Core Ideas

- Nonuniform flow has proven to be the rule rather than the exception in nearly all soils.
- Computational and technological advancements are promising for nonuniform flow.
- They allow improved visualization and characterization of structures across scales.
- We need to translate apparent complexity of geosystems into reproducible outcomes.
- Those outcomes must be of generalizable applicability in flow and transport research.

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Current Insights into Nonuniform Flow across Scales, Processes, and Applications

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This introduction to the special section Nonuniform Flow across Vadose Zone Scales is a brief summary of this special section's diverse contributions covering nonuniform flow across a wide range of scales, processes, and applications. We summarize the 17 articles constituting this special section and hope that those contributions are positive steps toward a new, generalizable, and comprehensive paradigm to modeling flow and transport in porous media.

There is something oddly uniform about nonuniform flow: its ubiquity in nearly every soil type and across all scales. Supported by a vast canon of observational studies conducted across a wide range of scales, the preferential distribution of water and solutes through various unsaturated soil profiles suggests that nonuniform movement represents the rule, rather than the exception, for flow and transport through porous media. Nonuniform, non-equilibrium, and preferential flow are among the most common ways to describe the types of flow that can derive from macropores, textural contrasts, dynamic pore structures, soil water repellency, and other soil heterogeneities. These flows have been observed in numerous settings, from tillage-induced porosity contrasts in loam soils to crack networks that form in clay-rich soils and to saturated (and saturation-overshoot) fingers that appear when sandy soils become rapidly wetted. However, this richness in observing nonuniform flow has not yet translated to a sufficient understanding of their associated causes and implications.

Identifying the features and processes of nonuniform flow has long beguiled both experimentalists and modelers, with classic equilibrium flow and transport models such as the Richardson–Richards and advection–dispersion equations proving insufficient to treat such problems. The literature is still divided on whether these flow problems can be treated mechanistically (thus remaining limited by our ability to provide adequate conceptualizations and theory), empirically (thus dependent on collecting sufficient data to identify and decipher emergent properties associated with nonuniform flow), or stochastically (thus driven by intrinsic complexity and heterogeneity). Many studies, particularly those based in classic soil physics, often focus on characterizing such heterogeneities in physical soil features using descriptions of parallel and distinct domains. These approaches can still retain information on soil-water characteristics curve (and thus capillary forces) and hydraulic conductivity relationships (e.g., through multimodal pore size distributions), thereby maintaining a logical linkage to the fundamental theories that form the basis of our current pedologic training. Other studies posit that nonuniform flow processes can only be explained using frameworks that go beyond classical theory; otherwise, the development of physically consistent models will always be constrained by the limitations in our knowledge and understanding of the genesis, evolution, and distribution of dominant soil properties and of the intrinsic structural complexity and heterogeneity of porous media, along with the experimental and computational barriers for visualization, characterization, and modeling of flow.

In recognition of this continued debate, and of the many knowledge gaps that have emerged along the way, this special section provides a collection of novel approaches to identify, quantify, and model nonuniform flow processes. These contributions represent a range of conceptualizations of flow processes and actualizations of important datasets. Here, we summarize the different articles that comprise the special section.

Nonuniform Flow across Vadose Zone Scales: The Special Section

This special section contains 17 outstanding contributions spanning scales, disciplines, and processes, thereby covering a gamut of experimental and modeling domains. Some contributions focus on characterization, while others present new experimental evidence and observations that improve the understanding of nonuniform flow and still others offer new modeling tools and insights for flow and transport across all scales.

As an invited contribution to this special section, Beven (2018) outlines the historic evolution of knowledge about preferential flows, focusing on the period between 1864 and 1984. Her summarizes a century-old general denial of theoretical and multiscale experimental evidence of preferential flow, even though the initial discovery and documentation of these processes predate the establishment of equilibrium concepts by Edgard Buckingham and Lorenzo Richards. Beven reviews the developments of preferential flow models and ends with a positive outlook highlighting current appreciation of the role of preferential and non-equilibrium flows in flow and transport across all scales. He advocates for an explicit incorporation of preferential and non-equilibrium processes in teaching soil physics and hydrology and points out the fact that the equilibrium Buckingham–Richards paradigm still represents a primary concept underlying the teaching of soil physics and hydrology. He instead urges a new paradigm for modeling soil water flows and transport.

Other contributions to the special section focus on the scale of single fractures. Here, fluid movement is often characterized by nonlinear flow and mass partitioning, leading to much uncertainty in the dynamics of fluid movement within unsaturated flow paths. Noffz et al. (2019) conducted a series of controlled laboratory experiments that isolated horizontal fracture-filling processes when water moved vertically across the fracture interface as drops and rivulets. The results showed that rivulets led to greater fracture wetting and that partitioning dynamics into the horizontal fracture can be described using a Washburn-type solution for capillary imbibition. Thus, the results suggest that analytical solutions may have practical application for describing fracture flow processes.

In another study, Shigorina et al. (2019) studied the influence of fracture roughness and fluid injection rates on flow patterns and infiltration dynamics. They showed that low infiltration rates exhibit flow instabilities, fingering, and intermittent flow regimes across a wide range of fracture roughness. They also showed that increased fracture roughness attenuates flow velocity and induces flow discontinuities and thus the formation of flow fingering, snapping rivulets, and preferential flow paths.

Nieber et al. (2019) developed a numerical approach based on the Reynolds-averaged Navier–Stokes equation, coupled with suspended sediment transport equations for the modeling of turbulent flow and internal erosion of a uniform diameter soil pipe. Their modeling results were consistent with experimental data, provided that the pipe wall roughness and soil erodibility were properly chosen. This study proves that macropore wall erosion due to flow can be modeled, thus allowing the capture of macropore size dynamics.

The studies of Noffz et al. (2019), Shigorina et al. (2019), and Nieber et al. (2019) push the boundaries of process understanding at the scale of individual fractures and fracture junctions. However, further advancements are needed to scale up such developments to the core, column, and pedon scales where heterogeneous and interconnected dynamic networks of cracks and macropores can dominate flow and transport behaviors. Several contributions focused on technological, computational, and theoretical advancements in pore network characterization. With three-dimensional imaging and advanced digital imagery analysis, Leue et al. (2019) developed a quantitative method that can distinguish between biopores and cracks in X-ray computed tomography images. This method allows pore structures to be abstracted into more functional domains, which can improve modeling of flow and transport in porous media. This approach also offers the potential to enhance understanding of sorption and mass exchange processes, particularly when the type, morphological properties, and coating of different pores and preferential flow pathways are important for understanding and characterizing dominant processes.

Batany et al. (2019) conducted a column study to isolate the effects of flow rate and viscosity on solute transport. In their experiments, the presence of an artificial macropore affected solute breakthrough curves under high flow rates, with the macropore acting similar to a pipe-like conduit. A decrease in flow rate and viscosity increased the rate of solute diffusion, boosting the mass transfer between the macropore and the surrounding matrix. However, the breakthrough curves deviated from expectation modeled using classic dual-porosity models, which failed to correctly simulate the specific shapes of the observed breakthrough curves (specifically they observed a main peak followed by a plateau). Thus, these experiments conducted illustrate the importance of macropore flow and exchange during solute transport while also revealing unexpected results that should form the basis of future investigations.

Preferential flow processes can lead to rapid leaching of different nutrients and contaminants away from the root zone and deeper into the groundwater. Glæsner et al. (2018) examined the ability of dairy manure slurry to leach via preferential flow after subsurface injection. They modeled leaching data from nine intact soil columns and compared steady-state with intermittent irrigation. The classic single-domain equilibrium model was used along with dual-porosity models that were hypothesized to better represent non-equilibrium transport processes. The results showed that by capturing mass exchange between pore regions, the multidomain models characterized the observed flow and transport dynamics, in particular, for columns with intermittent irrigation, which may better resemble field conditions than steady flow.

Bogner and Germann (2019) applied the viscous flow approach as a theoretical framework for the investigation of the

"Pushing Out Old Water" (POOW) phenomenon, in which water reaching streams during storms is derived from preexisting soil moisture storage. They validated the POOW concept using tracer injection in soil columns, demonstrating delay of the tracer in comparison to the wetting fronts along with a rapid exchange between the mobile water in the macropores and the immobile water remaining in the sessile parts of the matrix. This conclusion highlights yet another successful application of the viscous flow approach and opens doors for future research into tracer transport and POOW from the column to the catchment scale. The latter represents a scale where improved understanding of POOW processes is key for advancement at various theoretical fronts, particularly in differentiating mean water velocities from celerities.

Preferential flows not only are major contributors to the flow of fluids and transport of chemicals (nutrients or contaminants), they also can function as microbial hotspots. Franklin et al. (2019) monitored O_2 depletion by soil microbes as proxy for microbial activity in Hele–Shaw cells. The results provided visual evidence of microbial hotspots along and adjacent to preferential flow pathways. This contribution adds to the accumulating experimental evidence of the active and dynamic biophysical function of preferential flow pathways and reinforces their important role in biogeochemical cycling.

Moving from soil columns to the pedon and plot scales, shrinkage cracks that form in Vertisols and other soils with vertic properties often act as conduits for preferential flow to occur. Bagnall et al. (2019) assessed the impact of the initial hydration condition on infiltration and wetting front characteristics. Through a series of irrigation experiments, they showed that the wetting front moves faster and deeper under dry initial conditions, than in wet soils. Furthermore, soil water content is a primary explanatory variable for the formation and connectivity of shrinkage crack networks, making it critical to obtain accurate soil water content readings in these soils. Similarly, Bagnall et al. (2018) assessed the influence that (i) air- and water-filled cracks and (ii) uncertainty in bulk density sampling have on neutron moisture probe readings. Their results provide critical observational data on how cracks influence moisture readings from neutron probes depending on their size and state. Armed with this information, future research endeavors can better measure preferential flow processes using these types of sensors.

Filipović et al. (2019) compared two-dimensional single-domain vs. one-dimensional dual-domain representations of the heterogeneity of flow and mass transport due to tillage and compaction. They examined whether the heterogeneity in pore space resulting from nonuniform soil compaction could be accurately characterized using an effective one-dimensional, vertical dual-permeability model. Their results show that with proper parameterization, one-dimensional dual-domain representations provide relatively similar simulations of observed tracer movement to a two-dimensional single-porosity model.

The studies of Glæsner et al. (2018) and Filipović et al. (2019) reinforced the notion that improved parameterization of structural heterogeneities and advancing the abstractions of biophysical interactions in dual (or multiple) domain representations are areas of high potential impact to the modeling of nonuniform flow and transport. As such, characterization of structural and hydraulic properties of dual-permeability systems is crucial for the quantification of preferential flow in soils. Basset et al. (2019) proposed a low-cost experiment to isolate macropore flow from matrix flow through the injection of water and a non-Newtonian fluid in saturated infiltration experiments. Their model results demonstrated good agreement with the experimental data obtained from accurate scans of sands coupled with capillary tubes representing synthetic macropores. The use of non-Newtonian fluids offers a new, low-cost, and practical perspective for the characterization of multi-permeability systems.

Model development represents an important component of understanding non-equilibrium flow processes. In particular, advances in multi-domain models have facilitated conceptual separation between matrix and fast-flow domains of the soil profile, which can better recreate rainfall-runoff dynamics and infiltration processes within heterogeneous soils. This special section offers several advances on developing and utilizing multi-domain models for describing nonuniform flow and transport. To advance modeling efforts in dual-domain porous media, Stewart (2019) and Lassabatere et al. (2019) presented two models for advancing analytical methods in dual-domain modeling and the development of robust dual-domain infiltration models, respectively. Stewart (2019) designed an analytical model for water infiltration under constant rain intensity and a macropore domain conducting water at unit hydraulic gradient. This solution extends the Green–Ampt infiltration model to a dual-domain framework using macropore flow with negligible capillary potential, thus similar in form to kinematic wave approximation under saturated flow conditions. The proposed model performance was evaluated with numerical simulations using the Richards equation and with a sensitivity analysis of the different model parameters on bulk water infiltration.

Building on their model for dual-permeability soils (Lassabatere et al., 2014), Lassabatere et al. (2019) introduced a new infiltration method (BEST-2K) that extends the classic BEST infiltration method for the hydraulic characterization of dual-permeability soils. The method requires additional inputs from a supplementary infiltration experiment under unsaturated conditions (using a tension infiltrometer) to complement the classic ponded (Beerkan) infiltration experiment and the other traditional inputs. The BEST-2K method estimates the entire set of hydraulic parameters of hydraulic functions of the fast-flow and the matrix domains. The method was validated with synthetic and field data, thus presenting a new way to characterize dual-domain structured porous media.

Glaser et al. (2019) presented exciting new evidence that constrains the scale dependence of the dominant physical process at plot and catchment scales. They demonstrated that well-performing parameters at one scale are typically not equally successful in

improving hydrologic modeling at another scale. More specifically, they showed, through Monte Carlo simulations, that dual-permeability simulations of vertical preferential flows were successful in reproducing tracer concentrations in multi-depth irrigation experiments at the plot scale. However, these parameters did not translate to the catchment scale, where lateral subsurface flow (another nonuniform flow process) was more important to the reproduction of the hydrological response than the dual-permeability approach.

Finally, preferential flows that result from freeze–thaw dynamics are critically important to understanding the hydrology of frozen soils. Demand et al. (2019) highlighted the importance of advancing research on seasonally frozen soils where infiltration rates can be strongly reduced by thin layers at high saturations compared with unfrozen conditions. They demonstrated that reduced soil infiltrability caused by water frozen in the pore space depends on water content and salinity. Water infiltration was maintained by preferential flow through connected air-filled bio-macropores. These macropores allowed water to infiltrate through the frozen depths of the soil and reach deeper unfrozen horizons.

Altogether, these articles advance our collective understanding of nonuniform flow processes and represent a compelling compendium of the state of the science.

Acknowledgments

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