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Update

Core Ideas

- The soil profile is the critical scale for representation of soil hydrology also at larger scales.
- Natural soils do not follow well-defined hydraulic properties.
- Concepts are needed to model hydraulic nonequilibrium and hysteresis.
- Spatial patterns of functional soil types need to be identified.
- These can account for vertical stratification of hydraulic properties and structural attributes.

Scale Issues in Soil Hydrology

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Soil hydrology is a key control for the functioning of the terrestrial environment. Many environmental issues that we need to tackle today are directly linked to soil water dynamics. This includes agricultural production and food security, nutrient cycling and carbon storage, prevention of soil degradation and erosion, and last but not least, clean water resources and flood protection. However, these problems need to be addressed at the scales of fields, regions, and landscapes, while soil water dynamics and soil hydraulic properties are well understood and typically measured at much smaller scales—the comfort zone of soil physics. An obvious problem is how to link these vastly different scales and how to profit from small-scale understanding to improve our capability to predict what is going on at the large scale. In this update, this problem is discussed based on insights gained during the last decades. As a synthesis, a two-step scaling approach is proposed for modeling soil water dynamics from local to landscape scales where the scale of the soil profile is the stepping stone.

Abbreviations: PTF, pedotransfer function; REV, representative elementary volume.

After all, water flow in soil is governed by its porous structure. The most critical challenge of soil hydrology is given by the fact that this porous structure is heterogeneous at all spatial scales ranging from sub-micrometer spaces between individual soil particles to the distribution of a huge variety of soil types in landscapes whose porous structures depend on the parent material of soil formation and other local soil-forming factors including land use and agricultural soil management. While this structural heterogeneity is a fascinating feature of soil, it is at the same time a long-lasting pain in the neck for modeling soil water dynamics (Pachepsky and Hill, 2017). On the one hand, the problem increases with scale because of the increasing number of nested hierarchical heterogeneities. On the other hand, since most flow and transport processes forget about small-scale perturbation when going to larger scales (Vogel and Roth, 2003), the complexity of adequate process descriptions can typically be reduced. Hence, there is also the chance that it becomes even simpler and less complex when moving to larger scales. As an example, the heterogeneous velocity distributions and complicated flow fields at the pore scale translate to some simple dispersion coefficients at larger scales once the travel distance is long enough so that a complete mixing of solutes within the heterogeneous velocity field can be assumed (Butters and Jury, 1989; Roth, 1995). This is true for relatively simple porous media such as sand packings but is hardly achieved in natural soil. Yet, a pore-scale description is not advisable and would rather complicate matters. Anyway, beyond some cubic centimeters, it is simply not possible with current technologies to resolve soil structure at the pore scale where the physics of water dynamics is well understood. This is because the sheer volume of data cannot be handled and the required computing power is missing. Therefore, we need to cope with appropriate scale transitions in our model concepts, which is a formidable scientific challenge, and we need to turn on our brains instead of big computers, which is more exciting anyway. This is not limited to the transition from pore to continuum scale but goes on at larger scales where larger scale structures and heterogeneities appear.

The comfort zone of soil physics and soil hydrology is the scale of some 10 cm where well controlled experiments can be performed using undisturbed soil cores (Hopmans et al., 2002a). At this scale the concept of a "representative elementary volume" was introduced (REV) (Bear, 1972). It refers to the notion that the volume of the sample is large enough to contain all the pore-scale heterogeneities, and the measured properties are thus

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meaningful for characterizing the material. With respect to soil hydrology, these properties are the water retention characteristics and the unsaturated hydraulic conductivity function, which are considered to provide an integral description of the subscale pore structure as a simplified, emergent, or upscaled entity. However, given the heterogeneity of soil structure along a soil profile and the spatial correlation length of structural features such as elongated macropores, it is not obvious if something like a REV actually exists.

Regardless of this averaging problem, when going from single pores to porous media, it is undoubtedly a widely accepted and well established approach to switch from a molecular level at the pore scale to the so-called continuum scale where continuous variables such as water content and water potential are considered. For water flow, the physical consistence of the transition from the Navier–Stokes equation at the pore scale to Darcy and Richards equations at the larger scale has been demonstrated based on the assumption of hydraulic equilibrium with respect to the soil hydraulic functions (Roth, 2008).

During the last decades, substantial progress was made in measuring soil hydraulic functions at the core scale (Hopmans et al., 2002b; Weller et al., 2011), and there is a variety of pedotransfer functions (PTFs) to estimate the parameters of these functions based on more easily available soil properties such as soil texture, bulk density, and soil organic matter (Pachepsky and Park, 2015; Vereecken et al., 2010; Pachepsky et al., 2006). Yet, all these efforts are concentrated at the comfort scale where soil cores can be handled in the laboratory and where the proxy variables used in PTFs can be assumed to be well defined material properties directly accessible through measurements.

Besides improvements in the determination of soil hydraulic properties, tremendous progress was made especially in analyzing soil structure using X-ray tomography also at the very same scale of soil cores. With that, the observed phenomena such as preferential flow can now be better associated with features of the soil pore structure, which finally can be related to soil management or the activity of soil biota (Koestel and Larsbo, 2014; Naveed et al., 2013).

There is still room for intriguing developments at the comfort scale of soil cores, which probably is one reason why the vast majority of publications in the field of soil physics is concentrated at this scale. Another reason certainly is that the investigated soil volume can be considered to be "known" in terms of its intrinsic properties (i.e., particle size distribution, pore structure, surface chemistry, etc.) so that the results can be interpreted with respect to actual ongoing processes. Larger scale applications are partly left to other disciplines such as, e.g., hydrology and atmospheric sciences while soil physicists often complain about inadmissible simplifications—but how can we do better?

The motivation of this update is to pinpoint the critical obstacles when moving to larger scales. This starts with an analysis of the type of structures and heterogeneities across scales that are relevant for water dynamics. This is followed by an analysis of the hydraulic phenomena that are produced by these heterogeneities and if and how these phenomena can be represented at the next larger scale. Finally, this leads to a separation of characteristic scales and the identification of suitable scale thresholds (Pachepsky and Hill, 2017). Thereby, the scale of soil profiles (i.e., pedons) appears to play a key role and is analyzed in more detail. Finally, a two-step scaling approach is proposed to transfer our process understanding to the landscape scale, taking into account the most relevant structural features.

Spatial Heterogeneity in Terms of Structure

A journey through the entire range of scales in soil from a single pore to the globe is depicted in Fig. 1, showing the hypothetical outcome of some measured soil property when continuously increasing the scale represented by the sample volume (i.e., the support scale of the measurement). Starting at some point below the soil surface located either in the pore or solid phase, the increasing sample volume should stay within the soil so that it should not expand to the atmosphere above or the geological parent material underneath. The considered soil property can be any, such as porosity or hydraulic conductivity. Characteristic structures that are deemed to be relevant for water dynamics are illustrated by pictograms. They follow various hierarchical levels as typically distinguished in soil science (i.e., aggregates, soil horizons, pedons). Although the course of the measured values is merely hypothetical and could have an increasing or decreasing trend across scales, there is quite some evidence that the variance of the measurement is expected to increase at the transition between different hierarchical levels, while this variance is reduced for sample volumes that are well between the boundaries of such hierarchical levels if they exist.

Hierarchical levels in subsurface structures could be related to the notion of a REV according to Bear (1972); however, then such REVs are obviously not a global but rather a local phenomenon. The structure of soil rather follows the notion of a discrete or continuous hierarchy according to Cushman (1990), depending on the shape of the hierarchical plateaus. These various hierarchical levels have also been denoted as "holons" or "sub-wholes" (Wagenet, 1998). The presence of these hierarchical levels can be observed in many soils up to the scale of pedons. There are aggregates within a soil horizon having similar properties. Measurements taken within a soil horizon, the comfort zone of soil physical measurements, typically do not differ too much. At larger scales, similar soil types can be found at various locations in the landscape, which actually is a major fundament of pedology. However, such hierarchical levels are much less obvious beyond the scale of pedons when we are looking at the spatial distribution pattern of soils in the landscape. At this level, no local stationarity of subsurface properties can be found anymore. This also led to the notion of the uniqueness of place at the level of catchments (Beven, 2000).

Based on these considerations illustrated in Fig. 1, it appears that the transition from the pedon scale toward the landscape is

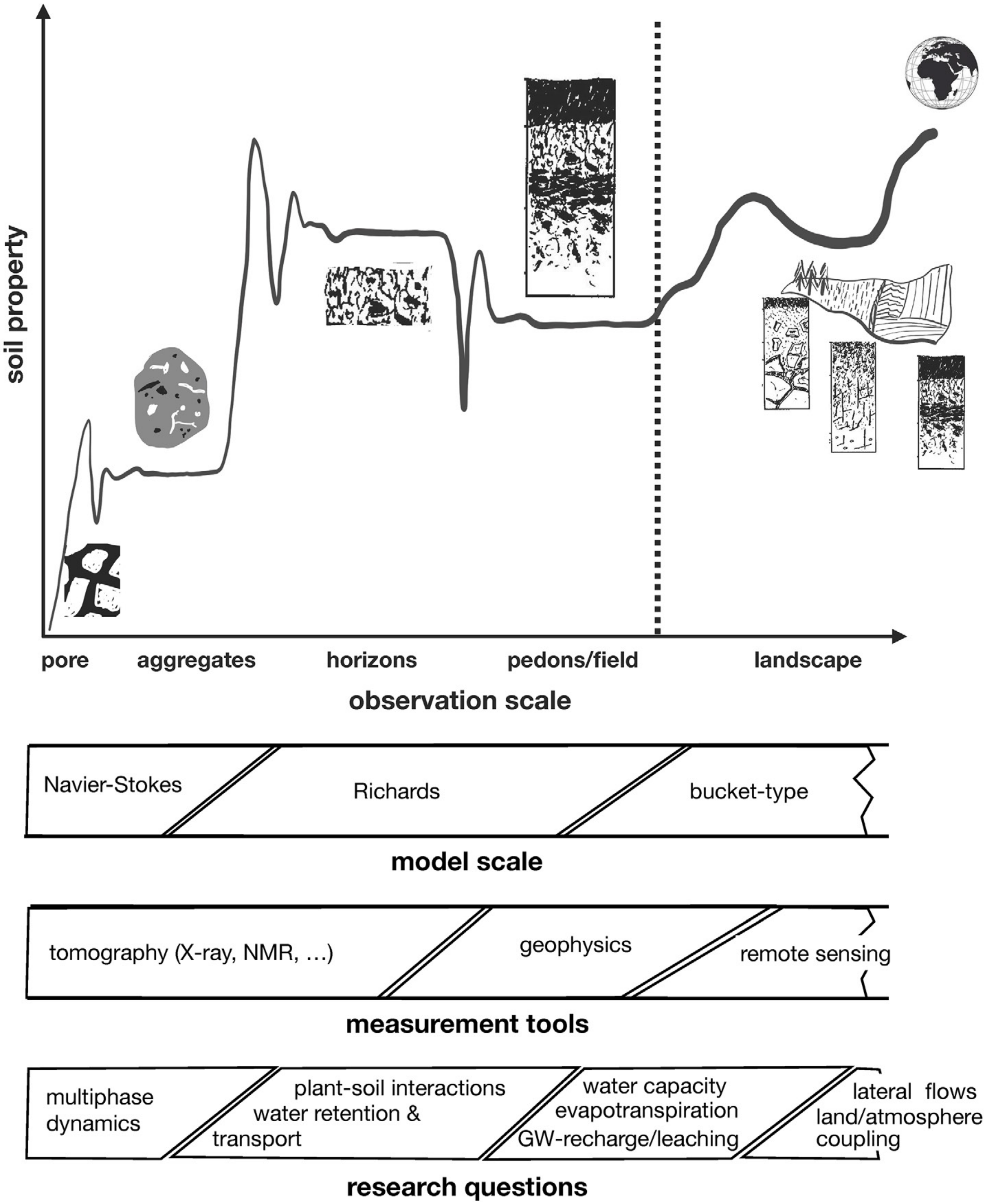

Fig. 1. Scale dependence of soil properties at different hierarchical levels from aggregates through soil horizons and pedons to landscapes together with typical model concepts, scale-dependent observation tools, and typical research questions at the various scales.

significant in terms of the type of the underlying structure. This transition is corroborated by the observation that at the pedon scale we look at structures vertically linked through historic and currently acting pedogenetic processes, while beyond the pedon scale we are looking at the horizontal distribution of various soil types in the landscape linked by the underlying geology and historical geomorphological processes. This might be the reason why, in many previous studies on the subsurface hierarchy of scales, the pedon scale is placed in some central position (Pachepsky and Hill, 2017; Lin, 2003; Wagenet, 1998). As discussed below, this central position manifests itself also when looking at soil hydrology or other soil processes.

Scales and Scale Transitions of Water Dynamics

The hierarchical structures described above are all relevant for water movement, and thus there are scale transitions in water dynamics as well. This is also reflected by characteristic research questions that are typically addressed at the different scales. Examples are given in Fig. 1. A recurring question along this journey through scales is: which smaller scale processes do have an impact on phenomena at the larger scale and how can these phenomena be described at the larger scale without dragging along unnecessary ballast from all the small-scale details? This question is addressed here while moving from pores to landscapes.

At the pore scale, substantial progress was made during the last decades due to two major developments. First, the ever increasing computing power allowed pore-scale simulations of fluid dynamics (Raeini et al., 2012; Meakin and Tartakovsky, 2009), which helped to link structural properties with water and solute transport through the soil (Ahrenholz et al., 2008). Second, new tomographic techniques led to considerable new insights into multiphase dynamics. It is now possible to directly visualize local water saturation within the pore space and even the movement of individual water–gas interfaces during changing water saturation (Schlüter et al., 2017; Hoogland et al., 2016). Based on continuously improving tomographic techniques, this is now possible for three-dimensional natural porous media and not just two-dimensional artificial micromodels. This provides new avenues to explore phenomena that have been well known for a long time but without being well understood. Examples are hydraulic nonequilibrium and hysteresis, as nicely documented long time ago, e.g., by Vachaud and Thony (1971) but rarely considered in the evaluation of measured data.

At the transition to the core scale, i.e., centimeters to decimeters—the comfort scale—these pore-scale processes have implications for water dynamics at this larger scale. It has been shown that water content and water potential are not in immediate equilibrium according to some static water retention curve during drainage or infiltration (Hassanizadeh et al., 2002; Diamantopoulos et al., 2012; Weller and Vogel, 2012). The question then arises whether we should still invest in measuring the water retention curve and the related parameters with ever-increasing precision given the insight that this curve is rather an idealized approximation to what is actually happening in the field, where stable equilibria are rarely observed. Or, alternatively, should we invest in developing concepts to describe nonequilibrium dynamics, which may also include preferential flow and hysteresis. The latter can be considered as hydraulic nonequilibrium with a pretty long time scale of equilibration. An impressive collection of long-term monitoring data for water content and water potential showing hysteresis and hydraulic nonequilibrium was presented by Hannes et al. (2016), which is discussed further below. When relating measurements of water content and water potential, the different support volume of the measurements needs to be considered. This is typically larger for water content measured by time- and frequency-domain probes than for water potential measured with tensiometers. Yet, there is considerable evidence that infiltrating water does not follow some instant energetic minimum according to a static water retention curve. In contrast, there is some evidence that water dynamics sensitively accounts for the accessibility of the pore space, eventually followed by a slow equilibration toward some energetic minimum behind the infiltration front. This might have a more important impact on the redistribution of infiltrating water than the uncertainties of the parameters of some static water retention curve.

At the core scale representing the scale of soil horizons, the importance of structural pores becomes evident. This is typically reflected by bimodal water characteristics (Durner, 1994) or, with respect to solute transport, by non-Gaussian breakthrough curves of conservative tracers. Based on noninvasive imaging techniques, which are available today, the importance of biopores and other structural pores could be demonstrated in many studies (Koestel and Larsbo, 2014; Naveed et al., 2013).

Another emerging structural feature at this scale are plant roots and their influence on the hydraulic properties in the rhizosphere. During the last decade it became evident that water retention and hydraulic conductivity are significantly affected by root exudates that have an increased water capacity but tend to become hydrophobic during desiccation (Moradi et al., 2012). This may increase the efficiency of plants to extract water and may protect plants from losing water to the dry soil.

Another relevant feature at the core scale are heterogeneities in terms of wettability. Zones of reduced wettability are typically related to the distribution of organic matter, where a nonlinear increase in the contact angle is observed during desiccation (Doerr et al., 2000). This might have significant impact on the shape of infiltration fronts (Leuther et al., 2018) and leads to additional hysteresis of the water characteristics (Bachmann et al., 2007).

At the transition to the scale of pedons, the importance of structural macropores persists. The phenomenon of preferential flow at the pedon scale has been an issue in soil physical research for decades. A more recent review was provided by Jarvis et al. (2016). Since the first ideas to separate a macroporous and a matrix domain (Jarvis et al., 1991; Gerke and van Genuchten, 1993), this dual-porosity approach is still the state-of-the-art for how preferential flow is modeled at the scale of pedons (Šimůnek and van Genuchten, 2008). However, despite all the newly available visualization techniques to analyze the soil pore structure, the required parameters cannot be inferred from directly observable structural properties with sufficient accuracy (Gerke, 2012). Hence, they are typically determined by inverse modeling, which makes the models rather descriptive than predictive. A fundamental difficulty is that preferential flow domains are sensitive to the imposed water flux, the related water potential, and the actual distribution of air and water within the pore space. Hence, flow domains are changing depending on the hydraulic state and can hardly be described by lumping all flow pathways into one domain described by a fixed set of parameters. This was recently demonstrated for solute dispersion in pure sand by Kumahor et al. (2015) and was discussed for preferential flow and the importance of antecedent moisture by Nimmo (2012). Moreover, the experiments to calibrate the parameters are often done at the core scale and under constant-flow conditions, which is just the most convenient way to measure breakthrough curves. For an upscaling to the pedon scale, the vertical length of preferential flow paths is critical (Jarvis et al., 2017) and whether they are connected to some outlet at the lower end such as the groundwater or tile drains (Klaus et al., 2014). This not only depends on the presence of structure-forming agents such as earthworms or plant roots but also on the type of soil, which impacts the activity of theses agents and makes it difficult to develop a more general understanding. This is probably why very little work has been done along these lines.

In case of the modified hydraulic properties in the rhizosphere, it seems not to be evident if and how this feature impacts water dynamics at the scale of pedons except that the optimum range for root water uptake could possibly be extended toward the dry range. This impact is more obvious in case of the spatial heterogeneity of wettability, which can massively affect infiltration fronts all along the soil profile (Ganz et al., 2014; Oostindie et al., 2011). In numerical simulations based on the Richards equation, this can be considered by assuming a dynamic contact angle as a function of water potential, while the rewetting time appears also to be relevant (Deurer and Bachmann, 2007). However, the spatial structure of wettability producing preferential flow paths remains a crucial unknown. The impact on water flow paths is amplified by the positive feedback between local water content and the local contact angle, leading to the initiation of flow fingers at locations where the water content is above some critical level (Rezanezhad et al., 2006).

At the scale of pedons, some structural features already recognized at the core scale persist but at a higher level of organization. This is true for roots and macropores, which need to be addressed according to their vertical extent, with a focus on activity for roots (Jackson et al., 2000; Feddes et al., 2001) and continuity for macropores (Jarvis et al., 2017). As a new structural feature, soil horizons appear as a vertical stratification of hydraulic properties that are highly relevant for water dynamics. Being a result of pedogenetic processes, soil horizons exhibit distinct physicochemical properties and pore structures. In agricultural soils, the contrasting properties of soil horizons are intensified by tillage, which is not only true for the tilled horizon but also below where the soil is often compacted due to heavy machinery. The upper few millimeters of soil is a special layer that is always somewhat different from the material below. It is exposed to the atmosphere and the direct impact of precipitation and wind. Although rather shallow, this layer can have a significant impact on water dynamics. Compaction and the formation of crusts leads to more surface runoff and might facilitate capillary rise and evaporation, while a coarse-textured structure or some organic mulch at the soil surface increases the infiltration capacity and prevents water loss through evaporation (Schlüter et al., 2012).

Water flow patterns along pedons are highly complex, and nearly anything imaginable can be found. This became pretty obvious when dye tracers were introduced to visualize infiltration patterns (Flury et al., 1994). These patterns are typically changing at the interface between soil horizons where the flow might either converge toward some preferential flow paths or diverge if the overlying layer exhibits preferential flow while the layer beneath does not. These phenomena cannot be investigated at the comfort core scale and, thus, there is not much work done along these lines as well.

What complicates matters is that flow patterns and pathways are highly sensitive to the flow rate and water content. Almost all dye tracer experiments reported in the literature were done at high flow rates close to water saturation. This allows the experiments to be completed in a reasonable time, but in most cases it does not reflect the general situation under natural boundary conditions. At lower flow rates and lower water saturations, preferential flow paths are typically less pronounced and flow patterns are more homogeneous (Vogel et al., 2006).

Typical research questions at the scale of pedons are dealing with the water capacity available for plants, water and solute fluxes to the groundwater, or gas fluxes toward the atmosphere. The most appropriate model concept seems to be the Richards equation, which can be solved very efficiently in one dimension while soil horizons of contrasting hydraulic properties can be considered, at least in principle. Considering solute transport, the generation of preferential flow paths and the phenomena of converging–diverging flow behavior along the soil profile becomes highly relevant in terms of residence and travel times and therewith the buffer capacities for nutrients and contaminants. This is less critical for the mean flux of conservative solutes such as NO_3, but it is the key to understanding the translocation of reactive substances such as P (Haygarth et al., 1998; Bol et al., 2016) or pesticides (Klaus et al., 2014). Although models tools have been developed that deal with preferential flow, they are difficult to parameterize independently without fitting to observed solute fluxes so that large predictive uncertainties remain.

It should be noted that the pedon scale discussed here is thought to be equivalent to what is often termed the “field scale,” which is usually the scale of an agricultural field where the soil properties are considered to be laterally homogeneous, and thus one-dimensional models (i.e., at the pedon scale) are typically used.

At the transition to the landscape scale, the features observed at the pedon scale (i.e., hydraulic nonequilibrium and preferential flow) persist. As long as the soil is not water saturated, its potential to adapt the hydraulic conductivity makes sure that the average water flow is mainly vertical. This allows modeling of water fluxes based on an additive approach of parallel, one-dimensional soil columns.

Despite the enormously heterogeneous structure from pores through aggregates and soil horizons, the local hydraulic conductivity is always adjusted so that the imposed water flux can be conducted. If some infiltrating water hits a compacted horizon with reduced porosity and reduced saturated conductivity, the water content of this horizon is increased so that the required conductivity is obtained. This is possible because local hydraulic conductivity is not a constant but a highly nonlinear function of the water content. As a consequence, water flow in soil is mainly vertical as long as the soil is not saturated, and this is true even in hillslopes with some oblique layers of contrasting hydraulic properties. This allows simplified descriptions such as the infiltration model proposed by Green and Ampt (1911), and parallel, one-dimensional models for pedons within a landscape can be justified, which indeed simplifies hydraulic modeling substantially.

Obviously the limits of these one-dimensional simplifications are reached as soon as the soil is water saturated or the imposed water flux exceeds the saturated hydraulic conductivity. In both cases, the water content cannot be adjusted anymore and lateral water flux at the soil surface or at the surface of some impeding soil layer, also termed *interflow* (Ahuja et al., 1981), becomes dominant. Hence, we are back to a challenging three-dimensional problem with additional structural heterogeneities to be considered including micro- and macrotopography of the soil surface and of impeding soil layers below ground as well as the horizontal connectivity of different soil types in the landscape. As with converging–diverging flows fields and the dynamics of preferential flow at the pedon scale, the onset of lateral flows is another manifestation of the adaption of flow patterns and pathways in response to changing water content as a general feature of the unsaturated zone. This is a fundamental difference from saturated groundwater flow, where the hydraulic conductivity is given by the pore structure of the material and can be considered to be locally constant in time. In contrast, the structure of the conductivity field in unsaturated soil and at its surface is highly dynamic and adjusts itself to the imposed boundary conditions.

At the scale of landscapes, an additional structural feature appears, which is the horizontal distribution of functional soil types along the topography of the landscape. As explained above, water and solute fluxes toward the groundwater or the atmosphere are mainly vertical as long as the soil is not close to water saturation, and thus water flows can be modeled at the pedon scale and are additive with respect to the functional soil types in the landscape. This spatial pattern including the topography becomes especially relevant at high water contents or high precipitation rates (i.e., larger than the saturated conductivity) when lateral flows become active.

In any case, different soils in the landscape having different hydraulic properties should be distinguished because averaging hydraulic parameters for different soil types to define some representative soil type is critical. This is because averaging nonlinear hydraulic properties is prohibited. As a plain example, a hypothetical landscape comprised of 50% sandy soils and 50% clay soil does not at all behave like a silty loam.

If even larger scales are considered, as for example done by remote sensing (e.g., SMOS/SMAP and GRACE) with footprints having a resolution of 36 km and beyond, soil types cannot be distinguished anymore and lateral flows can be neglected again. In this case, however, the focus is not on water dynamics in soil but typically on the coupling between the atmosphere and the land surface.

A Two-Step Approach for Upscaling

The journey through scales as illustrated in Fig. 1, from the perspective of both subsurface structures and water dynamics, provides some evidence that the scale transition from soil profiles to the spatial patterns of soils in the landscape is particularly important, relevant, and special. This is because structures within soil profiles are directly linked through continuous processes of flow and transport, which are overall vertical in unsaturated soil. In contrast, structural patterns beyond soil profiles depend on geomorphological processes and are only linked occasionally at high water saturations when lateral flows occur.

These considerations suggest a two-step approach for upscaling soil water dynamics to the landscape scale. As a fundamental basis, the spatial pattern of soils in the landscape having characteristically different layering and hydraulic properties (i.e., functional soil types) needs to be identified—this is of course easier said than done, but there are existing soil maps that are being steadily improved. Then, as a first step, water dynamics along the one-dimensional profiles of each functional soil type can be modeled using the specific stratification of hydraulic properties.

Ideally, this should include macroscopic effects of the small-scale heterogeneities such as hysteresis, hydraulic nonequilibrium, and converging and diverging flow fields along the soil profile. These aspects are not included in the classical Richards equation, which is typically used at this scale, but could be accounted for without sacrificing the physical basis of the Richards equation as discussed further below.

As a second step, water flow across the soil surface and/or seepage to the groundwater is obtained, including its spatial pattern at the landscape scale, which corresponds to the spatial distribution of functional soil types. As long as soils are unsaturated, this is a simple additive approach. In the case of local water saturation, lateral flow needs to be considered based on topography and the explicit spatial pattern of soil types or the lateral connectivity of saturated zones. Detailed simulations of surface runoff and interflow, however, are only possible for relatively small areas of hillslopes where the required data can be measured (Hopp and McDonnell, 2009; Warsta et al., 2014) but not for larger landscapes where residence times toward streams might be estimated from topographical attributes (McGuire et al., 2005).

Such a two-step approach is actually not a groundbreaking new concept. Indeed, many of the currently used "large-scale models" implicitly follow such an approach. This is true for models describing water flow such as mHM (Samaniego et al., 2010), land surface models like Noah (Niu et al., 2011) or the Community Land Model, or a model focused on the turnover of soil organic matter in addition to water dynamics such as LandscapeDNDC (Haas et al., 2013), ExpertN (Priesack, 2013), or Century (Parton et al., 1983). These models are mainly focused on matter turnover and water and gas fluxes between the soil and atmosphere and do not consider saturated groundwater flow.

Even though these models are often applied to regional and landscape scales, all these models are actually operating at the scale of a soil profile. They were developed locally but can be parameterized for different climates, soil types, and land uses so that they are considered useful tools also for larger scales. Yet, they represent a one-dimensional structure built up by a number of homogeneous horizontal layers—the classical description of a soil profile. The notation of "large scale" is coming from the fact that the considered soil profiles have a pretty large horizontal extent in the range of hundreds to thousands of meters. Thereby, soil attributes are necessarily averaged across a considerable number of different soil types, which may lead to considerable errors in the results, as discussed above. Hence, such models should account for the spatial pattern of soil types.

To improve the scaling of water dynamics from pores to landscape, we need (i) a better identification and separation of functionally different soil types at the level of landscapes and (ii) an improved one-dimensional model approach for water dynamics accounting for relevant phenomena at the scale of soil profiles. In the following, the actual challenges along these two lines are summarized.

Challenges at the Pedon Scale

The state-of-the-art to describe one-dimensional soil water dynamics is based on hydraulic properties, i.e., the water retention characteristic and hydraulic conductivity function, and using Richards equation to calculate water flow from local gradients in water potential. The required parameters for the hydraulic functions are typically measured in laboratory experiments or obtained from PTFs (Vereecken et al., 2010) where the hydraulic functions are estimated from more easily available data such as soil texture and bulk density.

However, the predictive potential of this approach for natural soils is limited. Due to their structural heterogeneities as discussed above, there is a rich phenomenology of water dynamics in natural soil that is not captured by the classical Richards equation assuming hydraulic equilibrium according to the hydraulic functions. An example for monitoring hydraulic state variables is shown in Fig. 2 adapted from Hannes et al. (2016). It shows measurements of water contents θ (using a time-domain reflectometry probe) and water potentials ψ (using a tensiometer) in the 30-cm depth of a Chernozem in Bad Lauchstädt, Germany, during 2013. The sensors were located close to each other within a lysimeter under natural boundary conditions. The precipitation during the measurement period is also shown in Fig. 2 (right). Obviously the state variables θ and ψ are not at all on some well-defined water retention curve and there are two separated pronounced hysteresis loops attributed to structural changes in the topsoil during the vegetation period. Moreover, there were two precipitation events with relatively high intensity under relatively dry antecedent moisture conditions (marked in red and blue). Under these conditions, the water potential rapidly drops toward zero (i.e., water is flowing

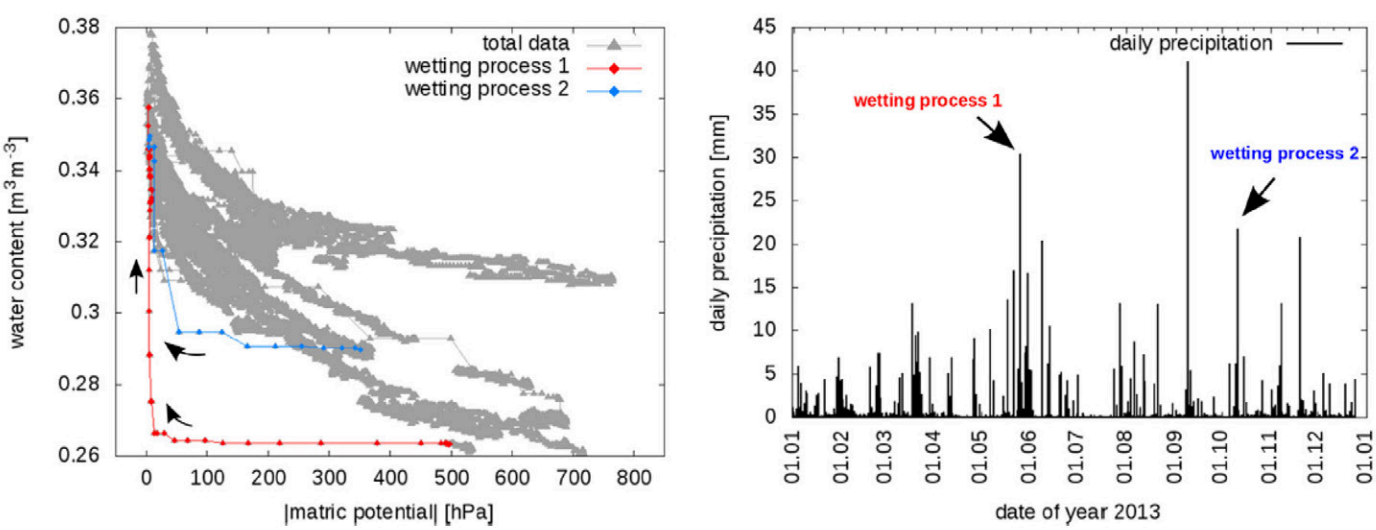

Fig. 2. Long-term monitoring of water content and water potential in the 30-cm depth of a Chernozem. Two wetting events are highlighted. (Taken from Hannes et al., 2016.)

down the macropores) while the water content is lagging behind (i.e., there is a redistribution of water behind the infiltration front). Such events are indeed more frequent during the year, but mostly the tensiometer was not working under the dry conditions before the rain event.

This illustrates that unique hydraulic functions are probably limited to some well-defined laboratory experiments and that the assumption of hydraulic equilibrium is violated under natural conditions, especially when water contents are changing relatively fast during infiltration events. The observed hydraulic nonequilibrium has significant impact on the redistribution of infiltration water along the soil profile. The phenomena shown in Fig. 2 are rather the rule than the exception. Hannes et al. (2016) analyzed different soils and observed the same patterns in all of them. Hence, to include hysteresis and hydraulic nonequilibrium is an actual challenge in soil hydrology. Due to these findings, it does not seem justified to invest a lot of effort in very accurate measurement of hydraulic parameters. To predict water dynamics in field soil, it might be more constructive to roughly estimate a hydraulic function, e.g., based on a PTF, and to include nonequilibrium processes at least conceptually, in contrast to accurate laboratory measurement of the hydraulic function while ignoring nonequilibrium processes. Indeed, Guber et al. (2006) found that the prediction of hydraulic state variables in a field soil based on PTFs was even better than those obtained from direct measurements of the hydraulic functions in the very same soil.

To include nonequilibrium phenomena in modeling water dynamics, the basic assumption of the Richards equation—that water content and water potential are in equilibrium according to some static water retention curve—needs to be sacrificed. This could be done by decoupling both state variables and introducing a term describing the dynamics toward equilibrium while still adhering to the basic concept of the Richards equation (i.e., to link the gradient in soil water potential to the flux by an effective hydraulic conductivity). Such a decoupling was proposed by Ross and Smettem (2000) and extended by Diamantopoulos et al. (2015), who separated fast and slow equilibrating pore domains.

In any case, to include hysteresis and nonequilibrium, the hydraulic description needs to be extended. The required parameters such as some time scale required to reach equilibrium along an infiltration front should ideally be derived from structural soil attributes that can be independently observed and measured (i.e., the connectivity of pores of different size). This leads to yet another challenge coming from the fact that the soil structure is typically not static due to bioturbation, swelling and shrinking, as well as tillage.

It should be noted that beyond the water dynamics within the soil, another source of considerable uncertainty is the distribution of active plant roots along the soil profile (Feddes et al., 2001), which is notoriously difficult to measure and even if known, the mechanisms of root water uptake within the rhizosphere can be variable in time and space (Carminati and Vetterlein, 2012). This forms another challenge for modeling water dynamics at the pedon scale.

Challenges at the Landscape Scale

The distribution of different functional soil types differing in terms hydraulic properties needs to be based on soil maps, ideally at a spatial resolution reflecting the typical correlation scale of soils in the landscape. At what length scale do we expect soil properties to change? Of course this depends on the local landscape attributes, but some 10 m is probably a good estimate on average.

During the last decades there was enormous progress in the field of pedometrics and digital soil mapping (Minasny et al., 2013), mainly due to the increase of computing power and the development of sensors especially for remote sensing. A recent review was provided by Rossiter (2018). This will continue to improve the availability of spatial information on soil properties and a resolution of some 10 m is not at all utopian anymore. In the context of soil hydrology, soil depth and the stratification of soil hydraulic properties is of utmost importance. Beyond that, also soil structural properties are highly relevant, as outlined above. The fusion of various sensor techniques (Grunwald et al., 2015), looking at the same soil at a given location from different perspectives, will certainly improve soil information with respect to functional properties.

However, at the scale of landscapes, there are no sensors to directly measure the vertical distribution of soil hydraulic properties. Instead, we need to rely on proxy variables and corresponding PTFs. While this was developed already some time ago for the estimating of soil hydraulic functions (Vereecken et al., 2010), the increasing availability of soil data allows us to extend this concept to other soil properties (Van Looy et al., 2017). A crucial candidate that is highly relevant for soil water flow is soil structure. This is especially true for the structure of the larger pore system often generated by soil biota, including plants, which is responsible for nonequilibrium dynamics. Despite the new noninvasive tools to visualize and quantify soil structure, it is notoriously difficult to quantify soil structure at the field scale (Rabot et al., 2018). Pedotransfer functions for soil structure still to be developed must take into account land use and agricultural soil management, which are key drivers for soil structure development.

Concluding Remarks

In this update on scale issues in soil hydrology, I tried to disentangle characteristic scale transitions in soil water dynamics when moving from the pore scale to the landscape. These transitions are marked by characteristic soil structures observable within different windows of scale. The major conclusions from these considerations are:

- Even if the landscape scale is addressed, the scale of soil profiles is the critical scale for a reliable representation of soil hydrology because flow and transport in unsaturated soil is mainly vertical, with gravity being the directing force.
- At the scale of soil profiles, our focus should not be on increasing the accuracy of measuring hydraulic parameters because under natural conditions the hydraulic state variables do not follow some well-defined hydraulic functions. Rather we

need to develop concepts to handle hydraulic nonequilibrium including hysteresis and preferential flow.

- At the scale of landscapes, we need to identify the spatial patterns of functional soil types and to develop PTFs accounting for the vertical stratification of hydraulic properties and soil structural attributes, especially those of the macropore network.

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