded data from all the tensiometers show a relaxation towards higher pressure heads, which cannot be described by the Richards equation (b). By plotting the data as a water retention curve, it becomes evident that the retention curve measured under dynamic conditions is shifted to the left during the flow interruptions, towards the equilibrium retention curve (c). The Dual-NE model can effectively describe the dynamics of the matric potential and most importantly, it can do so with the equilibrium water retention curve.

https://doi.org/10.5194/egusphere-2026-1738
Preprint. Discussion started: 13 April 2026

634 **Table 1.** Overview of the experimental setups for all the experiments, including the type of
635 boundary condition used. More detailed information on the experimental design can be obtained
636 from the cited references.
637

Name	Boundary condition	Type	Reference
multistep outflow/inflow	pressure head (stepwise)	wetting/drying	Diamantopoulos et al (2013)
continuous outflow	pressure head (smooth)	drying	Schultze et al (1999)
multistep Flux	flux	wetting/drying	Weller et al (2011)
capillary rise	pressure head	wetting	Reszkowska et al (2014)
transpiration	flux (sink)	drying	Unpublished data (Diamantopoulos, University of Bayreuth)
evaporation	flux	drying	Diamantopoulos and Durner (2012)

638