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HESS Opinions: Are soils overrated in hydrology?

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Abstract

Traditional "physically-based" hydrological models are based on the assumption that soil is key in determining water's fate. According to these models, soil properties determine water movement in ~~both~~ saturated and unsaturated zones, described by matrix flow formulas known as the Darcy-Richards equation~~s~~. Soil properties ~~would~~ also determine plant available moisture and thereby ~~control~~ transpiration. These models are data demanding, computationally intensive, parameter rich and, as we shall show, founded on a wrong assumption. Instead, we argue the reverse: it is the movement of the water through a porous medium, creating preferential patterns, that determines soil properties~~; while~~ water movement is primarily controlled by the ecosystem's reaction to the climatic drivers. According to this assumption, soil properties are a "consequence", rather than a "~~cause" of~~ water movement. It is not the soil that ~~is in control of~~ hydrology, it is the ecosystem. An important and favourable consequence of this climate and ecosystem-driven approach is that models developed with this approach do not require soil information, are computationally cheap, and parsimonious. Our assumption is motivated by several arguments. Firstly, in well-developed soils the dominant flow ~~mechanism is~~ preferential, which is not particularly related to soil properties, such as pF curves. Secondly, we observe that ~~it is~~ the ecosystem, rather than the soil,

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that determines the land-surface water balance and hydrological processes. Top-down analysis by large-sample datasets reveal that soil properties are often a poor predictor of hydrological signatures. Bottom-up hydrological models usually do not directly use field measurements of the soil, but "rebalance" the observed soil texture and translate it to soil structure by vegetation indices. Thus, soil-based models may be appropriate at small spatio-temporal scale in non-vegetated and agricultural environments, but introduce unnecessary complexity and sub-optimal results in catchments with permanent vegetation. Progress in hydrology largely relies on abandoning the compartmentalized approach, putting ecosystem at the centre of hydrology, and moving to a landscape-based modelling approach. This change in perspective is needed to build more realistic and simpler hydrological models that go beyond current stationarity assumptions, but instead regard catchments as the result of ecosystems' coevolution with atmosphere, biosphere, hydrosphere, pedosphere, and lithosphere.

1 Introduction

Soil is important. It forms the substrate of the terrestrial ecosystem and hence is a crucial element of the critical zone of life on Earth (Banwart et al., 2017). Recently it has been demonstrated that the soil forms an ecosystem in itself, full of micro-biotic and macrobiotic life (Ponge, 2015). Fungi forming dense underground networks live in symbiosis with vegetation, exchanging nutrients for carbon, which makes them responsible for the larger part of subterranean carbon storage (Domeignoz-Horta et al., 2021). Soils are full of life. Above ground live cannot survive without sub-surface life; they are both part of the same ecosystem. How this ecosystem functions, evolves and survives depends on the climatic and geological boundary conditions. Through evolution and natural selection, the ecosystem has found ways to make best use of the climatic and geological resources. In doing so, it manipulates the substrate on which it grows. It manipulates key hydrological characteristics such as: interception capacity, infiltration capacity, moisture storage capacity, preferential pathways to replenish moisture stocks and recharge, and subsurface drainage. So, soil is regarded as the key to hydrological processes (Lin et al., 2006). Yet, in (most

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established) hydrological models, soils are simplified to soil classifications (Freeze and Harlan, 1969; Refsgaard et al., 2022), such as sandy, clayey, or loamy soils with ~~their~~ related soil characteristics, such as porosity, moisture retention capacity, wilting point, plant available moisture, etc.~~, which~~ are subsequently combined by the rooting depth of the dominant vegetation (e.g. Drewniak, 2019, Lu et al., 2019). ~~But this is the wrong way round.~~

~~Traditionally,~~ hydrologists assume that the root zone storage is a function of plant available moisture and rooting depth (Yang et al., 2016). This approach considers plant available moisture and rooting depth as the independent variables, and root zone storage as the dependent variable. But it is the opposite. Plant available moisture and rooting depth are a function of root zone storage, given some environmental constraints such as soil type and soil depth. Obtaining the detailed spatio-temporal root and soil information at a global scale is virtually impossible (Or, 2019), but fortunately not necessary.

It is not the soil that determines the hydrology, it is the interaction between ecosystem and climate. The climate provides the driver to the survival strategy of the vegetation. As a result, the vegetation develops a rooting strategy, which results in a certain moisture buffering capacity (Gao et al., 2014; Wang-Erlandsson et al., 2016). Depending on the soil, this buffer translates in a root depth, extent, density ~~and~~ possibly access to deeper groundwater (McCormick et al., 2021). So, for hydrological modelling ~~it is not useful to measure soil characteristics and rooting depth. We~~ do not need to know these dependent variables if we can determine root zone storage directly.

2 The soil-centred hydrological perspective

It is a deeply rooted perception in hydrology that soil is key ~~in~~ controlling rainfall-runoff processes (Vereecken et al., 2022). Over a century ago, soil physicists developed the laboratory-scale matrix flow theory, which is still widely used in so-called "physically-based" hydrological and land surface models (LSMs) (Brutsaert et al., 2015; Xie et al., 2020). This theory describes flow in porous media based on equations that depend on soil hydraulic properties (e.g. porosity, hydraulic conductivity), which are typically ~~associated to~~ soil texture classes (e.g. clay, loam, sand). Darcy’s law describes matrix flow under saturated conditions through a porous medium

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under a head gradient. Richards' equation regards matrix flow under unsaturated conditions in the vadose zone, determining water flow direction and velocity. The matrix flow in most cases is regarded as a well-established theory, much like classical mechanics. To simulate catchment hydrology, matrix flow equations have been extended to distributed physically-based models, cutting catchments into rectangles or triangle fragments, and using topography to drive soil water movement vertically and laterally (Duffy, 1998; Refsgaard et al., 2022). The water infiltration and vertical redistribution in most land surface models are also based on simplified Richards equations, for example in diffusivity form (Vereecken et al., 2019). These models generally require many space and soil-dependent parameters that require substantial calibration and generally lead to equifinality.

However, by tracer field experiments, such as dye and isotope studies, matrix flow has been scarcely observed, simply because a well-prepared homogenous soil under lab conditions does not exist in nature. Most soils contain crevices, preferential channels, and openings that transmit free water quite rapidly to the sub-surface, which is termed as preferential flow (Beven and Germann, 1982; McDonnell et al., 2007; Beven, 2018; Zehe et al., 2021).

To allow for preferential flows, modelers proposed more complicated models, which involved even more free parameters to fit with observations. Unlike matrix flow, which has clear description of water movement in homogenous porous media, it is much more challenging to describe preferential flow by succinct mathematic equations. Although there have been dual-continuum, dual-porosity, or dual-permeability modifications (Jarvis et al., 2016), most models are still based on matrix flow theory (Weiler, 2017). Because of the extreme complexity of soil preferential flow in nature, it is extremely hard, if not impossible, to develop an accurate model to describe and predict even microscale water movement, the challenge is exponentially greater when we upscale preferential flow from spot-scale to hillslope or catchment scales (Davies et al., 2013; Germann, 2014; Or, 2019). However, this increase of model complexity, with more free parameters to calibrate, did not show a clear improvement in the simulation of soil moisture, groundwater head, and discharge (Glaser et al., 2019).

From the beginning, preferential flow theory was regarded as the main culprit challenging the

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foundation of physically-based hydrological models, but it did not help the model builder. The focus on preferential flow appeared not to shed light on a solution, but rather made the fog even denser.

Both matrix flow and preferential flow models are based on the *a priori* assumption that: soil properties are key in describing hydrological processes. In this study, we question the general validity of this assumption, and ask whether thinking outside of the box of the soil-based modelling framework ~~could~~ promote alternative, perhaps simpler theories, that help explain the observed patterns of hydrological variability.

3 Does soil variability matter in catchment hydrology?

3.1 ~~Does soil influence~~ the long-term water budget

~~Globally, b~~ased on ERA-5 data (the fifth generation of ECMWF atmospheric reanalysis), annual average terrestrial precipitation (P) is 745 mm/yr (111 km^3/yr), of which 440 mm/yr (65.5 km^3/yr, 60% of P) returns to the atmosphere as evaporation (E), and 305 mm/yr (45.5 km3/yr, 40% of P) generates runoff (Q) (Figure 1). ~~It is clear that~~ evaporation rather than runoff is the dominant flux after precipitation.

For terrestrial evaporation, the total global land area is 145 million km^2, of which 104 million km^2 (72%) is vegetated. Of total evaporation (E_{total}), soil evaporation only happens in the topsoil, with a limited amount, only 6% of E_{total} (Good et al., 2015). As evaporation from vegetation and ground interception accounts for 27%, transpiration is the largest flux at about 60-70% of E_{total} (Coenders-Gerrits et al., 2014; Lian et al., 2018). An increasing number of studies confirmed that landuse change, e.g. deforestation and afforestation, significantly alter runoff generation (Fenicia et al., 2009; Nijzink et al., 2016; Sun et al., 2020). Thus, vegetation, and more correctly the ecosystem~~, rather than soil,~~ is the determining factor of the global and catchment water balance.

3.2 Do soil-centred models reproduce observed patterns ~~of hydrological variability~~?

In reductionist thinking the lead paradigm is that "the whole is the sum of the parts" (Sivapalan et al., 2003). Bottom-up models are developed on the basis of small laboratory-scale laws, where the

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assumption is that microscale laws remain valid after upscaling. Due to the difficult-to-measure soil hydraulic properties (SHPs), such as the water retention characteristics, unsaturated and saturated hydraulic conductivity, modelers have used soil pedotransfer functions (PTFs) to correlate readily available soil properties, such as soil texture (i.e. sand-, silt-, clay-content), organic matter, and bulk density with SHPs (van Looy et al., 2017; Or, 2019).

There are several critical issues with this approach, which result in inevitable biases: 1) most soil property parameters are measured by pedologic surveys, at great expense and efforts (Van Looy et al., 2017). Due to limited field measurement, most soil property maps rely on uncertain interpolations and upscaling, which are based on soil-forming factors such as climate, parent material, topography, biota, and time (van Looy, 2017); 2) PTFs are usually obtained by using measurements from uniform soil samples, and performed in laboratory-scale experiments, which merely reflect disturbed and therefore unnatural conditions; 3) the parameters obtained at the laboratory scale are not necessarily the same at the modelled scale, which requires upscaling assumptions, which are difficult to verify, or recalibration, which is hampered by equifinality; 4) as emerging properties are scale-dependent, the processes that are important at lab or plot scale are not necessarily important at catchment scale (Blöschl and Sivapalan, 1995).

Figure 1. is a nice illustration of how a "physically based" model, making use of detailed soil information, can make completely wrong predictions under extreme circumstances (Beekman et al., 2014). On average, these models may function adequately, as almost all hydrological models do under average conditions, but the example of Figure 1. shows how during a relatively extreme drought in The Netherlands the modelled evaporation diverts considerably from observations.

The observed evaporation was obtained by interpolation of eddy-covariance and lysimeter observations using ETLook, an energy balance-based evaporation product (Bastiaanssen et al., 2012). The modelled evaporation was generated by the dominant Dutch hydrological model (NHI) which heavily relies on detailed soil maps and soil observations. The June 2006 picture in the lower part, in fact, mimics the soil map. Red (high evaporation) is seen on clay soils and purple (almost no evaporation) on sand. It is funny to see that in reality (top right) the forested sandy part at the centre of The Netherlands was evaporating lushly, whereas in the model (bottom right), this

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ecosystem appeared to be dead. In fact, all ecosystems continued ~~to evaporate well~~ during this dry month. Apparently, the ecosystems had prepared for this eventuality and had created enough root zone buffer to overcome this period of drought.

Although such mismatch between distributed model outputs and observed patterns are not infrequent, they are typically not regarded as a challenge to the basic model assumptions, but rather, as a problem associated to the uncertainty in model inputs. Hence, such soil-centred hydrological models remain vivid under the hope that "novel, highly resolved soil information at higher resolutions than the grid scale of LSMs may help ~~in~~ better quantifying sub-grid variability of key infiltration parameters" (Vereecken et al., 2022).

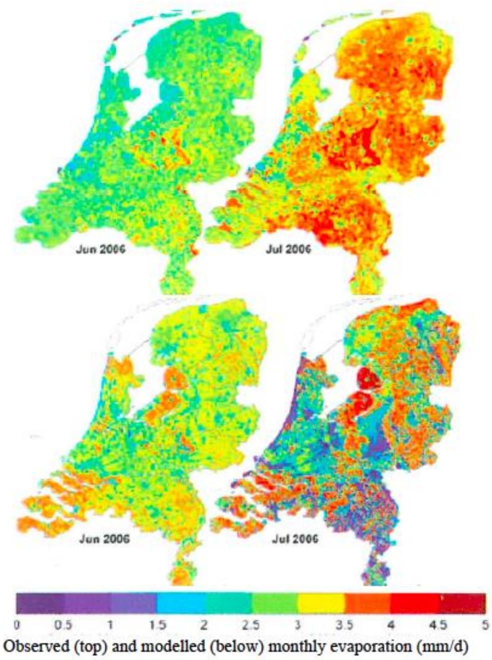

Figure 1. Evaporation during June (left) and July (right) of 2006 in The Netherlands. Modelled below and observed on top (from Beekman et al., 2014)

3.3 Is soil a good predictor for hydrological signatures?

The top-down approach, as a genuine way of learning from data, is amenable to systematic learning and hypothesis testing (Sivapalan et al., 2003), ~~which is~~ more suitable to understand the

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complex hydrological system. There are many predictors for hydrological signatures, including climate, vegetation, topography, geology and soil. Interestingly, in catchment hydrology, soil properties are often a poor predictor of hydrological signatures. Addor et al., (2018) used 671 catchments in the USA and found that, compared to soil, landscape features, i.e. vegetation and topography, have stronger correlations with hydrologic signatures, not only for mean runoff, but also for high-flow, low-flow, and runoff seasonality (Figure 2).

The soil may be important for small scale (agricultural) hydrology, but this importance is easily overridden by other factors at larger scale, for example climate, topography, vegetation, and geology. All these factors are intertwined, and result in preferential flow not only in the soil profile, but for all hydrological processes at multi-scales (Uhlenbrook, 2006), ranging from fingering, macropores, forest canopy, leaves, roots, fractures, rills and gullies, all the way to the river network, and even in the groundwater system (Savenije, 2018). These preferential flow patterns have great influence on all hydrological processes, including infiltration, percolation, groundwater discharge, and river channel routing (Rodrigues-Iturbe and Rinaldo, 1997; Sivapalan, 2006; Savenije and Hrachowitz, 2017). The infiltration capacity, in the absence of vegetation, may be a determining factor for infiltration excess overland runoff (Hortonian flow), but this scarcely occurs in natural vegetated landscapes where the ecosystem facilitates infiltration, even in arid regions (Zhao et al., 2019). In mature ecosystems, runoff is dominated by subsurface flow, which is a storage-discharge relationship. The preferential flow path, as the connector between small- and large-scale observations, makes the surface, rootzone and ground water systems react to rainfall as an integrated fill-and-spill system (Tromp-van Meerveld and McDonnell, 2006). This allows modellers to merely focus on input-output and storage change, to reproduce the complex rainfall-runoff processes through the heterogeneous but fractal patterned surface and subsurface.

Interestingly, in practice, simple catchment hydrological models, even without explicitly considering detailed matrix flow or preferential flow, can reproduce complex rainfall-runoff processes, with surprisingly good performance. The reliability and robustness of the widely used HBV (Seibert, 2018), GR4J (Perrin et al., 2001), Xinanjiang (Zhao, 1992), and FLEX (Fenicia et al., 2011; Gao et al., 2022), have been tested and validated in a wide range of regional and global

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hydrological studies (Bergström and Lindström, 2015; Mao and Liu, 2019; Wang et al., 2021). There are also examples of distributed models that describe the observed variability of hydrological signatures without relying on soil information (e.g. Boer-Euser et al., 2016; Fenicia et al., 2016; Gao et al., 2019; Dal Molin et al., 2020; Fenicia et al., 2022).

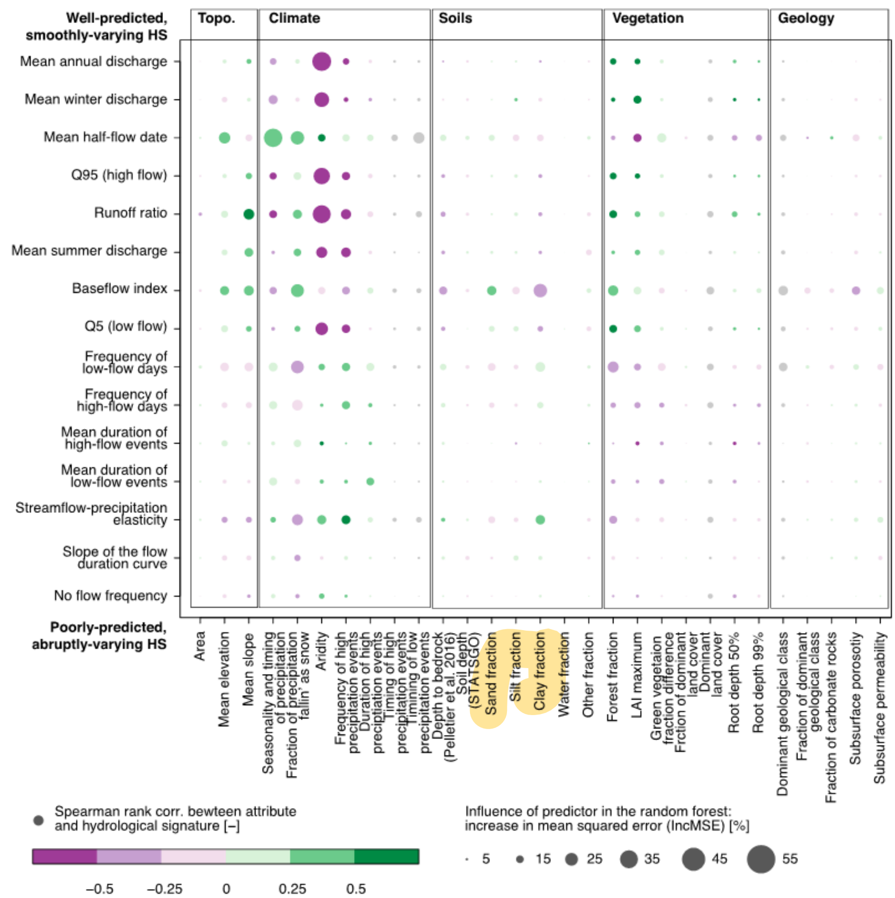

Figure 2. Comparison of the influence of catchments attributes and hydrological signatures for 671 U.S. watersheds (from Addor et al., 2018). Large, brightly coloured circles imply strong correlations and high influence. (Reprinted by permission of John Wiley and Sons).

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4 Putting the ecosystem at the centre of hydrology

4.1 The ecosystem is the ultimate water manager

Engineering hydrologists have a long tradition to focus on runoff generation, which represents at the same time the most valuable water resources and the cause of water related disasters, i.e. floods and droughts. There is limited realisation that runoff is merely the ecosystem's by-product of water use (Bonan, 2015), only accounting for 40% of the precipitation, while the ecosystem evaporates 60% of precipitation back to the atmosphere in its drive to grow and survive.

A natural ecosystem can only survive if it organizes its resilience. This resilience requires not only sufficient moisture storage in the root zone, to overcome critical dry spells, but also sufficient infiltration capacity and subsurface drainage to maintain moisture levels between acceptable boundaries: not too wet and not too dry. If given sufficient time, the ecosystem will improve the infiltration capacity both to replenish water in the root zone and to prevent runoff; seldom do we observe surface runoff in a natural environment. The ecosystem creates preferential flow paths that facilitate infiltration in order to retain nutrients and soil particles and to direct rainfall to where it is most needed. If there is too much infiltration, then sub-surface drainage by preferential recharge and sub-surface drainage patterns on hillslopes evacuates excess water. Preferential flow rapidly delivers the excess water, bypassing the rootzone, to the groundwater system (McDonnell, 2014). By wave propagation the groundwater head created by the recharge pushes pre-event groundwater to the streams (Kirchner et al., 2003; Hrachowitz et al., 2016; Worthington, 2019) also through preferential flow patterns (Savenije, 2018). In summary, prevailing preferential flow paths, mostly as a result of a variety of biological activities, determine rainfall partitioning and runoff generation, moving beyond plot-scale heterogeneity and process complexity, where landscape and ecosystem are the determining factors rather than the soil.

Modelers utilizing a bottom-up approach also noticed that the simple paradigm of using soil texture as a main predictor of SHPs is problematic (Bonetti et al., 2021). Gutmann and Small (2007) have shown that soil textural classes, across a range of climates and vegetation covers, merely explained 5% of the variance obtained from the real SHPs. It was found that 95% of the default soil parameters in a state-of-the-art landsurface model were significantly different from

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region-specific observations (Kishné et al., 2017).

With the biased observation and the scale effect, modelers need to recalibrate numerous free parameters. There are studies that "rebalance" the soil texture information and highlight the importance of soil structure, originated by soil biophysical activity (Or, 2019; Fatichi et al., 2020). These models do not directly use field measurements of the soil, but "rebalance" the observed soil texture and translate it to soil structure by vegetation indices, e.g. the aboveground vegetation biomass and leaf area index (LAI) (Bonetti et al., 2021). Involving vegetation cover and productivity prominently improved the hydrologic response with respect to runoff generation, infiltration and drainage (Or, 2019). Not only the physically-based models, but also the empirical soil-based models, for example the soil conservation service (SCS) method in SWAT model (soil water assessment tool), also involve landuse data to "rebalance" the soil-based curve number in catchment simulation (Arnold et al., 2012).

4.2 The rootzone is the key element in hydrology not the soil

Vegetation as a living organism optimizes its rootzone water storage to stabilize water supply at minimal carbon cost, and sometimes access to the deeper groundwater, to cater for periods of drought (Gao et al., 2014; McCormick et al., 2021). From a hydrology perspective, the vertical profile of the critical zone can be divided into different layers, i.e.: canopy, litter layer, root zone, water transition zone, unconfined groundwater, and confined groundwater. The most active layers in the critical zone defining rainfall partitioning and related hydrological processes include: the canopy, litter layer, and root zone. Globally, the vegetation interception storage capacity of terrestrial ecosystems is about 1-2 mm, estimated by remotes sensing LAI data (De Roo et al., 1996). The litter layer storage capacity differs in different ecosystems, but it is likely to increase the total interception storage capacity to around 2-5 mm (Shi et al., 2004). For determining the rootzone storage capacity of ecosystems, the mass curve technique appeared to work well locally and globally (Gao et al., 2014; Wang-Erlandsson et al., 2016) whereby use was made of ERA-5 evaporation data to estimate, resulting in a global average root zone storage capacity of 228 mm (Figure 3). Hence, rootzone storage capacity is significantly larger than interception and litter layer water storage capacities. Beneath the rootzone, water in the transition zone between root

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zone and groundwater ~~and the unconfined groundwater does not have phase changes,~~ and will be discharged as runoff under natural condition. The deep confined groundwater has a very long transit time, without much connection to surface processes, and is not considered in surface runoff calculation in most cases. Hence, the root zone storage plays ~~the~~ dominant role in catchment hydrology, determining how catchments respond to rainfall.

It is worthwhile noting that rootzone and soil have a strong connection, but are essentially different things. The soil profile can reach over hundreds of meters' depth, e.g. the Loess Plateau in China (Zhang et al., 2014), of which only the rootzone is the active ~~area, whereby the soil is merely the substrate of it~~. Rootzone storage can also be larger than soil water storage, for example in karst mountainous areas where soil is thin and discontinuous, bedrock storage serves as an important source of plant-available water (McCormick et al., 2021). Rootzone water storage is a more accurate term ~~in hydrology,~~ which cannot be measured directly, but with clear physical meaning, similar to the runoff depth and runoff efficiency.

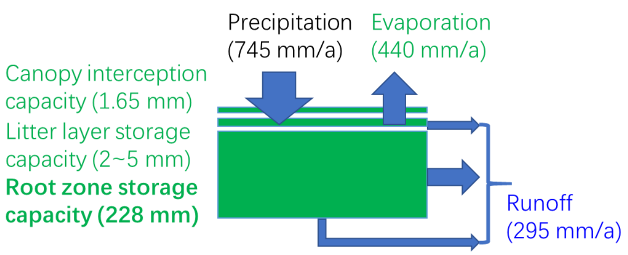

Figure 3. The importance of root zone storage capacity in catchment hydrology. All the numbers are global average values ~~in~~ vegetated area, obtained by ERA-5 data from 1980 to 2020.

4.3 Landscape-based model: the giant view of hydrology

A soil-based model is like an ant's perspective, observing a complex world of heterogeneities and randomness. Landscape, as the integration of topography and landcover, being the long-term co-evolution of ecosystem, atmosphere, lithosphere, pedosphere, hydrosphere, and human activities (Mücher et al., 2010; Wu, 2013; Troch et al., 2015) is rather the giant's perspective (Savenije, 2010). The pattern of hillslope, landscape and catchment only becomes visible when we zoom out well beyond the microscale of the soil or the human scale, for that matter.

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At landscape scale, hydrological laws can be simple: the fill and spill bucket model with thresholds and associated time scales and the linear reservoir for groundwater are physically-sound at hillslope and catchment scale (Savenije, 2010; Fenicia et al., 2011; Savenije and Hrachowitz, 2017). Landscape-based models also use conservation of mass and energy, but momentum transfer is made of conceptual relations that relate discharge to storage using landscape and ecosystem characteristics, such as travel times and a probability function for runoff thresholds. Geology as the substrates of hydrological processes also plays an important role on slow processes. Interestingly, the underground hydrogeology system seems also self-organized and structured (Savenije, 2018). For example, the recession parameter *k* is around 43 days in worldwide catchments regardless of their climate, topography, soil, and geology (Brutsaert and Sugita, 2008). Discovering these properties and related signatures benefit our understanding and prediction of the dynamic adaption of ecosystems to environmental change, and the subsequent impacts on hydrology (Gharari et al., 2014).

Explosive growth of remote sensing technology and powerful geographic information system (GIS) toolkits provide unprecedented opportunities, with a giant's view, to closely read landscapes and monitor their hydrological components in high spatial and temporal resolutions (Duan et al., 2021; Crow et al. 2022). Various measurement techniques, e.g. eddy covariance, make it possible to quantify the mass and energy budget at landscape scale (Jung et al., 2020; Lan et al., 2021). The GRACE satellite provides independent estimates of moisture storage on Earth (Famiglietti et al., 2015; Dong et al., 2022). These datasets form crucial complementary information to constrain landscape-based model parameters, validate the internal fluxes, and eventually give more physically-based and reliable simulation (Winsemius et al., 2006; Nijzink et al., 2018; Gao et al., 2020).

5 Why is the soil-based modelling tradition so rooted in hydrology?

Occam's razor tells us "Entities are not to be multiplied beyond necessity". This principle gives precedence to simplicity: of two competing theories, the simpler explanation of an entity is to be

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preferred. Therefore, if soil does not play a significant role neither in the water balance nor in rainfall-runoff processes, and if disregarding soil does not significantly affect model performance, there is sufficient and fair reason to exclude soil properties in hydrological modelling. But then: why are soil-based models so rooted in hydrology?

5.1 Agricultural bias

Since hydrology was born from chapters of agricultural and hydraulics textbooks (Rodríguez-Iturbe and Rinaldo, 2004), the misunderstanding that soils are the determining factor in hydrology is probably caused by the “agricultural bias”. In agriculture, the focus is on seasonal crops. A seasonal crop has limited time to develop a root zone storage that can buffer for longer term variability. At best, it can buffer for average dry spells that may occur within an average year. This is why modern agriculture requires water management by the farmer to buffer for natural fluctuations. In agriculture, ploughing destroys preferential infiltration and sub-surface drainage. It also limits the root zone storage capacity to the relatively small soil layer above the plough pan. In such cases it is indeed the moisture holding capacity of the soil that determines the root zone storage capacity.

As regards evaporation, it occurs in many ways: by transpiration, direct evaporation from leaf and ground interception, bare soil evaporation, open water evaporation, sublimation, ~~and in general from all phase changes where liquid or solid water turns into vapour~~. All these mechanisms obey different constraints and need to be modelled separately to arrive at a correct representation of total evaporation. In that respect, the dominant widely used Penman-Monteith equation, so successful in agriculture, is likely not appropriate to describe land-atmosphere interaction. Unfortunately, this “agricultural bias” has been dominant in most hydrological work. We argue that this deeply rooted soil-based perception may limit or even mislead the further development of hydrological science, especially for next generation professionals.

5.2 Unreliable intuition

Hydrologists intuitively concern about soil.~~ It~~ could very well by the perspective of the ant that causes it. As people, we are just too small to observe the larger scale processes that dominate landscape hydrology. We tend to dig holes in the Earth and try to infer larger scale behaviour from

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what we observe inside this hole. The human scale prevents us from seeing the larger picture. We need the giant's perspective to recognise the patterns present in the landscape.

At the human scale, assuming that soil properties, such as texture and porosity, matter makes intuitive sense. People tend to describe what they see (i.e. the consequence) rather than the cause, and if they see water flowing or disappearing in the ground they think that it is because of such soil properties. The role of the ecosystem as the driver is much more difficult to recognize, because it is hidden to the eye. It requires seeing the environment as a living thing, which continuously evolves and adjusts to changing circumstances. It also implies that the hydrological properties are not constant over time. The root zone storage, the most critical control on rainfall-runoff processes, is continuously changing in response to changing climatic and human drivers. Instead of describing the 'now' as an invariant and static condition, with environmental properties ~~as a given~~, one has to think of the history that determined these environmental conditions, which much more difficult to realise.

6 Conclusion

~~Hydrology is the blood stream of the ecosystem.~~ Runoff is merely the excess water after precipitation has replenished ecosystem's water deficit. Traditional "physically-based" models put soil physical properties at the heart of hydrology which is misleading for both process understanding and model development. In contrast we need an ecosystem-centred approach. ~~Nowadays there is much concern about the Critical Zone of the Earth, where virtually all life takes place.~~ The ecosystem is the ultimate manager of the critical zone, with hydrology as its blood stream. We advocate a paradigm shift to put ecosystem and landscape at the heart of terrestrial hydrology, and develop holistic and ~~alive~~ ecosystem-based hydrological models, with better representation of hydrological processes in Earth system science.

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