Capillarity

Vol. 19, No. 1, p. 26-38, 2026

Invited review

Advances in dynamic soil water retention behaviour and implications for vadose zone hydrology

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Keywords:
Vadose zone hydrology
soil water retention
transient flow
dynamic nonequilibrium effects
capillary dynamics

Cited as:
Yan, G., Liu, B., Bore, T., Torres, S. A. G., Li, L., Scheuermann, A. Advances in dynamic soil water retention behaviour and implications for vadose zone hydrology. Capillarity, 2026, 19(1): 26-38. https://doi.org/10.46690/capi.2026.04.03

Abstract:
In transient multiphase seepage, soil water retention behaviour deviates from equilibrium, leading to dynamic nonequilibrium effects in which suction and water content change asynchronously. This yields flow-rate-dependent soil water retention curves that critically affect predictions of fluid and solute transport in vadose zone and undermine the safety assessment of unsaturated soil slope stability. This brief review synthesises advances and challenges in understanding this behaviour through examining microscale multiphase physical mechanisms and macroscale influences of soil type and hydraulic history. Key experimental techniques, from instrumented soil columns to advanced electromagnetic and imaging methods, are evaluated alongside their limitations. There is also an analysis of continuum- and pore-scale numerical models, including those incorporating dynamic capillary coefficients, pore network models, and multiphase computational fluid dynamics. Despite progress, major challenges persist, including the empirical nature and scale-dependence of model parameters, path-dependent hysteresis, and the lack of a unified theoretical framework that couples dynamic capillarity with soil deformation. Future inter-disciplinary efforts integrating advanced experimentation, multiscale numerical modelling, and multiphase physics-based constitutive theories are essential to develop predictive tools for more accurate vadose-zone hydrology and related engineering applications.

1. Background and significances

Under transient hydraulic conditions, soil water retention behaviour has been playing a central role in vadose zone hydrology, governing infiltration, soil moisture redistribution, evaporation, and plant water uptake. The conventional soil water retention curve (SWRC), typically derived under static and equilibrium conditions (see the black curves in Fig. 1), assumes a unique relationship between water content and matric suction (Bear, 1972; Fredlund and Rahardjo, 1993; Lu and Likos, 2004). This assumption underpins most continuum-scale flow models, including Richards' equation and its variants (Richards, 1931), and has been widely adopted in hydrological, geotechnical, and petroleum engineering applications.

However, a growing body of experimental and theoretical evidence indicates that this equilibrium assumption is frequently violated under highly transient hydraulic conditions, in which water content and suction evolve asynchronously in

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Yandy Scientific Press

2709-2119

Received February 16, 2026; revised March 10, 2026; accepted March 25, 2026; available online March 28 2026.

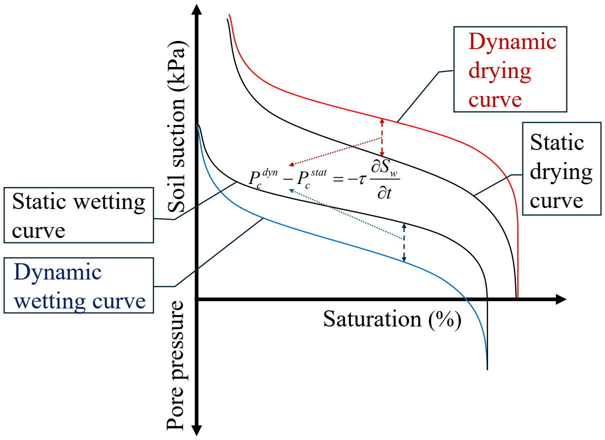

Fig. 1. Schematic of dynamic SWRCs departing from static curves on both drying and wetting paths, noting that air phase trapping matters with the hysteresis curves enclosed by both drying and wetting static curves, and the differences between dynamic and static soil suctions ($P_c^{dyn} - P_c^{stat}$) are quantified with a first-order relaxation term consisting of dynamic capillary coefficient (τ) and varying saturation against time ($\partial S_w/\partial t$).

response to rapid hydraulic loading (Topp et al., 1967; Schultze et al., 1997). This phenomenon was terminologically defined as dynamic effects or dynamic nonequilibrium effects in soil water retention behaviour (Hassanizadeh et al., 2002; Durner et al., 2014). In such cases, the detected instantaneous SWRC becomes flow rate-dependent, leading to discrepancies between the measured and predicted soil suction at each moisture content (see the coloured curves in Fig. 1), further influencing unsaturated soil hydraulic conductivity, the corresponding effective stress, and shear strength (Yan et al., 2022d).

Dynamic soil water retention behaviour is particularly relevant for natural and engineered systems subjected to rainfall pulses, evaporation cycles, irrigation, and rapid drainage or imbibition, such as slopes (Zhan and Ng, 2004; Bordoni et al., 2017; Das et al., 2022), embankments and dams (Scheuermann et al., 2014), as well as vadose-zone aquifers (Šimůnek et al., 2003). In these contexts, neglecting dynamic nonequilibrium effects may result in systematic underestimation or overestimation of transient responses of suction and moisture redistribution, ultimately impairing predictions of slope stability, ground settlement, and fluid and solute transport in vadose-zone aquifers.

With an aim to orient the future pursuit of this academic challenge, this review provides a concise yet comprehensive synthesis of current advances in dynamic soil water retention behaviour under transient hydraulic conditions, with particular emphasis on the underlying multiphase physical mechanisms, experimental characterisation techniques, and multiscale numerical modelling approaches. By critically examining both microscale processes and macroscale manifestations, this paper seeks to identify key challenges and knowledge gaps that hinder the development of predictive, physically based frameworks for vadose zone hydrology. The remainder of this review is structured as follows: Section 2 outlines the key aspects and fundamental challenges associated with dynamic nonequilibrium effects; Section 3 summarises recent advances in experimental investigations; Section 4 reviews progress in numerical modelling across multiple scales; and Section 5 discusses the broader implications and future research directions.

2. Key aspects and challenges

The investigation of dynamic nonequilibrium effects in SWRC mainly focuses on the following key aspects:

1) The microscale dynamic capillarity often neglected in the conventional theories;
2) The macroscale coupling effects of both porescale dynamic capillarity and local heterogeneities (i.e., multiple ink-bottle effects in pore networks generated due to various soil types, textures, and hydraulic history);
3) Theoretical, experimental, and modelling developments on this theme.

2.1 Microscale multiphase physical mechanisms

Research on dynamic soil water retention behaviour has identified several potential multiphase physical mechanisms underlying dynamic nonequilibrium effects. These include viscous resistance to rapid fluid redistribution, dynamic contact angle effects at the fluid-fluid-solid interface, air entrapment and compression, and pore-scale interfacial dynamics associated with snap-off and coalescence (Fig. 2) (Hoffman, 1983; Mumford and O'Carroll, 2011; Bianchi Janetti and Janssen, 2022). These mechanisms operate at different spatial and temporal scales, complicating the interpretation of macroscopic observations. Pore-scale investigations using micromodels, pore network models (PNM), and lattice Boltzmann methods (LBMs) have shown that dynamic nonequilibrium effects can arise even in geometrically simple pore structures at sufficiently high flow rates (Joekar Niasar et al., 2010; Joekar-Niasar and Hassanizadeh, 2012b; Karadimitriou et al., 2014). However, translating these microscale insights into continuum-scale constitutive relationships remains nontrivial (Guo et al., 2022).

2.2 Macroscale soil type, structure, and hydraulic history

The magnitude and manifestation of dynamic nonequilibrium effects are strongly influenced by soil type, particle and pore size distributions, fabric, and wetting-drying history. Ultra-low-permeable porous media often exhibit more pronounced dynamic behaviour than high-permeable porous media due to higher capillary forces and lower intrinsic permeability (Li et al., 2020), according to the first-established macroscale dynamic capillary coefficient model developed by Stauffer (1978) and many other modern models reviewed by Cai et al. (2022) and Chen et al. (2022).

Nevertheless, experimental results across the literature remain inconsistent (Hassanizadeh et al., 2002; Diamantopoulos and Durner, 2012a), even for sandy soils, reflecting differences in specimen preparation, boundary conditions, and measurement techniques. Yan et al. (2024) demonstrated that an in-

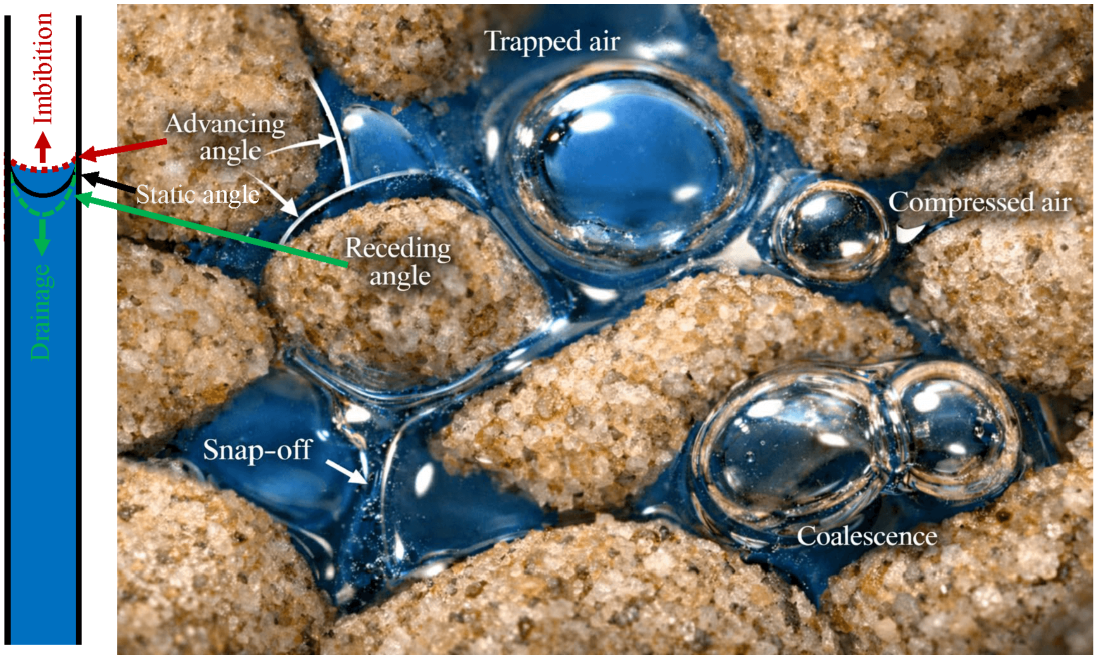

Fig. 2. A snapshot of multiphase physical mechanisms underlying dynamic nonequilibrium effects at porescale, including air entrapment and compression, dynamic contact angles in a snapshot with a two dimensional (2D) schematic, a snap-off and coalescence.

terplay between soil intrinsic properties and hydraulic loading conditions concurrently exerts a first-order control on transient water retention behaviour, with significant implications for interpreting laboratory measurements and upscaling results to field conditions. These findings underscore the need to consider soil fabrication and hydraulic loading history when studying dynamic soil water retention behaviour.

2.3 Experimental, modelling, and theoretical challenges

Reliable quantification of dynamic soil water retention behaviour requires accurate, high-resolution, and minimally invasive measurements of both water content and suction under transient conditions. However, sensor response time (Klute and Gardner, 1962), spatial averaging (Bottero et al., 2011a; Hou et al., 2014), and soil-sensor interaction effects (Guo et al., 2026) can significantly bias measurements, particularly during rapid wetting and drying events (Scheuermann et al., 2014; Yan et al., 2022a). These experimental limitations directly propagate into theoretical interpretation and model calibration.

From a modelling perspective, incorporating dynamic effects introduces additional parameters and governing equations, raising issues of parameter identifiability, numerical stability, and computational cost (Yan et al., 2022d). Establishing physically meaningful links between experimentally measurable soil properties and model parameters remains a central challenge.

Beyond experimental and numerical issues, several fundamental theoretical challenges remain unresolved. A primary difficulty lies in formulating a physically consistent constitutive relationship for dynamic nonequilibrium soil suction. Most existing theories extend equilibrium SWRCs by introducing a first-order relaxation term that links the dynamic nonequilibrium and equilibrium soil suctions through an empirical coefficient (Hassanizadeh and Gray, 1993b). While mathematically convenient, this formulation of dynamic capillary coefficient has the same dimension as fluid dynamic viscosity, which has been shown to vary with soil type and packing conditions (Chen et al., 2022; Sakhaei et al., 2022) as well as hydraulic loading history and boundary varying conditions (Zhuang et al., 2017b; Yan et al., 2022c).

Another theoretical challenge concerns the non-uniqueness and path dependence of dynamic soil water retention behaviour. Previous experimental and numerical explorations, including those reported by Scheuermann et al. (2014), Zhuang et al. (2017b) and Yan et al. (2022c), indicate that dynamic nonequilibrium effects differ markedly between wetting and drying processes and cannot be described by a single flow-rate-dependent SWRC. This observation contradicts the implicit assumption of reversibility embedded in many continuum-scale models and highlights the need for hydraulic loading path-dependent or hysteresis-aware dynamic formulations.

Furthermore, most existing theoretical frameworks implicitly assume rigid porous media and neglect hydro-mechanical coupling. In deformable soils, transient changes in suction may induce volume changes, fabric evolution, and alterations in permeability, which, in turn, affect soil water retention behaviour (Yan et al., 2022d). Except for a single attempt by Zou et al. (2022), who explored hydro-mechanical coupling in consideration of dynamic nonequilibrium effects, the lack of a unified theoretical framework that consistently couples dynamic capillarity with soil deformation remains a major limitation, particularly for soil hydrology issues involving fine-

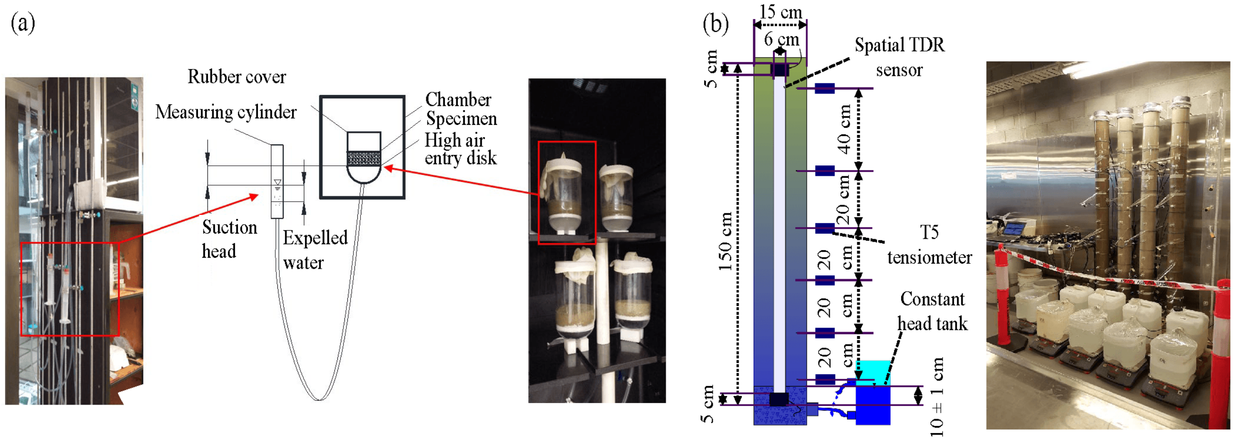

Fig. 3. Instances of the conventional and advanced experimental methods: (a) Bucher funnel method, and (b) 1D full-scale soil column tests integrating spatial TDR technique, multiple high precision tensiometers, and in/outflow logging, respectively, monitoring full soil moisture and suction profiles as well as water storage.

grained or structured soils.

Finally, there is no consensus on the appropriate multiphase hydrodynamic formulation for dynamic nonequilibrium unsaturated flow under highly transient flow conditions. Although thermodynamically consistent theories have been proposed (Hassanizadeh and Gray, 1993a, 1993b), their practical implementation often requires simplifying assumptions that obscure physical interpretation and hinder parameter identification. As highlighted in the studies of Zhuang et al. (2016, 2019), reconciling thermodynamic rigour with experimental observability remains an open theoretical challenge. To overcome this, an alternative solution, based on the earliest formulation of the single-phase transient seepage model proposed by Sposito (1980), rather than directly adopting the two-phase seepage model, is to formulate a multiphase physics-based theory.

3. Advances in experimental investigation

Experimental investigation has played a central role in advancing the understanding of soil water retention behaviour, particularly in revealing the limitations of equilibrium-based assumptions when soils are subjected to transient hydraulic conditions. Over the past two decades, experimental methodologies have evolved from classical static measurements toward integrated, high-resolution, and multi-physics monitoring systems capable of resolving dynamic water content-suction relationships across scales.

3.1 Conventional and advanced experimental methods

Traditional experimental investigations of SWRCs are largely based on equilibrium techniques, including the axis translation method, hanging column tests, and pressure plate extractors (ASTM D6836-02, 2003; ASTM D7664-10, 2010). These methods determine the relationship between soil matric suction and volumetric water content under steady-state or quasi-static conditions and have been widely adopted due to their conceptual simplicity, reproducibility, and standardisation (Fig. 3(a)). However, their reliance on instantaneous hydraulic equilibrium implicitly neglects flow rate-dependent effects, hysteresis evolution under nonequilibrium flow, and delayed pore-scale redistribution processes. As a result, such approaches are fundamentally inadequate for capturing transient soil-water interactions during infiltration, drainage, or rapid changes in boundary conditions.

To overcome these limitations, transient experimental setups based on instrumented soil columns have become increasingly prominent. These systems enable the imposition of controlled hydraulic boundary conditions while continuously monitoring the spatial and temporal evolution of water content and suction. Modern soil columns are typically equipped with distributed moisture sensors, such as time domain reflectometry (TDR) (Topp et al., 1980), frequency domain reflectometry (FDR) (Comandini et al., 2013), electrical resistivity and capacitance probes (e.g., EC-5) (Sakaki et al., 2010), together with suction sensors, including conventional tensiometers and high-capacity tensiometers (Scheuermann et al., 2005; Zhuang et al., 2017b).

Recent experimental research and developments reported by Yan et al. (2022d) demonstrate the increasing use of high-frequency electromagnetic techniques to resolve rapid hydraulic transients. Point-scale TDR (Topp et al., 1980; Luo et al., 2020; Das et al., 2022) provides local water content measurements with millisecond-level temporal resolution, while spatial TDR extends this capability by enabling quasi-continuous profiling of moisture along transmission lines embedded within soil columns (Scheuermann et al., 2009; Yan et al., 2024). When combined with tensiometers, these approaches enable simultaneous acquisition of transient water content and suction data, providing the experimental basis for identifying dynamic deviations from equilibrium SWRCs (Fig. 3(b)). More specifically, such integrated electromagnetic-hydraulic monitoring frameworks enable the observation of nonequilibrium phenomena, including delayed air-water interface movement, redistribution-induced suction overshoot, and flow rate-dependent retention behaviour. These experimental advances have significantly improved the capability to validate dynamic retention models and to link macroscopic observations with pore-scale processes inferred from theory and numerical simulations.

3.2 Advantages, limitations, and opportunities

Multiscale soil column experiments-ranging from representative elementary volume (REV)-scale setups to full-height laboratory columns-offer a powerful and flexible platform for investigating transient unsaturated flow. Their key strengths lie in the ability to impose well-defined boundary conditions, control initial states, and directly observe time-dependent hydraulic responses under repeatable conditions (Sakaki et al., 2010; Zhuang et al., 2017b; Yan et al., 2024). When densely instrumented, these systems provide detailed spatiotemporal datasets that are essential for identifying dynamic water retention effects and testing constitutive theories beyond equilibrium assumptions.

Despite these advantages, several limitations remain. Sensor installation can locally disturb soil fabric, alter pore connectivity, or introduce preferential flow paths, particularly in fine-grained or structured soils (Wagner et al., 2007; Yan et al., 2022a; Guo et al., 2026). Moreover, most sensors sample relatively small volumes, raising concerns about measurement representativeness and scale dependency, especially when extrapolating results to field conditions (Sakaki et al., 2007; Camps-Roach et al., 2010; Bottero et al., 2011b; Yan et al., 2022b).

Electromagnetic methods offer clear advantages in this context due to their non-destructive or minimally invasive nature and their ability to capture high-frequency dynamics. However, their application requires careful calibration and interpretation. Variations in pore water salinity, bulk density, and temperature can significantly influence dielectric responses (Robinson et al., 2003). In clay-rich soils, dielectric loss and interfacial polarisation effects further complicate signal interpretation, limiting the reliability of spatial TDR measurements (Scheuermann et al., 2009). These issues are emphasised by Yan et al. (2024) as key challenges that must be addressed before broader field-scale implementation.

Tensiometers provide direct measurements of matric suction and remain indispensable for experimental SWRC studies. Nevertheless, their operational range is constrained by cavitation, and their response time may be insufficient under rapidly changing hydraulic conditions (Klute and Gardner, 1962). These limitations highlight the need for complementary measurement techniques that capture both fast transients and extended suction ranges (Guo et al., 2023; Patwa and Bharat, 2023).

Beyond point-and-column-scale measurements, imaging techniques such as X-ray computed tomography (CT) (Wildenschild and Sheppard, 2013) and optical micromodels (Pyrak-Nolte et al., 2008; Karadimitriou et al., 2014) provide invaluable pore-scale insights into fluid-fluid interfaces, preferential flow paths, and interfacial dynamics (Fig. 4(a)). However, their applicability to natural soils is restricted by high costs, limited sample sizes, and challenges in achieving representative pore structures.

To break through these persistent experimental barriers, a full electromagnetic frequency approach, namely broadband dielectric spectroscopy (BDS) (Bore et al., 2022), is under development by the group of authors in the current literature review. This framework integrates high-frequency dielectric spectroscopy (often referred to as FDR) (Bore et al., 2024) with low-frequency spectral induced polarisation (Bore et al., 2026), thereby spanning multiple orders of magnitude in the frequency domain (Fig. 4(b)). Such integration enables the simultaneous monitoring of soil moisture, suction-related responses, and interfacial polarisation processes under transient flow conditions.

With continued research and development (R&D), BDS offers a promising pathway toward continuously tracking the dynamics of the air-water interface and other immiscible fluid boundaries (e.g., fluid-solid), effectively bridging the gap between macroscopic hydraulic observations and pore-scale interfacial physics. This approach holds significant potential not only for laboratory investigations but also for future field-scale applications in vadose zone hydrology, where dynamic nonequilibrium effects are ubiquitous and remain poorly constrained.

4. Advances in numerical investigation

4.1 Continuum-scale numerical models

Continuum-scale models form the theoretical backbone for engineering analysis of unsaturated flow and remain the most widely used framework for incorporating dynamic soil water retention behaviour into numerical simulations. Classical continuum descriptions are based on Richards' equation, which combines two-phase Darcy's law into the continuity equation for mass conservation (Fig. 5(a)). Since the 1960s, many studies have shown that Richards' model fails due to the non-uniqueness of unsaturated soil hydraulic properties (SWRC, relative permeability, and diffusivity) during fast drying and wetting processes (Rawlins and Gardner, 1963; Liakopoulos, 1964).

Hence, this failure motivated the development of several advanced theories that have been established to model dynamic nonequilibrium unsaturated flow at continuum scale, including the theories of soil moisture redistribution (Ross and Smettem, 2000) (Fig. 5(b)), dual-fraction with soil moisture redistribution (Diamantopoulos et al., 2012b), dual-porosity (Philip, 1968), dual-porosity and dual-permeability (Gerke and van Genuchten, 1993), and a comprehensive framework based on thermodynamics of capillarity (Hassanizadeh and Gray, 1993b), with an appended simplified version, a relaxation of dynamic nonequilibrium soil suction (Hassanizadeh et al., 2002) (Fig. 5(b)). A summary and detailed review of all theories, as well as the progress of theoretical validations, can be found in Yan et al. (2022d), which provides much more detail, as a full collection of them is beyond the current scope of this brief review.

The most widely used is the simplified theory based on thermodynamics of capillarity (Fig. 5(b)), in which, at the continuum scale, dynamic soil water retention is commonly represented by augmenting equilibrium SWRCs with

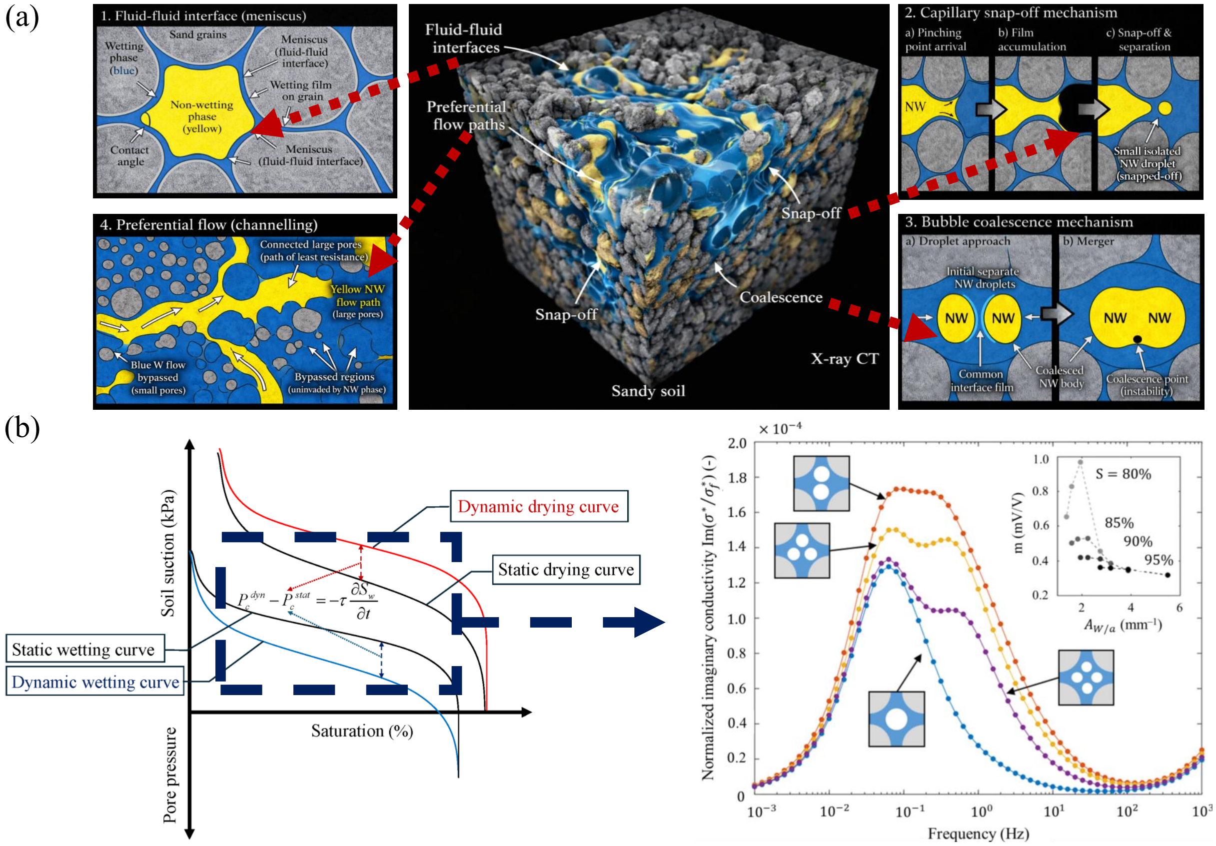

Fig. 4. Advanced experimental methods to detect interfacial dynamics: (a) A snapshot of microscale multiphase physical mechanism underlying dynamic nonequilibrium effects illustrated with a series of 2D schematics of porescale multiphase phenomena, such as fluid-fluid interfaces, snap-off, coalescence, and preferential flow paths, and (b) a simplified demonstration of modelled low-frequency (mHz-kHz) polarisation response of an unsaturated soil based on a preliminary study by the group of authors in the current literature review. The graph presents imaginary conductivity spectra for a water saturation of 80% with varying specific air-water interfacial area (Aw/a). The sketches (grey-mineral particles, blue-water, white-air bubbles) illustrate the respective bubble configurations. The grey curve represents the response without trapped air bubbles, capturing the polarisation processes at water-solid interface. Any changes in the response are attributed to increases in air-water interfacial area, i.e., different bubble configurations. For saturated systems with a continuous air phase, the response from water-solid interface is reduced when air-solid interface is extended.

flow-rate-dependent relaxation terms (Diamantopoulos and Durner, 2012a). This is because this simple theory not only can reconstruct the soil moisture dynamics through a redistributing process but also recover the dynamic capillarity in pore matrices of unsaturated soil (Fig. 5(b)). This is a very critical part that is missing in the aforementioned soil moisture-redistributing theories, which exclusively reconstruct the redistribution process by adopting concepts of dual fractions or dual-hydraulic properties (i.e., two porosities and permeabilities to deal with interaggregate and intraaggregated pore matrices, respectively, in unsaturated soil having preferential flow paths) without any consideration of dynamic nonequilibrium soil suction under highly transient flow conditions (Yan et al., 2022d). In physio-mathematics, the formulation introduces a first-order relaxation term linking the dynamic nonequilibrium and equilibrium soil suctions, characterised through a dynamic capillary coefficient coupled with a soil moisture redistribution process. This approach has been incorporated into Richards' equation (Fig. 5(b)) and related two-phase flow models (Hassanizadeh et al., 2002).

Such models are attractive for their compatibility with existing numerical frameworks and their moderate computational demands (i.e., they are easy to integrate into commercial packages, e.g., Richards and two-phase Darcy modules in COMSOL). Numerical studies showed that incorporating dynamic capillary terms significantly improves agreement between measured and simulated transient responses of dynamic nonequilibrium soil suction in column tests (Sander et al., 2008; Das and Mirzaei, 2012; Zhuang et al., 2017b; Zou et al., 2022).

4.2 Pore-to-REV-scale numerical models

Porescale numerical methods provide a physically based framework for investigating transient multiphase flow processes that equilibrium constitutive relationships cannot adequately describe. Multiphase computational fluid dynamics

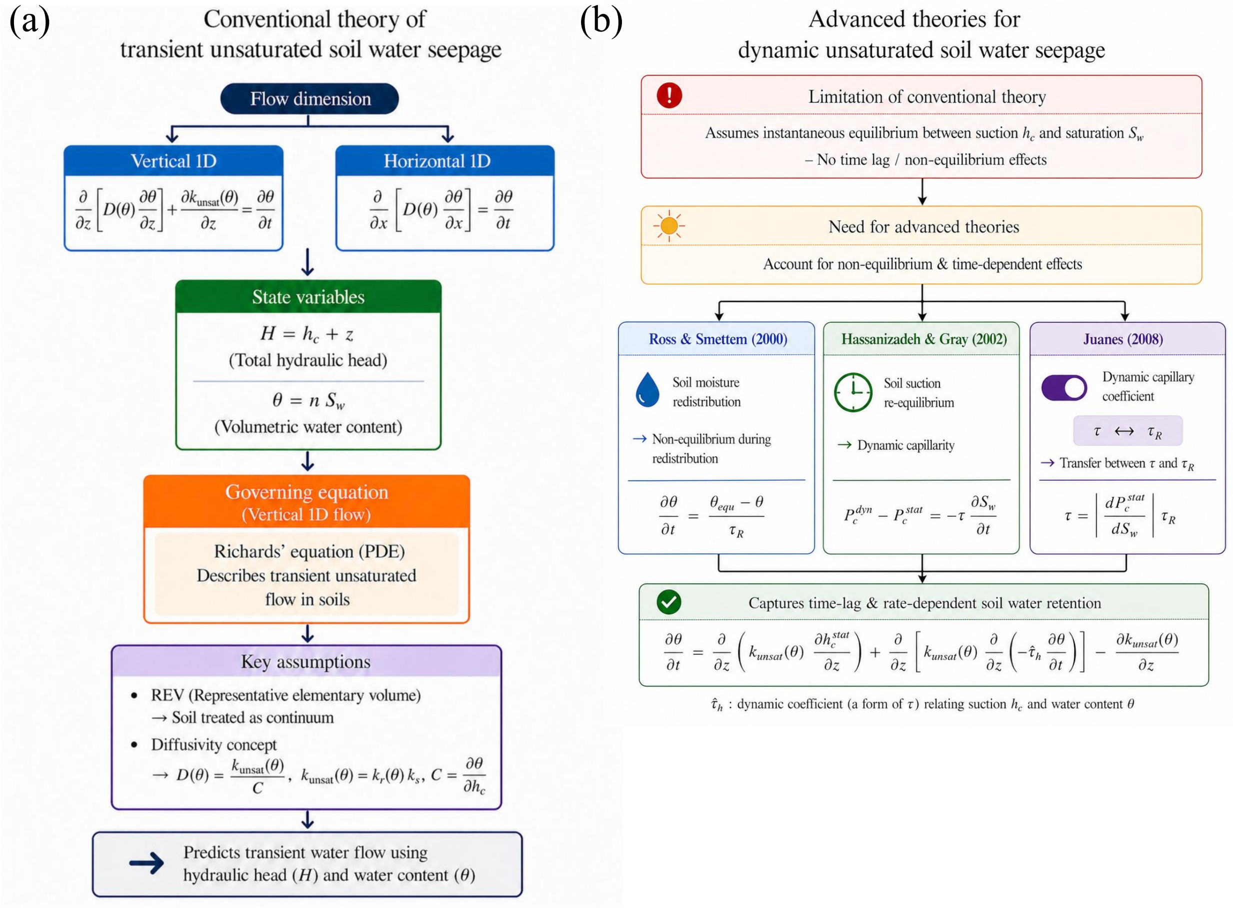

Fig. 5. The conventional and advanced theories for modelling transient two-phase flow in unsaturated soil: (a) the derived Richards' partial differential equation (PDE) in 1D where H = total water head, h_c = soil suction in hydraulic head, z = elevation head, g = gravitational acceleration, θ = soil volumetric water content, n = porosity, S_w = saturation, t = time, k_s = saturated soil hydraulic conductivity, $k_r = k_{unsat}/k_s$ = relative hydraulic conductivity, k_{unsat} = unsaturated soil hydraulic conductivity, C = unsaturated soil hydraulic storativity, and D = unsaturated soil hydraulic diffusivity; (b) two simplified advanced theories: the soil moisture redistribution and nonequilibrium soil suction re-equilibrium, followed by the transferring between τ_R = soil moisture redistributing time and τ = dynamic capillary coefficient; additional note that θ_{equ} = equilibrium soil volumetric moisture content, Δt = single time step, $P_c^{dyn} - P_c^{stat}$ = difference between dynamic and static soil suctions in pressure instead of hydraulic head, $\partial S_w/\partial t$ = temporal derivative of soil water saturation, all of which can be integrated into Richards' PDE as an 1D example herein.

(CFD) methods, such as multiphase LBM (Yan et al., 2022c), direct numerical simulation (DNS) coupled with volume of fluid (Ferrari and Lunati, 2013) or Level-Set (Helland et al., 2017), smooth particle hydrodynamics (SPH) coupled with continuum surface force (Sivanesapillai et al., 2016), and two-phase PNM (Joekar Niasar et al., 2010), explicitly represent porescale structures and fluid configurations, offering mechanistic insight into dynamic capillarity, interface motion, and phase redistribution.

DNS and LBM resolve the governing fluid dynamics at porescale by directly solving the Navier-Stokes equations or discretised Boltzmann equations within realistic or synthetic pore geometries (see a case of multiphase CFD in Fig. 6(a)). As a result, these approaches naturally capture fundamental displacement mechanisms, such as Haines jumps (Haines, 1930), snap-off events, and cooperative pore filling (Hoffman, 1975; Hoffman, 1983), which arise from rapid interface rearrangement and local force imbalance during transient flow. By explicitly tracking fluid-fluid interfaces and local pressure fields, DNS and LBM have demonstrated that capillary pressure is not uniquely related to saturation but also depends on interface dynamics, viscous dissipation, and flow history (Ferrari and Lunati, 2014; Ferrari et al., 2015; Li et al., 2018; Yan et al., 2021). In addition to both methods, SPH, as a fully Lagrangian particle-based method, is also well-suited for tracking large interface deformations and complex free-surface evolution without mesh reconstruction, making it attractive for simulating transient drainage and imbibition processes involving significant dynamic nonequilibrium effects. In specific, SPH directly resolve fluid motion and interface evolution at porescale, allowing the aforementioned basic displacement mechanisms to emerge naturally from local force imbalance and interfacial dynamics (Sivanesapillai et al., 2016; Sivanesapillai and Steeb, 2018). Similar to DNS

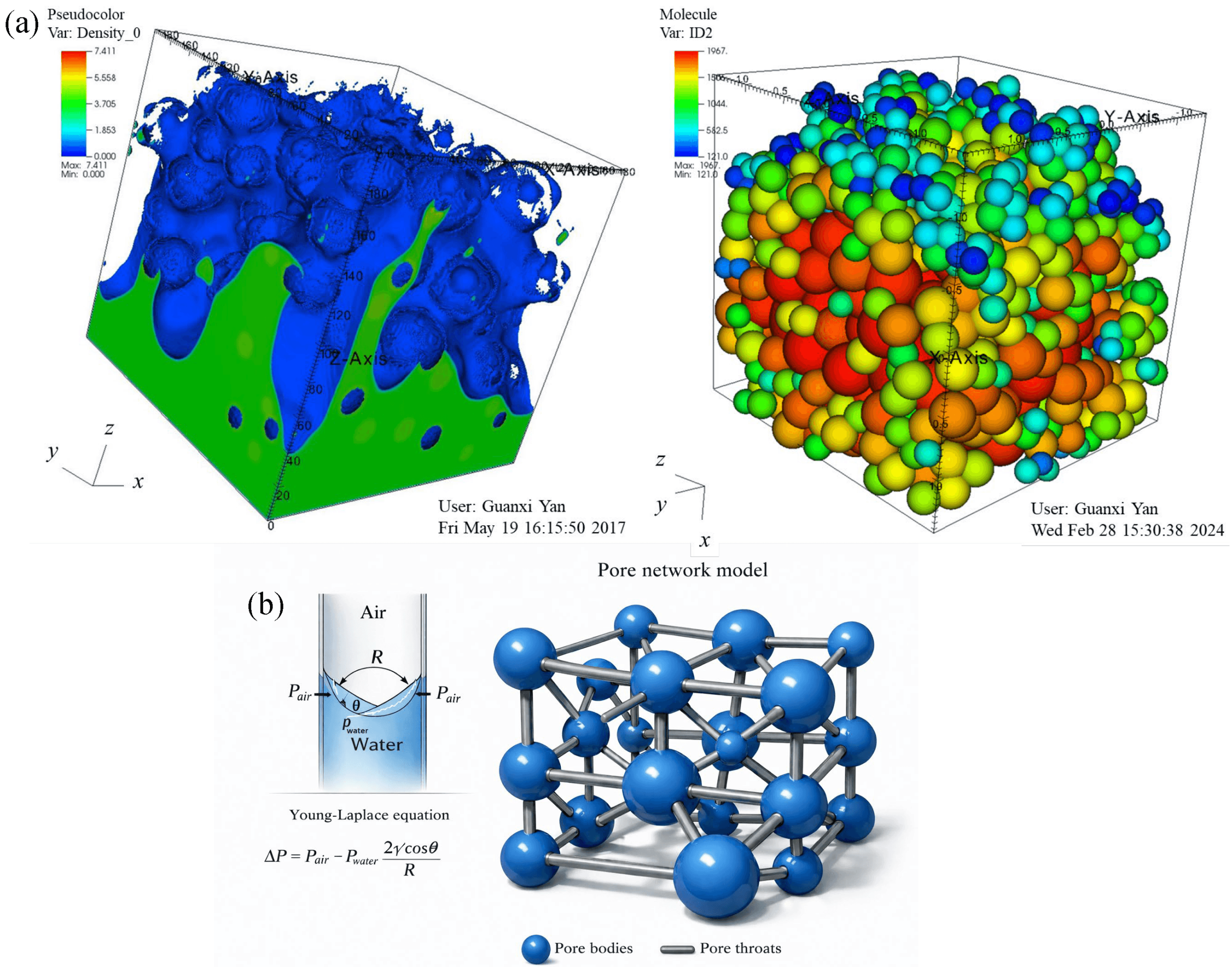

Fig. 6. Multiphase CFD and PNM demonstrations: (a) A 3D animation of two-phase displacement in a REV-scale package of colour-shaped grannular particles using multiphase LBM method; the pore matrices filled with blue colour indicate moisture-saturated space, while the void pores indicate air-filled space; the grain size distribution can be pre-set within a discrete elementary method model, followed by a true triaxial test (TTT) to achieve the targeted packing condition and (b) a showcase of PNM numerically modelling two-phase seepage based on the static Young-Laplace equation.

and LBM, SPH has demonstrated its ability to capture flow-rate-dependent capillary behaviour and interfacial dynamics. These methods therefore provide high-fidelity descriptions of dynamic capillarity and serve as powerful tools for interrogating the physical origins of dynamic nonequilibrium behaviour observed in transient two-phase seepage experiments.

However, the high computational cost associated with DNS, LBM, and SPH restricts their application to relatively small domains, typically at or below the scale of a single REV (Yan et al., 2022d). This limitation makes systematic parametric studies and direct upscaling to continuum-scale models computationally prohibitive, particularly for 3D, heterogeneous soil systems. In contrast to them, PNM offer a computationally efficient means of extending porescale insights to REV-scale. By idealising a pore matrix as a network of pores and throats governed by Hagen-Poiseuille law (i.e., laminar flow in pipes and capillary tubes) and static capillarity (i.e., Young-Laplace equation) (Fig. 6(b)), PNM significantly reduces computational effort while retaining key geometrical and topological features of the pore structure (Joekar-Niasar and Hassanizadeh, 2012a). Although individual interface dynamics are not explicitly resolved, PNM can incorporate effective representations of dynamic capillary pressure through flow-rate-dependent constitutive relationships and porescale averaging (Joekar Niasar et al., 2010). This makes them particularly attractive for investigating dynamic capillarity at larger spatial scales, where increasing computational efficiency and reducing numerical cost are critical.

Consequently, PNM are well-suited for exploring the influence of porescale heterogeneity (i.e., ink-bottle between pore bodies and throats in Fig. 6(b)), flow rate, and boundary conditions on REV-scale dynamic behaviour, while LBM, DNS, and SPH, which have been well validated by physical micromodels (Pyrak-Nolte et al., 2008; Karadimitriou et al., 2014), remain essential for resolving detailed interface physics and validating theoretical assumptions. Together, these numerical approaches form a complementary multiscale framework for linking porescale dynamics with continuum-scale descriptions of transient unsaturated flow.

4.3 Pros and cons of multiscale numerical models

On the one hand, continuum-scale models are suitable for engineering-scale applications but rely heavily on the experimental determination of relaxation coefficients, e.g., dynamic capillary coefficient or soil moisture redistribution characteristic time; both are physio-mathematically transferable according to Juanes (2008) to compute the first-order soil suction or saturation relaxation term (Fig. 5(b)). Nevertheless, there are a few cons in contrast to its pros. First, dynamic capillary coefficient is often treated as an empirical fitting parameter determined from transient flow tests, with limited understanding of its true physical meaning, since it has the same physical dimension as dynamic viscosity (Yan et al., 2022d). Second, this coefficient is highly dependent on soil type and fabrication (i.e., intrinsic seepage and water retention properties, e.g., porosity, hydraulic conductivity, fitting values within SWRC, soil wettability, soil water viscosity) (Stauffer, 1978; O'Carroll et al., 2010; Goel and O'Carroll, 2011), hydraulic loading history (e.g., drying, wetting, vertical, horizontal, and cyclic loading, i.e., hysteresis) (Zhuang et al., 2017a, 2017b), initial and boundary conditions (i.e., initial moisture and pressure/flow boundary variations) (O'Carroll et al., 2005; Sakaki et al., 2010; Yan et al., 2024), and temperature dependence (Hanspal and Das, 2012). Third, this coefficient is not unique across multiple scales (Abidoye and Das, 2014; Goel et al., 2016) due to micro- and macroscale local heterogeneities (Šimůnek et al., 2003; Mirzaei and Das, 2007). These, when combined, prevent the precise modelling of highly transient unsaturated soil flow in the vadose zone, underscoring the urgent need for research on this topic.

On the other hand, porescale numerical models provide complementary tools for investigating transient two-phase flow and dynamic capillarity at micro-to-REV scale. High-resolution methods (e.g., DNS, LBM, and SPH) resolve porescale fluid motion and interface evolution (Fig. 6(a)), naturally capturing Haines jumps, snap-off events, cooperative pore filling, and inertial effects (Ferrari and Lunati, 2014; Sivanesapillai and Steeb, 2018; Takeuchi et al., 2022; Yan et al., 2022c). DNS and LBM provide strong thermodynamic consistency, but are computationally the most demanding. Additionally, there are limitations in the two-fluid density and viscosity ratios (Yan et al., 2022c) and in the velocity ranges (Ferrari et al., 2015) for achieving clear interfacial separation between two immiscible fluid phases. SPH, as a mesh-free Lagrangian approach, is advantageous for simulating large interface deformations and highly transient processes, although numerical stability and limited benchmarking in porous media remain challenges (Sivanesapillai et al., 2016). In principle, these methods offer the highest level of physical realism and are therefore well-suited for interrogating the physical and thermodynamic origins of dynamic nonequilibrium capillary behaviour. Nonetheless, their substantial computational cost limits their use to relatively small domains, typically at or below a single REV, thereby constraining their use for macroscale parametric studies and direct upscaling of continuum-scale heterogeneities.

In contrast, PNM prioritise computational efficiency and scalability by idealising a pore space as a network governed by Poiseuille's laws. Through this simplification, the flow-rate-dependent SWRC can be successfully reconstructed using PNM solely due to the effects of microscale local heterogeneities (Joekar Niasar et al., 2009; Joekar Niasar et al., 2010), whereas the detailed interface dynamics are unavoidably neglected, given the fact that the static capillarity (i.e., Young-Laplace equation in Fig. 6(b)) has only been used to express the meniscus mathematically. This makes PNM particularly suitable for systematic investigations of heterogeneity and flow-rate-dependent effects on macroscopic dynamic nonequilibrium capillary behaviour, but it ignores contributions from interfacial dynamics at porescale.

Consequently, DNS, LBM, and SPH are most effective for resolving porescale multiphase physics and validating theoretical concepts at pore-to-REV scale, whereas PNM provides a practical and efficient pathway for extending porescale insights of local heterogeneities toward REV-scale behaviour and continuum-scale modelling.

5. Implications and prospects

The dynamic nonequilibrium effects in soil water retention behaviour represent a fundamental departure from conventional equilibrium-based theories, with significant implications for predicting soil moisture migration in vadose zone. As demonstrated throughout this brief review, neglecting these effects can lead to systematic biases in estimating dynamic nonequilibrium soil suction, moisture redistribution, solute transport, unsaturated soil effective stress, and shear strength-ranging from contaminant transport and aquifer recharge to slope stability and ground settlement.

From an engineering standpoint, the incorporation of dynamic capillarity into continuum-scale formulations provides a robust and pragmatic framework for improving the predictive capability of numerical simulations of rapid infiltration, drainage, and cyclic hydraulic loading processes. However, the empirical nature and scale-dependence of key parameters, such as the dynamic capillary coefficient, remain major obstacles to reliable field-scale application. Future research must focus on developing predictive relationships that link these parameters to measurable soil properties, fabric, and hydraulic history, thereby reducing reliance on site-specific calibration.

Experimentally, the integration of advanced sensing techniques-such as high-frequency electromagnetic methods, BDS, and imaging technologies-holds promise for capturing transient hydraulic states with minimal invasiveness and high resolution. These methods not only improve the characterisation of dynamic soil water retention but also offer potential insights into interfacial dynamics at porescale. Nevertheless, challenges related to sensor disturbance, spatial representativeness, and interpretation in heterogeneous or clay-rich soils must be addressed through improved sensor design, multi-sensor fusion, and robust data assimilation frameworks.

Numerically, the multiscale modelling paradigm-combining pore-scale methods (DNS, LBM, SPH) with PNM and continuum formulations-provides a powerful approach to bridge microscopic mechanisms with macroscopic behaviour. While pore-scale simulations reveal the multiphase physical origins of dynamic nonequilibrium effects, PNM and upscaling strategies enable efficient exploration of heterogeneity and flow-rate effects at the continuum scale. Future efforts should prioritise the development of hybrid models that systematically incorporate porescale insights into continuum descriptions, ensuring both physical fidelity and computational feasibility for engineering applications.

Theoretical advancements are urgently needed to address several lingering challenges: the formulation of a physically consistent, hydraulically path-dependent constitutive model for dynamic nonequilibrium suction; the integration of hydro-mechanical coupling in deformable unsaturated soils; and the establishment of a thermodynamically rigorous yet experimentally accessible multiphase flow framework. A shift toward physics-based, multiphase hydrodynamic theories-building on early transient seepage concepts but extending to dynamic, nonequilibrium, transient conditions-could provide a more unified foundation for future models.

In summary, the study of dynamic soil water retention is evolving from a specialised topic into an essential consideration for accurate vadose zone hydrology. Interdisciplinary collaboration across experimental, numerical, and theoretical domains will be key to transforming current empirical approaches into predictive, physically based tools. As climate change intensifies rainfall extremes and hydrological variability, improving our capacity to model transient unsaturated flow in vadose zone will be critical for resilience in infrastructure, water resources, and environmental management.

Acknowledgements

The author would like to acknowledge support from Geo-Group at School of Civil Engineering, the University of Queensland, Australia.

Conflicts of interest

The authors declare no competing interest.

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