Soil hydrology in the Earth system

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Abstract | Soil hydrological processes (SHP) support ecosystems, modulate the impact of climate change on terrestrial systems and control feedback mechanisms between water, energy and biogeochemical cycles. However, land-use changes and extreme events are increasingly impacting these processes. In this Review, we describe SHP across scales and examine their links with soil properties, ecosystem processes and climate. Soil structure influences SHP such as infiltration, soil water redistribution and root water uptake on small scales. On local scales, SHP are driven by root water uptake, vegetation and groundwater dynamics. Regionally, SHP are impacted by extreme events such as droughts, floods, heatwaves and land-use change; however, antecedent and current SHP partially determine the broader effects of extreme events. Emerging technologies such as wireless and automated sensing, soil moisture observation through novel synthetic aperture radars satellites, big data analysis and machine learning approaches offer unique opportunities to advance soil hydrology. These advances, in tandem with the inclusion of more key soil types and properties in models, will be pivotal in predicting the role of SHP during global change.

The terrestrial water cycle is undergoing rapid changes, resulting in an increase of extreme events, such as frequent and intense droughts, floods and heatwaves that promote wildfires, cause crop failure and threaten communities in arid regions[1–4]. Moreover, new evidence suggests that the green water boundary, which is determined by soil hydrological processes (SHP) and soil moisture status, has already been transgressed[5]. Such changes are important, as evapotranspiration, the second largest flux in the terrestrial water cycle, returns about 60% (REF.[6]) of the total precipitation that reaches the land surface to the atmosphere and is strongly controlled by SHP.

The global increase in droughts and floods in the last decade pointed out the need to improve our understanding and parameterization of SHP[7,8] — the storage of water in the vadose zone, evapotranspiration, infiltration, redistribution, drainage, capillary rise and run-off (FIG. 1). Although these processes are confined to a thin layer of soil, and this layer only stores 0.05% of the total freshwater on Earth, SHP have a pivotal role in supporting life in natural and managed ecosystems, in modulating the impact of climate change on terrestrial ecosystems and in controlling feedback mechanisms between the water, energy, and carbon and nitrogen cycles[9–11]. The partitioning of incident radiation and precipitation on the land surface and into fluxes of energy, water and matter from terrestrial surfaces is also controlled by SHP[9,12], and, in turn, these fluxes impact groundwater levels[9].

Differences in soil properties (such as texture, organic matter and structure), their spatial distribution and overlying vegetation cover affect SHP, resulting in differences in the provision of soil moisture supply to crops, infiltration and run-off[13]. Regional impacts of climate change on the land surface also impact soil hydrology, requiring understanding of SHP beyond the soil profile or pedon scale (FIG. 1). Based on this awareness, hydropedology was introduced[14] two decades ago with the aim of integrating hydrological and pedological knowledge to better understand and predict SHP at the landscape scale. Later on, hydropedology[15] was embedded in the critical zone concept, which frames soils in a landscape and regional context, and analyses SHP from the bottom of the groundwater through the vadose zone, vegetation and into the atmosphere[16]. This concept enables local processes such as bypass flow, water accessibility and hydrophobicity to be conceptualized in a landscape context. It also allows to consider effects of soil structure, spatially varying soil horizons and anisotropy on local and non-local water flow.

In this Review, we highlight the role of soil hydrology in the Earth system. We discuss key soil properties that influence SHP, the estimation of soil hydraulic parameters and highlight the links between water and

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https://doi.org/10.1038/s43017-022-00324-6

Key points

- Local-scale soil hydrological processes regulate climatic effects on the global terrestrial water cycle by controlling energy and greenhouse gas fluxes.
- Regional-scale soil hydrology is modulated by land-use and climate-change effects on soil structure.
- Global-scale soil hydrology benefits from emerging technologies and big data analysis, but still faces parameterization challenges related to soil properties, such as soil structure and soil hydraulic parameters.
- Processes such as freeze-thawing, cryoturbation, peat degradation, and swelling and shrinking control soil hydraulic parameters in distinct soil groups, such as permafrost and peat soils.

carbon cycles, with a focus on carbon-rich soils. Next, the importance of local-scale SHP in understanding root water uptake, vegetation and groundwater dynamics and feedbacks are demonstrated. The role of SHP in controlling and modulating the impact of extreme events such as droughts, floods and heatwaves, and how soil hydrology contributes to assessing drought and floods are then described. Finally, we explore the potential of new emerging technologies for advancing the field of soil hydrology.

Soil properties and hydrology

Physical, chemical and biological properties of soils impact water fluxes (FIG. 1), for instance, how water is transferred to deeper soil layers or kept in the upper soil layers. Many of these properties (such as soil structure) and their related hydraulic properties evolved slowly over decades to millennia. However, they are sensitive to changes in land management and global change and can undergo rapid alteration[17] (FIG. 2). Soil properties, their hydrological parameterization and the impact of some characteristics in particular, such as carbon content, are discussed in this section.

Soil structure. Soil structure is the spatial arrangement of particles in soil, which determines pore size distribution, connectivity and tortuosity. Soil structure formation differs among different soil groups (BOX 1), depending on factors such as climate, regional geology, hydrology and biological activity. At the microscale, soil water flux is controlled by aggregation processes: organic gluing agents such as extracellular polymeric substances and microbial gums, and inorganic cementing agents such as carbonate precipitates and oxyhydroxides bind primary particles to form clay-sized and silt-sized organo-mineral complexes (<20 μm diameter). With adherence to fungal hyphae and fine roots, soil further clusters into microaggregates and macroaggregates (20–250 μm and >250 μm respectively) and, finally, peds[18,19] (FIG. 1). The voids or pores existing within and in between the aggregates are usually small (up to a few μm in diameter) and of high tortuosity[20]. These pores mainly contribute to capillary water flow in the soil matrix and, thus, to its hydraulic conductivity and water retention within the soil profile[19]. They generally indirectly affect infiltration, as it depends on the initial soil water content at the onset of infiltration processes[12], but they can dominate near-surface water flow processes in older, structured soils.

Natural soil-structure-forming processes create larger-scale pores in between macroaggregates and peds. These macropores include cracks formed by shrinkage in clayey soils due to soil drying (such as in Vertisols), but, in many terrestrial systems, vegetation and soil fauna are two of the main factors in macropore formation. Both root systems and burrowing activity of the soil fauna (FIG. 2) create such biopores. In Phaeozems, Chernozems or Luvisols with silty texture, for example, the biological formation of macropores by plants is stabilized by earthworms[21,22] and other burying animals. In contrast to the interaggregate and intra-aggregate pores, macropores are wider in diameter (up to several mm or even cm), have low tortuosity and often connect the soil surface with the subsoil to a depth of several metres[23,24] (FIG. 1). In loamy and silty soils, in particular, the accumulation and persistence of macropores alters SHP and gas exchange significantly. Under most soil conditions, macropores are drained and contribute to enhanced gas exchange pathways in the soil. During intense precipitation events, however, water-filled macropores can contribute to rapid infiltration and transmission of water through the soil profile via preferential flow pathways[24–26].

Natural soil structure formation takes decades to centuries, yet it may be disrupted by a single tillage or erosion event, which has large ramifications for soil functioning and carbon storage. Agronomic management of soil structure, for example, produces short-lived and fragile seedbed for crops[27]. Tillage induces loss of macroporosity, interrupts pore continuity and potentially forms compacted plough pans that impede root growth and vertical water fluxes (FIG. 2). Tilled soil surfaces are prone to aggregate slaking during heavy rain, causing the clogging of fine pores and formation of surface crusts[28]. The degree to which these processes occur varies with tillage and land-use practices[29,30]. However, the largely unknown timescales of aggregates and macroporosity turnover challenge assumptions of stable pore-size distributions used in SHP modelling. As a result, soil structure is a key property that is lacking in current hydrological, land surface and Earth system models.

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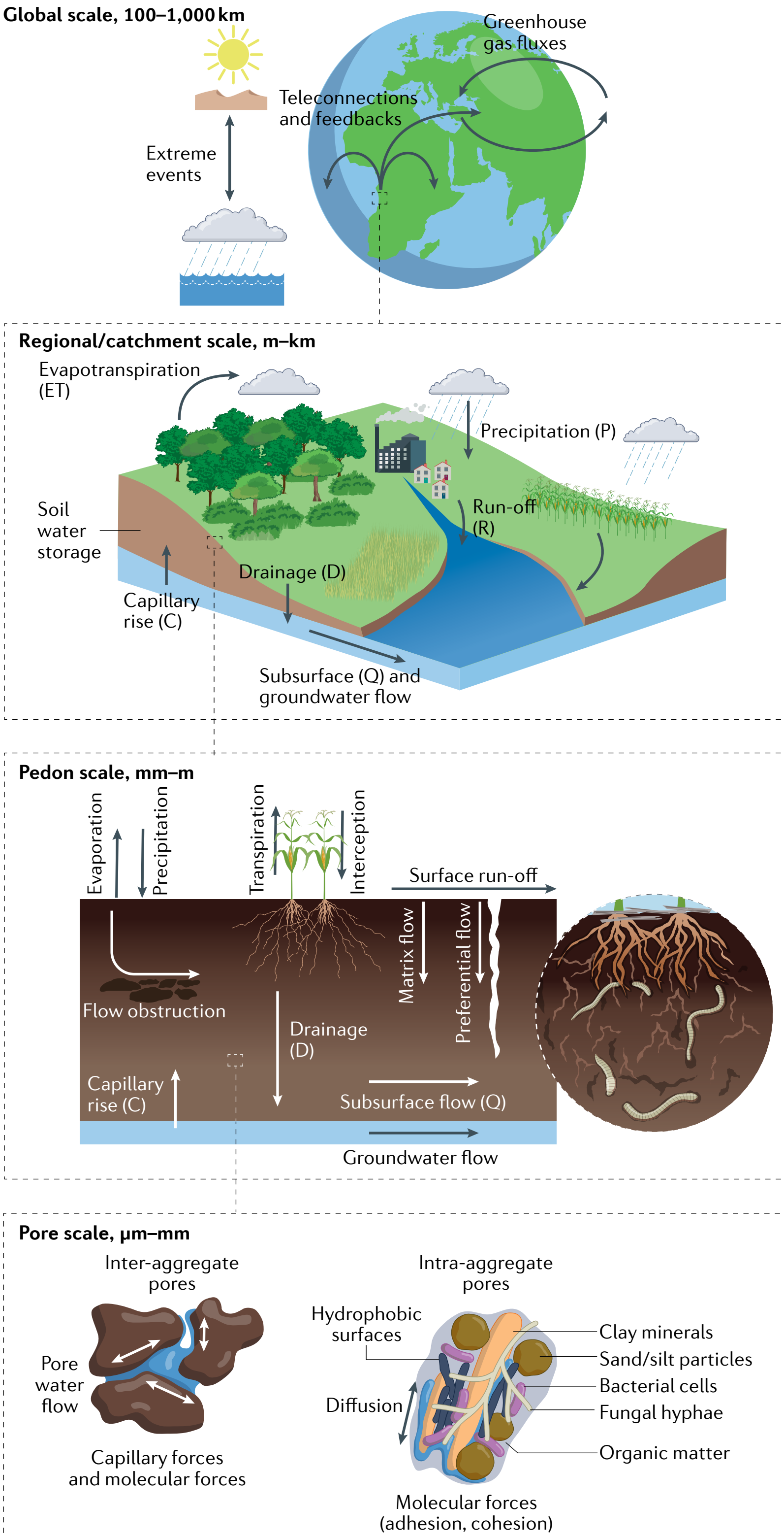


Fig. 1 | **The soil hydrological system from the pore to the global scales.** Soil hydrological processes (SHP) are connected across scales and local-scale SHP impact SHP at pedon, regional and continental scales. At the global scale, SHP can influence larger-scale atmospheric processes, such as droughts and convective rainfall events, through feedback processes and teleconnections, and can modulate the impact of extreme events. At the regional scale, similar processes occur but, in addition, water is now routed through the landscape. At the soil profile or pedon scale, hydrological processes include drainage, evapotranspiration, soil water storage, capillary rise and run-off generation. Typically, water flows either through the matrix or through preferential flow paths, such as macropores and cracks. At the pore scale, capillary and molecular forces act on the pore soil water. Inset of earthworms in soil is adapted from REF.[27], CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/).

Carbon-rich soils. The SHP of carbon-rich soils have unique properties, such as a high capacity to store plant-available water and, often, a shallow groundwater level relative to other soils. Carbon-rich soils are unevenly distributed globally. For example, permafrost-region soils are widely distributed across high latitudes and altitudes. Indeed, permafrost regions span 13.9×10^6 km^2 in the Northern Hemisphere alone[31], storing an estimated 1,700 Pg of carbon[32,33]. Part of the carbon-rich soils (mainly in permafrost regions but also elsewhere) are classified as peatlands. These cover 3% of the global land surface only, but store approximately 644 Pg of carbon[34] and a substantial portion of near-surface freshwater with widespread atmospheric exchange.

The shallow groundwater level is a key controlling factor of soil moisture dynamics in peat and permafrost soils. Owing to their high content of organic matter, carbon-rich soils frequently have total pore volumes of 70 to >90% and pore sizes reaching 5 mm (REF.[35]). This high macroporosity dampens groundwater-level fluctuations and, thus, importantly, stabilizes the wet conditions that are critical to inhibit aerobic soil organic matter decomposition. The shallow groundwater conditions are further supported by a low hydraulic conductivity, K, of deeper organic soil layers or the flow barrier of the permafrost layer, which limits the drainage losses and causes trapping of rain, snowmelt or run-on water[36].

The factors leading to shallow groundwater levels in carbon-rich soils are being markedly altered directly and indirectly by humans. In dry conditions, the structure of the soil organic matter of carbon-rich soils substantially changes due to microbial decomposition and irreversible compaction[35]. The soils lose their high water storage capacity and, thus, groundwater-level fluctuations are amplified, which eventually further enhances decomposition. These alterations in organic soil structures can be observed in peatlands that were drained by humans, leading to enhanced decomposition and causing large greenhouse gas emissions[34]. Another threat to the shallow groundwater levels of carbon-rich soils is exerted by ongoing permafrost thaw, which might increase drainage losses and initiate a negative feedback loop between soil moisture and decomposition[37].

Despite the critical role of SHP in carbon-rich soils in the carbon cycle, specific SHP for such soils are currently only beginning to be implemented in a sophisticated manner in land surface models (LSM) and climate models[38,39]. Conventional hydrological concepts for groundwater that are based on the TOPMODEL[40] and that relate subgrid-scale topography to groundwater

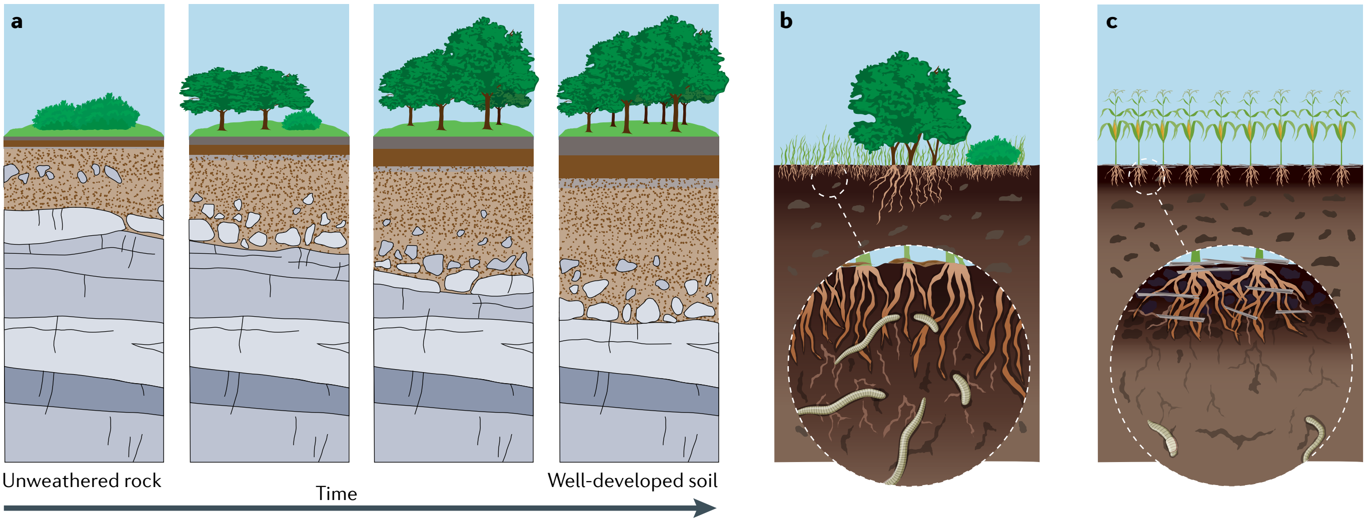


Fig. 2 | **The soil structure formation and timescales. a** | Soil genesis induces the formation of differentiated horizons and characteristic structures over centuries to millennia, depending on climatic conditions and other soil-forming factors (parent material, vegetation, topography). **b** | Natural soil structure develops over hydrologic timescales often expressed by formation of soil aggregates and accumulation of biopores that facilitate water infiltration and reflect signatures of soil–vegetation–biota interactions. **c** | Managed soil structure is a result of fragmentation by mechanical forces (tillage) that occur over agronomic timescales (cropping cycles); it is characterized by mechanically unstable soil fragments near the soil surface for crop seed bed often underlain by a compacted plough pan and is associated with disruption of biopores and ecological food webs. Part **a** is adapted with permission from REF.[202], CC-BY-NC-SA 4.0 (https://creativecommons.org/licenses/by-nc-sa/4.0/). Parts **b** and **c** are adapted from REF.[27], CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/).

table and soil moisture variability fail in the extensive flat terrains typical of most peat-rich and carbon-rich permafrost soils and miss critical small-scale processes relevant to shallow groundwater conditions[36,41]. In response, modules to simulate the shallow groundwater and other specific features of peat-rich and carbon-rich permafrost soils were added to a number of LSM[36,41,42]. There are currently two major challenges in advancing the reliability of these efforts.

First, there is a lack of spatial input data for peatlands and carbon-rich permafrost soils that could be used to parameterize spatially variable soil hydraulic properties and lateral water fluxes. About half of the carbon soils classified as peatlands are bogs and, in contrast to fens, by definition, are solely fed by rainwater and do not depend on water inputs from surface water or the aquifer underlying the peat layer[43,44]. Given the lack of spatial input on the distribution of bogs and fens, current peat-specific global land model implementations assume all peatlands to be either bogs[41] or fens[45].

Second, the hydraulic properties of peat-rich and carbon-rich permafrost soils are dynamic at different timescales, which critically control their resilience to short-term and long-term changes in boundary conditions[35,37]. In addition, the thermal soil properties affect freeze-thaw cycles, with strong implications for soil water flow dynamics[46]. Soil moisture fluctuations can cause reversible changes in soil properties due to swelling and shrinking, but there are also irreversible changes to hydraulic properties caused by cryoturbation, permafrost thawing or enhanced peat degradation in response to climate change or direct anthropogenic disturbance. These changes are typically accompanied by a change in vegetation that is the main substrate provider for the future organic layers. The implementation of these key ecohydrological feedbacks will be critical in simulating trends over multiple decades[47,48].

Soil hydrological parameterization. A reliable parameterization of SHP is critical for its representation in soil water balance models, hydrological models, LSM, and climate models and Earth system models[12,49]. In these models, the fluxes and states of soil water are mostly described by Richards' equation (Eq. (1)), which links the Darcy–Buckingham flux law with conservation of mass:

$$\frac{\partial \theta}{\partial t} = -div\,.\,\vec{q} - S \qquad (1)$$

where $\vec{q} = -\mathbf{K}(h,\theta)\nabla(h+z)$ with $\vec{q}$ the Darcy flux, div is the divergence operator describing the local sinks of $\vec{q}$, h is the soil matric potential, z the vertical coordinate and $\mathbf{K}(h,\theta)$ the soil hydraulic conductivity tensor, which becomes a scalar quantity, $K(h,\theta \equiv K)$ for isotropic one-dimensional domains, and S describes a general external sink–source term, such as root water uptake. Frequently used numerical model codes to solve Richards' equation have been extensively reviewed[50]. The use of Richards' equation requires explicit knowledge of key soil hydraulic functions: the soil moisture retention $\theta(h)$ and K. These characteristic functions describe the volumetric water content or K as functions of soil water tension (matric potential). The choice of hydraulic functions and associated parameters have a substantial impact on model performance in terms of water fluxes in the soil water balance and model numerical stability[51]. Moreover, spatial variability of soil hydraulic parameters has to be accounted for to correctly describe SHP. The determination of these functions for larger-scale approaches remains an ongoing challenge.

Direct measurements of soil hydraulic properties are often difficult and time-consuming[52,53], and impossible at larger spatial scales. Pedotransfer functions (PTF) were, therefore, developed to estimate soil hydraulic parameters, as well as parameters in equations related to soil heat flow and biogeochemical parameters from readily available soil properties, such as soil texture, bulk density and organic carbon content[54]. PTF based on simple soil properties translate this information in soil hydraulic parameters that can be used to estimate SHP, such as soil water storage, infiltration and evapotranspiration (BOX 1) in LSM[12,54] (FIG. 3). There is, however, increasing awareness that other pedological properties and processes also affect soil hydraulic properties and, thus, soil water dynamics (BOX 1).

The use of PTF can, however, sometimes lead to inaccurate or even false parameterizations of the functions used to describe the soil hydraulic properties. Several reasons account for this failure. The determination of basic and hydraulic soil properties is frequently conducted with different measurement methods[54,55], thus, producing systematic biases and inconsistent results[55,56]. There is a poor representation of specific soil properties, such as the distribution of soil organic matter, that significantly affect modelling of hydraulic functions, in particular in peatlands and carbon-rich permafrost soils.

Box 1 | **The diversity of soils and pedotransfer functions**

Easy-to-measure soil physical properties, such as texture, bulk density and organic matter, are used in pedotransfer functions (PTF) to estimate soil hydraulic properties. This approach assumes that these attributes dominate in determining soil hydraulic properties and applies auxiliary simplifying assumptions of homogeneity, unimodality of pore size distribution, while ignoring differences in rock fragments, mineralogy, chemical and biological properties. This approach does not account for the nuanced differences in soils and their specific properties[59]. Therefore, next-generation PTF are needed to integrate specific rock fragments, mineralogical, biological and chemical interactions that alter soil hydraulic properties[28,33].

Current databases used to develop PTF must be expanded to include physical, chemical and biological properties of diverse soil groups, which are typically found in large parts of Africa, South America, India, the Middle East, Japan, China and Australia. Examples of soil groups[204] with notable properties not yet accounted for in PTF are:

- Formation and persistence of preferential flow paths due to animal burrows common in silty soils such as Phaeozems, Chermozems or Luvisols; these paths are stable unless disturbed by management.
- Temporal formation of preferential flow paths due to swelling and shrinking processes in Vertisols caused by the presence of three-layer clay minerals.
- Good drainage in Ferralsols and Acrisols due to pseudo-aggregate formation from two-layer clay minerals and oxides, as well as in some Andosols exhibiting low bulk density.
- Low water storage capacity in Leptosols due to percentages of rock fragments, affecting both the soil hydraulic and thermal properties, which are, therefore, frequently not effectively parameterized.
- High water storage capacity in Histosols due to high organic matter contents.
- Crust formation in, for example, Gypsisols or clayey Solonetzs and clayey Solonchaks, distorting infiltration patterns.
- Dense subsoil layers leading to stagnant water in Planosols, Stagnosols or Plinthosols.

Early attempts have been made to develop PTF for tropical soils in Brazil[196] with a dedicated hydrophysical database. Unfortunately, adequate high-resolution data are frequently missing for other parts of the tropical and subtropical world, such as in Africa, hampering similar progress in other regions.

Finally, soil structure is not explicitly represented in soil hydraulic functions and related PTF development[57].

Such limitations have prompted efforts to revise the soil-centred framework by considering environmental covariates that modify soil structure and properties such as vegetation cover and type[26,58], and climatic soil-forming processes that alter clay type[59,60]. These local variations not encapsulated in the standard texture-based PTF offer a means to improve soil hydraulic parameterization and potentially improve the representation of hydrologic processes in LSM. Further options to account for soil structure in PTF include the incorporation of geometrical properties of structured soils derived from non-invasive techniques such as micro-computed tomography or magnetic resonance imaging[61] and applying machine learning methods to adapt to soil-class-specific information within continuous PTF[62,63].

Local-scale hydrology

Soils play an important role in local hydrology, including buffering the precipitation signal (P) and storing incoming water. At the scale of soil pedon, a field or a forest stand, the moisture status of soils, the vegetation and the groundwater dynamics impact each other. For example, the uptake of water by plant roots, described by the sink term S in Eq. (1), controls transpiration fluxes (T). The proportion of water uptake relative to precipitation varies with climate, vegetation type and the soil properties. This section discusses how climate, soil and vegetation properties influence each other and the soil water balance (FIG. 4).

Root water uptake in soils. Transpiration is driven by the available energy that can be used to evaporate water (T demand) and is downregulated by stomatal closure that responds to the energy required to extract soil moisture (T supply). The simplest models of transpiration supply from root water uptake use a stress function that expresses how the ratio of transpiration supply to demand declines with decreasing fraction of total available soil moisture in the root zone. This total available soil moisture is the moisture stored in the root zone at water potentials between −10 kPa for sandy soils or −30 kPa for silty soils (field capacity) and −1,500 kPa (permanent wilting point). However, the impact of globally increasing transpiration demand on total transpiration and vegetation stress is uncertain[64] — many models only consider soil moisture content and are not directly sensitive to T demand. As a result, the models overcompensated by having an oversensitivity to soil moisture. The inclusion of plant hydraulics in the soil–plant–atmosphere systems allows the leaf water potential needed to sustain a given transpiration rate to be estimated for a given soil water distribution. For example, as stomatal regulation depends on leaf water status, soil–plant hydraulic models mechanistically link stomatal regulation to soil drying[65].

Soil moisture is usually non-uniformly distributed in the root zone due to alternating infiltration and evaporation at the soil surface, and the distribution of roots and water in the root zone affects the total root

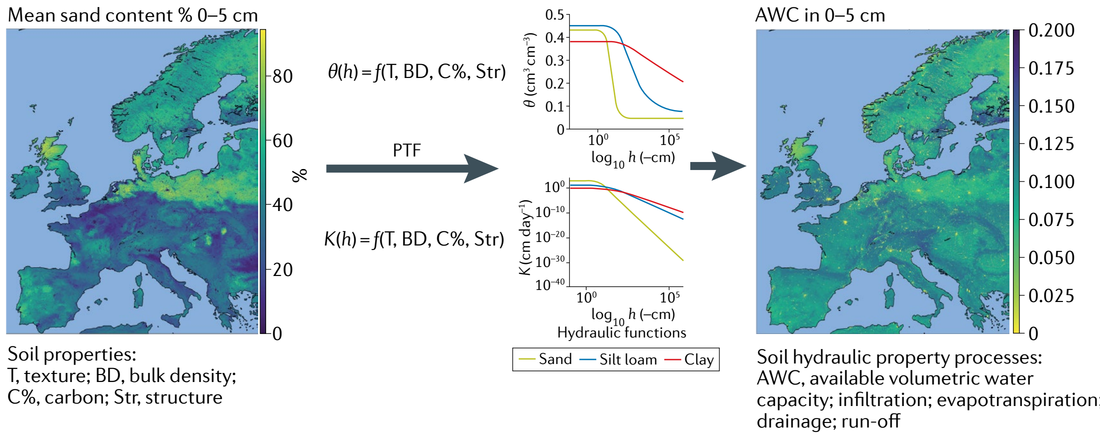


Fig. 3 | **The pedotransfer functions concept.** Pedotransfer functions (PTF) are used to predict soil hydraulic properties from soil properties, which can then serve as a basis for estimating large-scale soil hydrological processes, such as water storage, infiltration, evapotranspiration, drainage and run-off. This process is demonstrated here for soils from Europe, based on the mean sand content (far left panel). The hydraulic conductivity (middle lower panel), K, indicates the ease with which water can flow in the soil: the value of this parameter will decrease rapidly with decreasing θ. Together with the gradient in hydraulic potential ($\nabla(h+z)$, with h being determined by the water retention curve and z the vertical coordinate), K determines the flow of water in the soil, thereby affecting the processes of infiltration, redistribution, drainage, root water uptake and evaporation. The information contained in the water retention curve (middle upper panel) also provides the models with parameters that determine how much water a certain soil can hold in its pore system (the available volumetric water content (AWC), as shown in the far right panel) and how easy it is for the roots to take up this water (that is, how tightly the water is being held in the pores).

water uptake. Roots can shift water extraction to wetter zones (root water uptake compensation) and can redistribute water from wet to dry soil zones, bypassing the soil through root water redistribution and hydraulic lift[66,67] (FIG. 4). These hydraulic processes are driven by water potential gradients and depend on soil and root hydraulic properties[66,67]. Reported magnitudes of these water transfers[68] range from 0.04 to 3 mm day^{-1}. The water transfers can prevent surface layers from drying out, which would cause a strong reduction in microbial activity[69]. Water transfers from root water uptake can also delay stomatal closure by several weeks and maintain transpiration from plants that access deeper groundwater during drought spells.

Parameterizing root hydraulic properties in plant hydraulic models is important in understanding soil hydrology but it remains challenging. Therefore, a number of assumptions and simplifications are used, including neglecting the resistance to axial flow in the root system. However, root water uptake in deep roots does not increase with root length, as axial conductance becomes limiting[70], therefore, root water uptake is overestimated. As a result, approaches to simulate root water uptake that account for the distribution of radial and axial conductance in root system networks[71] have been developed[72]. Then, using upscaling approaches, information about root architecture and root hydraulic traits can be incorporated directly into larger-scale soil–plant hydraulic models[73,74].

The resistance to flow from bulk soil to root surfaces through the rhizosphere becomes increasingly important when the soil dries out[75]. Root exudates and mechanical effects of root growth influence the hydraulic properties of the rhizosphere and, consequently, root water uptake[76,77]. An additional complexity is that the conductivity of the root–soil interface is reduced when roots and soil shrink during soil drying and contact to the soil is lost[78]. How plants engineer the rhizosphere and its impact on SHP is a multifaceted problem that includes microscale soil and root mechanics and hydraulics. These small-scale processes are key to understanding how plants affect soil structure and infiltration processes, which are important feedback mechanisms that structure and sustain vegetation in water-limited ecosystems.

The adaptation of vegetation and its hydraulic properties to environmental conditions, referred to as plant plasticity, can be predicted by invoking optimization principles, but it remains unclear why they apply when natural selection is not a mechanism for optimization. Unravelling the mechanisms that couple growth and stress physiology and plant hydraulics will be crucial for a mechanistic modelling of plant and vegetation plasticity. This coupling entails the coupling of phloem carbon transport and xylem water flow, and how they respond to changing environmental conditions[79], as well as a comprehensive understanding of how changing environmental conditions in the soil are sensed by plants[80] and signalled between the plant organs or individual plants.

Soil, climate and vegetation properties. Climate and local vegetation greatly impact soil hydrology. Soil properties, climate and management are all linked with vegetation properties, and, in turn, the root zone soil moisture. Infiltration of surface run-off (run-on) and capillary rise from groundwater also contribute to root zone soil moisture, and the groundwater table depth is important to predict and produce global maps of root distributions[81]. Run-off–run-on processes and groundwater recharge and flow are scale-dependent lateral flow processes that both determine and are influenced by vegetation growth, composition and patterning[82,83].

Ecohydrological models that solve a stochastic root zone soil water balance[84] use two dimensionless numbers to characterize its dependence on soil, vegetation and climate properties. These are the number of average daily rainfall events required to fill the plant-accessible soil water reservoir and either the Budyko[85] dryness index (long-term potential evapotranspiration to precipitation rate) or the ratio of the time to deplete the plant-accessible water reservoir by potential evapotranspiration to the characteristic time between rainfall events. Such models can predict the change in vegetation properties as a function of soil and climate and assess the development of vegetation in the course of climate change. When coupled to an optimization of the carbon cost for root development, stochastic ecohydrological models[86,87] could reproduce the relation between root zone depth, climate and soil type, with deeper roots in seasonally dry, semi-arid to humid tropical regions and less likely in medium-textured soils[88].

In arid and semi-arid regions, soil evaporation, infiltration and run-off from non-vegetated surfaces play a crucial role in the ecohydrology, vegetation patterning and water balances of catchments. These processes are controlled by soil surface hydraulic properties that, in turn, depend on soil structure. Aggregate destruction and crust building by rain splash on barely vegetated soil surfaces reduces the infiltration capacity, leading to increased surface run-off. In contrast, infiltration capacity, run-on and preferential flow-reducing water losses through evaporation from the soil surface are larger in vegetated patches with macropores created by roots and soil fauna and water repellency owing to increased organic matter input[17]. Manipulation of these processes by changing soil surface hydraulic properties is the basis of water-harvesting and water-saving methods in dryland agriculture that focus on the reduction of soil evaporation from bare soil and increasing run-on and infiltration. However, near-surface soil structure and soil hydraulic properties vary strongly with depth and time, which complicates accurate prediction and simulation of soil evaporation[89] and rapid infiltration.

Data on root distributions are scarce and models often underestimate the rooting depth from which plants can extract water, especially in stony soils (like Leptosols) and (weathered) bedrock[90,91]. In addition to root distributions, plants can also adapt root hydraulic traits such as xylem cavitation resistance to adapt to environmental conditions. To access strongly bound soil water, desert shrub species develop higher cavitation resistances in loamy than in sandy soils[92]. The differentiation of root systems of different species to access specific subsurface niches[93] and interactions from deep rooting species facilitating water uptake from wet, deep soil layers to shallower, drier layers with subsequent water uptake by species with shallow root systems[68] are used to explain the higher resilience and productivity of mixed ecosystems[94]. However, the mechanisms and conditions under which mixed species perform better than homogeneous systems are context-dependent and not fully understood[95,96]. Higher productivity can lead to an overcrowding effect, which reduces resilience to drought. Mechanistic modelling of root water uptake in these complex ecosystems is important for a better understanding of the below-ground competition for and facilitating water uptake[97]. Yet, upscaled relations between soil moisture distribution and root water uptake of different species or individuals sharing the same land surface and soil volume and that are derived in a bottom-up approach based on canopy and root hydraulic traits are still lacking.

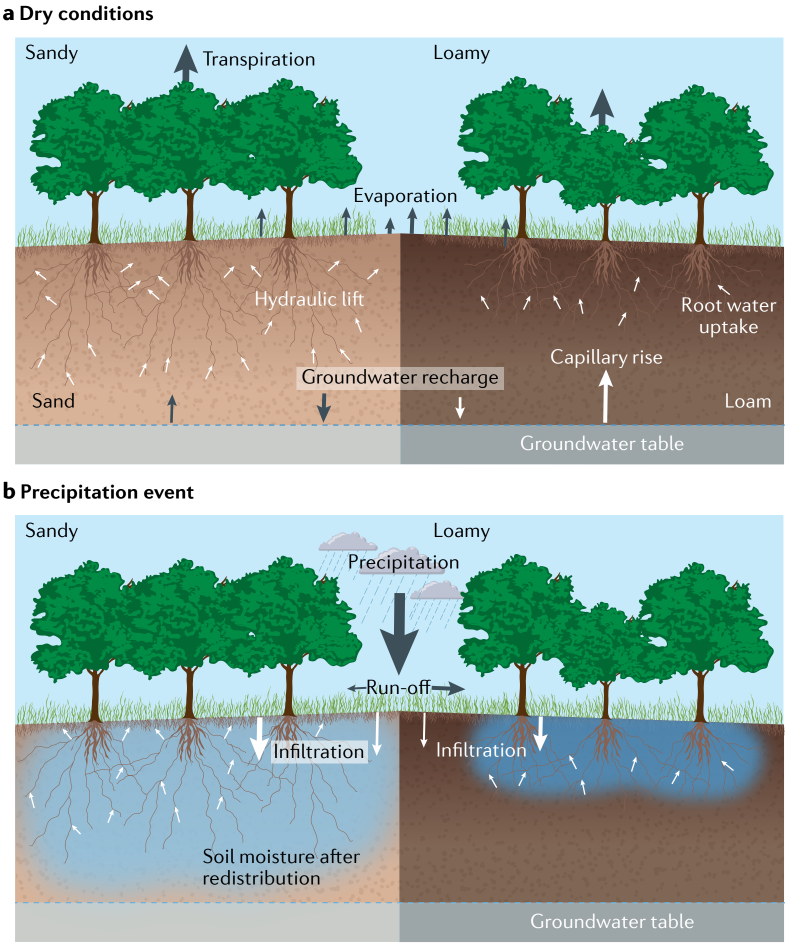


Fig. 4 | **Effect of soil properties and moisture status on water fluxes in the soil–plant system. a** | The water fluxes during a dry period in sandy soils (left) and loamy soils (right) with and without vegetation. During dry periods, more water is lost by transpiration from vegetated areas than by evaporation from the soil surface in non-vegetated areas. This phenomenon occurs because vegetation can extract water from deeper soil layers, leading to larger groundwater recharge in non-vegetated areas. In sandy soils, evaporation losses are lower than in loamy soils due to smaller capillary forces in sandy soils. Capillarity sustains larger upward flows from the groundwater to the root zone in loamy than in sandy soils and deep root systems act as hydraulic lifts that take up water from deeper and wetter soil layers and release it into shallower and drier layers. Loss of soil structure in non-vegetated areas leads to less infiltration and more run-off from non-vegetated surfaces during precipitation events. Biopores and soil structure that is stabilized by organic matter input in vegetated areas increase the infiltration capacity of vegetated areas, where water can be transferred rapidly by preferential flow to deeper soil layers. **b** | Sandy and loamy soils after a precipitation event. Water is redistributed faster and to deeper soil layers by matrix flow in sandy than in loamy soils. To access this redistributed water, vegetation develops deeper roots in sand than in loamy soils.

Vegetation and groundwater feedbacks. Changes in vegetation and land cover impact water, energy and carbon exchanges between the land surface and the atmosphere. Vegetation cover reduction leads to an increase of soil evaporation. Since the travel distance of water to the surface where evaporation takes place is much larger than that to the absorbing root surfaces in the root zone, the water storage that can be depleted by soil evaporation is much smaller than what can be extracted by plant roots. As a consequence, a decrease in vegetation cover generally leads to a decrease in evapotranspiration losses, an increase in groundwater recharge and run-off, larger warming of the land surface and higher air temperatures near the surface.

Soil surface and root zone drying are mitigated by upward capillary flow from the subsurface. It sustains evapotranspiration during dry spells and decreases groundwater recharge on a longer timescales, and depends on the wetness of the subsurface and, ultimately, on the groundwater depth. The non-linear dependence of soil hydraulic properties on soil water content is propagated into a non-linear relation between groundwater depth, subsurface moisture content and upward capillary flow. For groundwater depths greater than roughly 1 m, the root zone stays wet and evapotranspiration is controlled by the available energy, whereas groundwater deeper than 10 m has no influence on root zone wetness and land surface–atmosphere interactions[98]. The depth range over which groundwater depth influences land surface–atmosphere interactions depends on the soil hydraulic properties and the rooting depth. Steady upward capillary flow at typical potential evapotranspiration rates can be maintained over a few cm in sandy and heavy clay soils up to roughly 1 m in loamy soils[99]. Rooting depth can adapt to the specific site conditions and to changes in groundwater depth that are not too fast or too strong and do not exceed adaption rate (root growth rate) and the cost–benefit ratio of this adaptation[100].

Large-scale impact of soil hydrology

Soil hydrology plays a central role in shaping the impacts of climate change on terrestrial ecosystems, and SHP are central to the feedback effects of the land surface on the Earth's climate system[101]. This section explores these feedback processes and the effects of extreme climate events. The importance of terrestrial water storage (TWS) in deeper soil layers and its more precise quantification for the response of the terrestrial system to climate change will then be discussed.

Climate system feedbacks. Land use, land-use change and climate change impact SHP and feed back to the climate system via direct and teleconnected processes, leading to large uncertainty in regional climate predictability[102]. For example, increased soil moisture can trigger precipitation events, especially under spatially heterogeneous soil moisture conditions, with precipitation preferentially falling on dry patches of land[103]. Similarly, increased deforestation has led to large changes in precipitation patterns in Rondônia, Brazil, in the range ±25% between the upwind and downwind parts of the deforested area relative to the mean precipitation of the entire area[104]. Agricultural intensification, especially in combination with irrigation, can lead to cooling at the subcontinental scale due to increased evapotranspiration and persistent changes in atmospheric circulation and moisture transport, as observed for the Midwestern United States[105]. In contrast, drought at the regional, continental and global scales is exacerbated by the feedbacks of decreasing soil moisture on land surface temperature and relative humidity, leading to a decrease in precipitation, which, in turn, exacerbates this feedback loop[106].

Major soil moisture perturbations can last much longer than the cause of the perturbations and, therefore, also represent a long-term feedback on the climate system[107]. For example, there is a strong positive relationship between heatwave intensity and drought severity for water-limited regions, such as the Southwestern United States[108] and the Mediterranean[109]. In wetter regions, such as the tropics, a strong link and feedback loop between precipitation and soil moisture has also been identified[110]. Ultimately, these multiple interactions and feedbacks between soil, land surface and atmosphere can be summarized as a negative soil feedback loop between soil moisture and temperature (a decrease in soil moisture leads to an increase in temperature) and a positive feedback loop between soil moisture and precipitation (an increase in soil moisture leads to an increase in precipitation)[9].

Local SHP play an important role in controlling and modulating the impact of extreme events, such as high-intensity rainfalls, as well as prolonged droughts and heatwaves, on the land surface, but also the consequences caused by sea-level rise on soils in coastal areas, such as saltwater intrusion and inundation. For example, increased likelihood of large-scale flooding and soil erosion could arise from changes in infiltration capacity at the land surface, loss of soil porosity and a decrease in soil organic matter[111]. Moreover, local SHP control the impact of sea-level rise on soils in coastal areas, such as saltwater intrusion and inundation[112].

To project the behaviour of floods and extreme low-flow conditions into the future, it is essential to attribute such changes to their driving processes. The predominant mechanism of run-off generation is overland flow when rainfall intensity exceeds the infiltration capacity at the soil surface[113]. In this context, infiltration capacity is highly susceptible to land-use changes, such as those associated with more intensive agriculture[114]. However, flooding in larger watersheds is usually caused by storms of lower intensity and longer duration[115], which generate surface run-off through the mechanism of saturation excess when the water table reaches the soil surface. This mechanism is controlled more by soil depth and less by land-use change, which explains the decreasing importance of land-use change with increasing scale.

Extreme events could also alter intrinsic soil properties that control SHP. Prolonged droughts can promote macropore formation, primarily through the formation of cracks in clay-rich soils[116]. Changes in effective porosity due to climate change would result in changes in saturated soil K ranging from −55% to +34% in five different physiographic regions in the

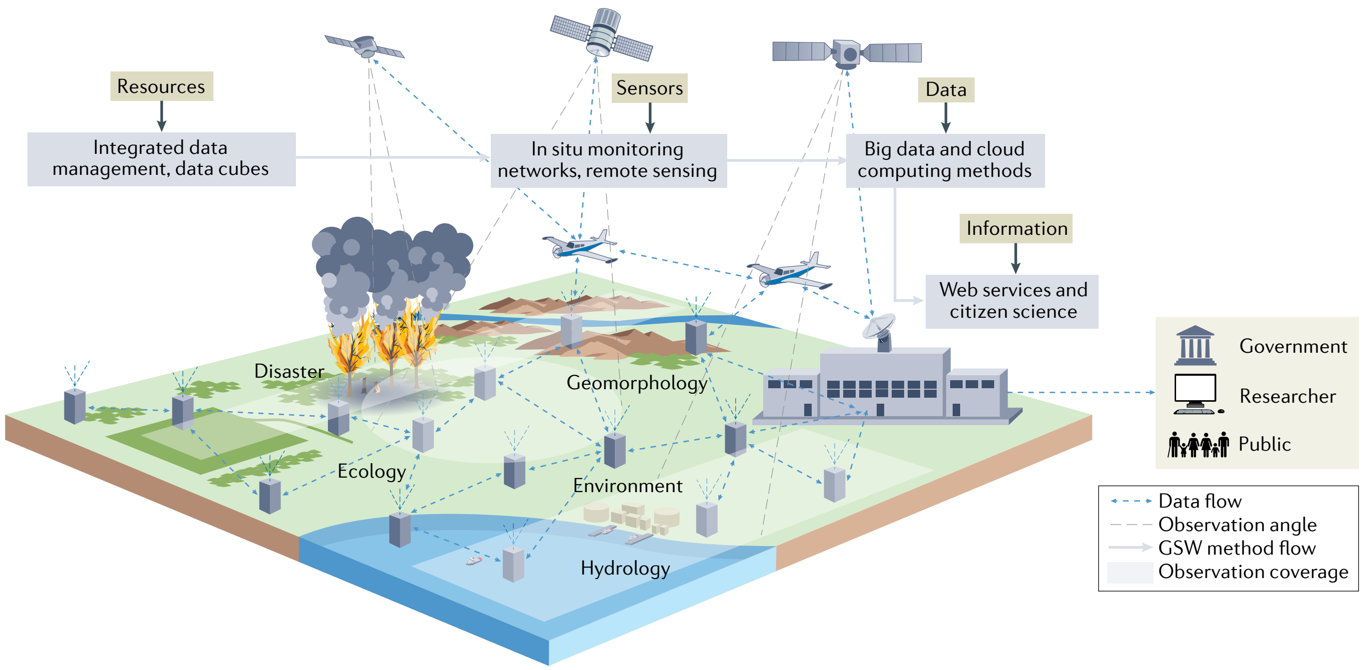


Fig. 5 | **Cyber-physical infrastructures for soil hydrology.** This infrastructure encompasses various sensing and data sources for soil hydrology research and stakeholder transfer. Sources include integrated data management and data cubes (BOX 2) with data from orbital, airborne, terrestrial or marine wireless sensors. Higher-level information can be generated using big data and cloud computing methods, as well as citizen science approaches and web services for researchers, governments and the public. As an example, wireless and in situ sensors (grey boxes on the land surface) provide near-real-time soil hydrological information that can be injected into models using data assimilation methods or data-driven approaches. GSW, global surface water. Figure adapted with permission from REF.[203], Elsevier.

USA, depending on whether climate change results in an increase or a decrease in precipitation at the regional scale[117]. High-intensity rainfalls could lead to sealing of the soil surface, a reduction of soil porosity and, thus, a reduction in infiltration capacity of soils. This reduction in infiltration capacity could, in turn, cause increased overland flow and soil erosion.

Terrestrial water storage. Subsurface and groundwater storage dynamics are important not only for the impacts of climate change on terrestrial systems and their feedback to the climate system but also for water resources[118] and carbon cycling[119]. However, these dynamics are currently not well understood[120] and cannot be suitably constrained by observations, except in the regions with shallow soils. Surface soil moisture, temperature and precipitation can be measured at the land surface with sensors or from satellite-based systems, but there is a lack of observational capabilities at depth. To infer the terrestrial water budget, information is needed on water storage and residence time at depths below the vadose zone.

Owing to a lack of observations, long-term changes in TWS were often simply assumed to be zero, for example, in water balance models[121]. Since 2002, however, the gravity satellite missions GRACE and GRACE-FO have provided global observations of TWS anomalies[122]. In general, soil moisture dynamics exhibits an increasing phase shift and decreasing amplitudes with depth. Combining soil water and soil temperature measurements with GRACE data in the central USA, over 40% of the variability in water storage of the unsaturated zone was found to occur below 75 cm, while groundwater storage variability was well correlated and comparable in magnitude to soil moisture variability in the uppermost 4 m (REF.[123]).

TWS is not in equilibrium at decadal timescales for natural and anthropogenic reasons[118,124]. On the global scale, the variability of water stored on continents responds strongly to the El Niño–Southern Oscillation, resulting in pronounced sea-level declines. For example, the exceptional sea-level decrease in 2011 was explained by Australia's endorheic hydrology responding to intense rainfall[125]. The GRACE data have shown that hydrology models underestimate decadal trends and have helped identify the need for better representation of soil column depth and layers, snow storage and groundwater storage changes in coupled climate models[126].

Emerging technologies

To adequately inform soil hydrological and LSM and to better use existing observational capabilities, there is a need for improved data acquisition, data curation and analytical tools (FIG. 5). This section presents an overview of the status of modern sensing technologies, citizen science approaches, cyber infrastructures and global data cubes to advance our understanding of SHP at all scales.

Sensing soil hydrology. Information on soil water content, temperature, matric potential and other states requires a variety of established and novel technologies that capture their high degree of variability in time and space[127]. Established in situ point methods include electromagnetic approaches to measure in situ water content, for example, time-domain reflectometry[128], time-domain transmission[129] and capacitance[130] and impedance sensors[131]. Other point-based approaches use thermal soil properties (thermal pulse sensors)[132]. In situ-sensed soil moisture has been coupled with the remote sensing data to acquire large-scale soil profile moisture variation using physically based methods[133], data assimilation methods[134], (semi-)empirical methods[135], data-driven methods[136] and statistical methods[137] (FIG. 5).

Field-scale soil moisture measurements can be obtained by non-invasive methods, such as cosmic-ray neutron sensing, global navigation satellite systems reflectometry, gamma-ray monitoring and ground-penetrating radar[138]. Regional to global coverage of near-surface soil moisture content is usually achieved with satellite-based sensors, such as the Soil Moisture and Ocean Salinity (SMOS), Soil Moisture Active Passive (SMAP), Advanced Scatterometer (ASCAT)[139] and Advanced Microwave Scanning Radiometer (AMSR-E/AMSR-2), with a resolution of tens of kilometres[140–142]. Through integration of multisensor satellite platforms, higher spatially resolved[143] or global long-term (1978 up till now) soil moisture products[144] are generated.

Native finer-resolution data (tens of metres) involve synthetic aperture radars (SAR), such as the European Space Agency's Sentinel-1 (REF.[145]) and the Japan Aerospace Exploration Agency's ALOS-2 (REF.[146]). The upcoming SAR missions NISAR (NASA-ISRO Synthetic Aperture Radar)[147] and ROSE-L (Radar Observation System for Europe in L-band)[148] operate at longer wavelengths than previous SAR sensors, allowing better penetration of vegetation cover and are able to monitor soil moisture over a depth of about 5 cm. Soil moisture information down to a depth of about 25 cm will be provided by P-band sensors used by the European Space Agency's BIOMASS mission[149] and the SigNals Of Opportunity: P-band Investigation (SNOOPI). The latter exploits transmissions from telecommunications satellites reflected at the Earth's surface to retrieve soil moisture[150]. Similarly, the global navigation satellite systems reflectometry concepts use navigation signals of opportunity to perform scatterometry with ground-based[151] or space-borne receivers[152]. The relatively lower cost of sensors that take advantage of such existing 'signals of opportunity' theoretically enables more frequent observations by making it cost-effective to fly a large number of sensors. These sensing systems provide a unique opportunity to better inform LSM and to constrain soil hydrological fluxes using, for example, data assimilation approaches or machine learning approaches.

Monitoring networks and citizen science. Understanding the impact of anthropogenic change on SHP and designing adaptation strategies requires long-term observations[153,154]. The concept of soil hydrologic in situ monitoring networks is increasingly relevant for a range of environmental issues[155], leading to an increasingly multidisciplinary focus of long-term observatories[154], often coordinated as networks[156,157]. Ongoing national and international observatory networks that include soil hydrological observations are Critical Zone Observatories (CZO)[156,158], National Ecological Observatory Network (NEON)[159], Terrestrial Environmental Observatories (TERENO)[160], Terrestrial Ecosystem Research Network (TERN)[161] and International Soil Moisture Network (ISMN)[162], providing in situ soil moisture data from 2,842 stations worldwide.

These networks can be supported by public participation of non-scientists, known as citizen science[163]. Citizen science ranges from community-based data collection to Internet-based execution of various scientific tasks, with the help of large numbers of volunteers and crowdsourcing[164,165]. New sensor development, data processing and visualization have opened new opportunities for engaging the public in scientific research[166]. For example, low-cost, low-maintenance soil moisture sensors have enabled the development of large-scale public sensor networks[167]. Another citizen science project used human perception to evaluate similarity and dissimilarity between spatial patterns in the simulation results of a hydrologic model[168], which provided additional information that is valuable for model diagnosis. However, citizen science is typically staff-intensive and requires proper training and education of those involved[165], as well as openness to data sharing[169], requiring dedicated time, resources and careful planning. Techniques are also being developed to assess and increase the accuracy of crowd-sourced environmental data, including blockchain-based crowdsourcing systems that are being developed to better motivate users to upload rare data more accurately and in an environmentally friendly way[170].

Cyber infrastructure and big data. Cyber-physical infrastructures provide solutions for the integrated management of heterogeneous data resources including live sensors, sensor models and simulation systems; collaborative observation systems based on multiple platforms, such as wireless sensing networks and remote sensing; and methods for scalable processing and fusion of multi-sourced environmental data (FIG. 5). In environmental research, these infrastructures are particularly helpful, as they combine different types of data, such as real-time wireless sensor network data with global remote sensing data.

Cyber-physical infrastructures are also increasingly important in implementing the Internet of things (IoT)[171], which provides real-time environmental data, enabling large-scale networks and possibly continental coverage in the near future[172]. Growing global internet access to support the IoT will enable real-time data collection from billions of smartphones or remote research platforms; adequate cyber-physical infrastructures are essential to manage the petabytes of data that could be produced in the future by such systems[173]. These data will support new insights that advance fundamental aspects of soil science. The processing of the vast amounts of IoT data takes place in virtualized data centres that allow a large number of users to access and collaborate on the data in order to gain new insights that advance fundamental aspects of soil science. However, the associated data are often discrete and irregular.

A radical rethinking of the deployment and use of these new observing systems[173], and the cyber tools needed to harmonize and synthesize these unstructured data into a comprehensive picture of Earth system processes and properties, is necessary.

Data management is not only needed for new data, though. Soil hydrology has been recorded by satellites, monitoring networks and governments for decades. However, these data are often underutilized owing to a lack of availability, discoverability, accessibility, storage capacities, processing methods, visualization and dissemination tools, or high-performance computing facilities with low usability levels. Here, public analysis-ready data repositories with the possibility to apply new processing and analysis methods, ideally with affordable processing power, are needed[174]. Both public and private entities invest in this field of big data accessibility and cloud computing, such as Data and Information Access Services (DIAS) of the European Commission, Theia in France, Big Data Analytics Platform (BDAP) of the Joint Research Center, Copernicus Data and Exploitation Platform (CODE-DE) of the German Aerospace Center, Google Earth Engine and Open Data on Amazon Web Services. Furthermore, there is a growing recognition that data storage principles are needed to enable the reuse and repurposing of data; for example, the FAIR principles (findability, accessibility, interoperability, reusability) are now being adopted in many venues.

Basic land surface data are typically available on cloud platforms, and sometimes also soil moisture information, but more detailed soil hydrology data need to be processed with new approaches. Here, portable and efficient software container solutions like Docker and Kubernetes[175] can be implemented, as well as interactions with scripts of common languages such as Python and R via application programming interfaces performed. These solutions also open up the potential to apply deep learning methods to perform advanced analytics approaches similar to those used for the SoilGrids250m soil information data, such as random forest, gradient boosting or multinomial logistic regression techniques[176]. For example, training environmental monitoring data to point-scale in situ soil measurements could provide spatial maps at sufficient accuracy for further implementation in regional or global soil hydrological simulations. Moreover, methods for generating new soil hydrological understanding could benefit from a combination of both process and empirical modelling[177].

The wealth of data being generated provides news opportunities to explore novel data analysis methods. Machine learning approaches such as artificial neural networks and support vector machines have been widely used in the past several decades to simulate various hydrological processes, including soil water dynamics[178,179]. In addition, machine learning approaches have been successfully applied to the prediction of soil moisture using remote sensing data[180,181]. It is important, however, that such models are first trained on a dataset that contains as much data and as many conditions as possible, so that they can also take unusual events into account and achieve good prediction accuracy. Given suitable input data, machine learning approaches can also be used for irrigation planning and agricultural water resource management[182].

Summary and future perspectives

Over the past two decades, the field of soil hydrology embraced the challenge of quantifying and understanding the influence of SHP at catchment, regional and continental scales. These advances have been made possible by an unprecedented increase in measuring capabilities empowered by novel remote sensing technologies and new ground-based technologies to measure key SHP, such as soil moisture storage and evapotranspiration. Daily, and even subdaily, global observations such as soil moisture and evapotranspiration are now a reality. These new measuring capabilities open up new perspectives to better predict and constrain key components of the soil water balance, such as root water uptake that determines evapotranspiration, infiltration that controls partitioning of rainfall into water that infiltrates the soil and that generates run-off and groundwater recharge. Accurate predictions of SHP such as root zone moisture storage and evapotranspiration are also key to better representing and quantifying the planetary boundary for green water, which defines a global safe operating space in respect to human water use and Earth system functioning.

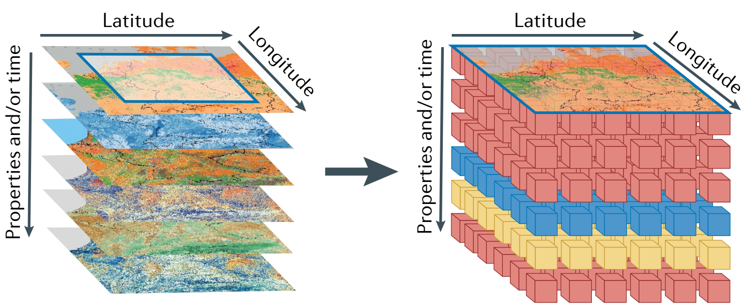
In the future, soil hydrologists will increasingly need to address challenges related to adapting land management in the frame of ongoing climate change, land-use change and permafrost thaw. Now, more than ever, a better understanding of key SHP and the accurate estimation and forecasting of soil moisture dynamics is needed.

Data cubes are a promising innovation that support SHP understanding (BOX 2). We envision the development of the next generation of PTF and geomorphic functions in their georeferenced and local-attribute-based context to greatly enhance SHP-related information. Such a development will also support continual improvement as more information enters into the local hypercube. The richness of information and advanced analytical methods will supersede our present, non-referenced generic-attribute-based PTF and offer local and updatable referenced hydrologic and surface information at an ever-increasing resolution and expanding temporal record[183].

For effective exploration, management, querying and updating of the massive geospatial information, the community will need to embrace hypercube-based visualization[184], which extends traditional space-time cubes into higher dimensions spanned by contemporary soil and environmental information (BOX 1). Cloud computing will also play a central role in the management, extraction and direct simulation of spatial data (Google Earth Engine)[185]. The potential for rich soil (and environmental) information unique to a location, where local and extrapolated new measurements and observations are harmonized and integrated using ensemble machine learning tools to continuously update and improve data quality and derived parameters, holds great promise for reducing uncertainties of present Earth system models.

Box 2 | The soil data hypercube

The confluence of rapidly expanding Earth observing platforms, availability of massive computational resources and the urgent need to provide information for increasingly complex and highly resolved Earth system models creates opportunities for individual georeferenced characterization of the Earth surface[205]. The hypercube approach stacks gridded geospatial data according to standardized global coordinates, such as DGSS (DGGSs)[206] and adding a *z*-dimension for various information layers that incorporate localized legacy data, vegetation, geomorphic, climate and other environmental attributes, and soil variables at different depths (see figure). This data structure provides unique opportunities for data fusion and temporal information assimilation to derive parameters or variables, and enhance the quality of inputs to Earth system models applications. This structure is especially useful because novel machine learning approaches can be used to impose physical constraints and extract auxiliary information for the representation of SHP. Combined with modern data cube geospatial data management and analysis software, such as that provided by the Open Data Cube (ODC) initiative, a unique indexing of grid cells down to 150-m resolution[207] is now possible.



The representation of soils and SHP strongly impact the predictions of hydrological and biogeochemical processes using LSM. Despite its importance, however, the role of soil structure and its dynamic impact on SHP and soil biogeochemical processes have been almost completely neglected in many models. A closer cooperation between soil scientists and global land surface and climate modellers is urgently needed. In particular, we call for efforts to improve the description of SHP processes in models using PTF. Although dual-modal and multimodal hydraulic functions have already been developed[186,187], they are currently not used in LSM and reliable PTF for these functions are not yet available.

In addition, there is a need for unifying theoretical soil physical approaches, which requires fully coupling soil hydraulic, thermal and gas flow properties[188,189]. This approach would allow for a more consistent description of interactions and feedbacks between the soil water balance, the thermal regime and the carbon fluxes in LSM. Ideally, multiscale PTF should be developed that can be used seamlessly from the soil profile to the global scale, building, for example, on the development[190,191] of multiscale Bayesian neural-network-based PTF, which allow upscaling and downscaling of soil hydraulic parameters.

Most models rely on a single set of PTF to estimate soil hydraulic properties[54,192], causing statistical bias, underestimation of PTF uncertainty and overconfidence in the predictive ability of PTF. To alleviate such bias, ensemble PTF that unify multiple sets of PTF are recommended[192,193]. Moreover, it is important to take into account the effect of rock or gravel content on soil hydraulic properties[194], as this is generally overlooked in most PTF. PTF assume that estimated properties are constant in time. Yet, we know that properties like saturated *K* and porosity vary not only in space but also in time, due to land management[55]. The next generation of PTF should, therefore, account for this temporal dependence.

These are suggestions for improved PTF implementation, but there are large gaps in the data that are used in these models. Indeed, most of the measurements for PTF parameterization originate from arable land and have been developed for temperate regions. These PTF frequently fail in fine-textured soils of the tropics and subtropics[195,196]. Owing to absence of glaciation, these soils are highly weathered, and in Ferralsols and Acrisols, low-activity clays dominate the mineral composition (BOX 1). These clays react with oxides and form pseudo-silt and pseudo-sand, microaggregated structures with the hydrology of silty or sandy sites. With some additional macroaggregates formed with inputs of soil organic matter as found in Cambisols, the parameters used to describe the soil hydraulic properties of tropical soils generally differ from those of respective soils in temperate climates[59,195]. Therefore, there is an urgent need for PTF development for soils that formed below natural vegetation and taking different regions into consideration[197,198].

Carbon-rich soils are also poorly represented by PTF. We recommend that future research on the hydrology of carbon-rich soils should specifically emphasize conducting detailed field studies in data-scarce regions, such as large parts of tropical[199] and permafrost peatlands[37], to understand and quantify the variability of local feedback mechanisms. There is also the need to combine remote sensing data on hydrology[200], vegetation and peatland type[44,201] with soil hydrological models to eventually constrain the spatial variability of parameters. This approach will contribute to simulating the feedback loops between water, energy and biogeochemical cycles on Earth.

Published online: 02 August 2022

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Acknowledgements
W.A., N.B., C.M., J.V. and H.V. acknowledge support from the Deutsche Forschungsgemeinschaft under Germany's Excellence Strategy, EXC-2070 - 390732324 (PhenoRob). W.A., H.B., N.B., C.M., J.V. and H.V. acknowledge support from the Terrestrial Environmental Observatories (TERENO) funded by the Helmholtz-Gemeinschaft, Germany. The authors were also supported by the Deutsche Forschungsgemeinschaft – SFB 1502/1-2022 - Projektnummer 450058266.

Author contributions
H.V., W.A., S.L.B., H.B., N.B., C.M. and J.V. led the conceptualization, writing and figure drafting. D.O., M.B., G.B., A.C., A.G.K., J.K., I.N., S.S.-D., A.V., M.Y. and Y.Z. supported in equal parts the conceptualization, writing and figure drafting.

Competing interests
The authors declare no competing interests.

Peer review information
Nature Reviews Earth & Environment thanks Jan Hopmans, Carlos Rogerio de Mello and Qing Zhu for their contribution to the peer review of this work.

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