Proceedings RootS25
3rd International Workshop on Soil-Vegetation-Atmosphere Interaction
Boldrin D, Cecconi M, Cotecchia F, Leung A, Pedone G, Perrini P, Romero E, Tagarelli V, Zdravković L (eds)
ISSN: 3107-300X

doi: doi.org/10.53243/RootS2025-17

Is soil the soul of hydrology?

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ABSTRACT: Soil hydraulic properties are central to the functioning of hydrological processes at the catchment scale. Traditionally, these properties are assumed to be primarily determined by soil texture—a foundational assumption embedded in many hydrological theories and models. This contribution challenges that paradigm, proposing instead that vegetation—and more broadly, the ecosystem—plays a dominant role in shaping soil hydraulic properties. This shift in perspective suggests that soil hydrological behaviour may be inferred from vegetation characteristics. In this view, hydrological processes can be simulated without requiring direct measurements of soil properties, yet still grounded in physical principles. Furthermore, it implies that for hydrological models to remain predictive under environmental change, they must account for how vegetation dynamically adapts to water availability. The contribution illustrates this approach using simple conceptual hydrological models and how it connects to larger scale analyses.

Keywords: Root zone; soil; hydrological models

1 INTRODUCTION

Virtually all hydrological models that simulate the hydrological cycle and its key processes must represent the soil compartment in some way. Soil hydraulic properties (SHPs) play a crucial role in determining how much water infiltrates into the ground, how much percolates to deeper layers, how much runs off the surface, and how much is retained in storage.

Physically based models, which explicitly describe these processes using the theory of flow in porous media, are typically formulated at the so-called representative elementary volume (REV) scale (Fatichi et al. 2016). The fundamental equation governing flow in unsaturated porous media is the Richards equation. Soil hydraulic properties appear in this equation through two closure relations — the soil water retention curve, $\Theta(\psi)$, and the hydraulic conductivity function, $K(\Theta)$, where Θ is the relative saturation, ψ is the pressure head, and K is the hydraulic conductivity.

Conceptual models, typically developed to represent hydrological processes at the catchment scale, describe the soil compartment as a simple reservoir characterized by a maximum storage capacity (Fenicia et al. 2025). The relative saturation within this reservoir, Θ, primarily controls runoff generation, expressed as $Q_u/P=f_Q(\Theta)$, where Q_u is runoff and P is precipitation, and actual evaporation, expressed as $E_u/E_P=f_E(\Theta)$, where E_u is actual evaporation, and E_P is potential evaporation. These functions act as closure relationships that represent the soil's hydraulic behaviour. Depending on the specific model structure, other processes—such as percolation to deeper soil layers—may also be represented as functions of Θ.

Regardless of whether a physically based or conceptual model is used, soil hydraulic properties cannot be directly measured at the relevant scales. The reason is primarily practical. For physically based models, obtaining the necessary data would require extensive sampling—essentially riddling the catchment with holes to characterize spatial variability. For conceptual models, direct measurement would demand quantifying fluxes and storages over areas of several square kilometers, which is well beyond feasible observational capability.

There have therefore been numerous attempts to relate soil hydraulic properties to measurable soil characteristics, such as soil texture. Because soil texture maps are widely available, texture has often been used as a proxy variable in hydrological models. Pedotransfer functions (PTFs) have been developed for this purpose — empirical, regression-based, or machine-learning models that estimate soil hydraulic parameters (or entire retention and conductivity curves) from easily measured soil attributes such as texture (sand, silt, and clay fractions), bulk density, organic matter content, and porosity. Today, PTFs represent the standard approach for linking soil texture to hydraulic properties in hydrological modelling.

Traditional PTFs are developed primarily for agricultural soils in temperate climates, and have shown limitations in predicting SHPs, especially under natural conditions. These models often overlook the influence of parent material, vegetation, land use, and climate on SHPs (Weber et al. 2024).

At the microscale, SHPs are significantly affected by preferential flow, a phenomenon not solely dependent on soil texture but also on soil evolution and structure. Recent research has highlighted the importance of incorporating soil structure corrections into PTFs. Bonetti et al. (2021) proposed a framework that integrates remotely sensed vegetation metrics with local soil texture to adjust PTF-derived saturated hydraulic conductivity, accounting for biologically induced soil structure.

While PTFs are practically useful, they are essentially regression models that identify correlations rather than causal mechanisms. They indicate which factors are important for soil hydraulic properties but do not explain why these factors exist or how they are interconnected.

In order to provide a interpretative framework, we proposed an ecosystem perspective (Gao et al. 2023). According to this perspective, vegetation actively shapes soil properties to support its survival and growth. Its persistence during dry periods demonstrates the need for access to water, implying that vegetation modifies soil to store sufficient moisture during dry spells. At the same time, vegetation minimizes surface runoff, which can cause erosion—consistent with the observation that runoff is rarely seen in undisturbed natural environments. Thus, vegetation appears to balance two competing demands: retaining enough water for survival while removing excess water to prevent soil damage.

This simple perspective can also inform hydrological modeling by providing a conceptual basis for estimating key parameters in a reservoir-type representation of the soil compartment. The aim of this work is to illustrate this perspective through a simple case study that captures its essential features, while referring to other studies for more advanced developments. More broadly, the intention is to encourage a widening of hydrological modeling frameworks to explicitly incorporate ecosystem functioning, thereby enhancing their predictive capability under changing climatic conditions.

2 METHODS

Figure 1 shows a typical conceptual model structure. The model consists of a threshold reservoir (UR), which controls the partitioning of precipitation between infiltration, discharge, and evaporation, as described in Section 1. Discharge from the UR is then divided between a fast reservoir (FR) and a slow reservoir (SR), both of which are linear. The UR controls partitioning of precipitation between infiltration, discharge, and evaporation, following quadratic transition functions similar to those in GR4J (e.g. Fenicia et al. 2025). The quadratic form ensures a smooth threshold between wet and dry regimes, facilitating behavioural realism.

Such simple conceptual models, which are abundant in the hydrological literature, aim to reproduce the hydrograph response with minimal complexity while maintaining interpretability. Each model component has a clear and identifiable function within the hydrograph: the FR and SR reservoirs represent the fast and slow responses, respectively, while the UR reservoir reflects the variability of the runoff coefficient. This coefficient governs how much precipitation becomes streamflow, a quantity known to vary significantly, particularly on a seasonal basis.

The hydrological model described takes as input Precipitation and Potential Evaporation, and outputs streamflow Q. It has four tunable parameters: the maximum storage of the UR reservoir (S_{uMax}), the partitioning coefficient (C), and the timescales of the fast (FR) and slow (SR) linear reservoirs. While all these parameters can be calibrated, our goal here is to estimate them directly from data.

The reservoir timescales can, for example, be estimated by fitting a straight line to the hydrograph on a logarithmic Q-axis. The partitioning coefficient C corresponds to a baseflow index, which can be readily determined using baseflow separation techniques. Our primary focus is on S_{uMax}, which we calculate using a simple mass balance approach.

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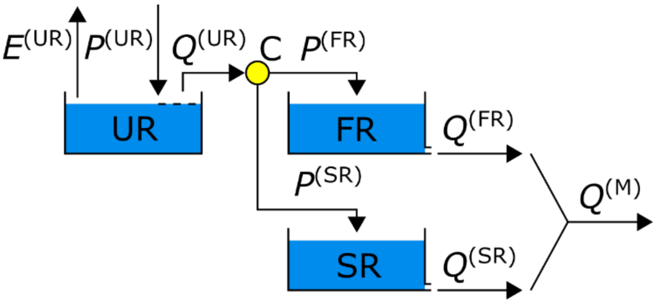

Figure 1. Conceptual model structure showing the upper reservoir (UR), fast (FR), and slow (SR) reservoirs. The UR uses quadratic transfer functions to smooth threshold behaviour, similar to GR4J. Inputs are precipitation (P) and potential evaporation (EP); output is streamflow (Q)

In particular, we calculate the maximum water deficit using the provided precipitation and potential evaporation time series. We apply simple reservoir-sizing principles commonly used in engineering. Conceptually, one can plot cumulative inflow and cumulative demand over time. Whenever cumulative demand exceeds cumulative inflow, the difference must be supplied from storage. The largest vertical gap between the demand and inflow curves represents the required reservoir capacity. In our case, inflow is represented by precipitation, and demand by evaporation.

Mathematically, the required storage is expressed as:

$$S_{\text{required}} = \max_{t\in[0,T]} \left\{ 0, \int_0^t [E(\tau) - P_{\text{in}}(\tau)]\, d\tau \right\} \quad (1)$$

This operation can be done for each hydrological year in the time series, to obtain a population of required storages to bridge dry spells. The value to be used can be related to the life expectancy of a particular type of vegetation (Gao et al. 2014). In this study, we adopt 90% of the maximum to represent an adaptive, conservative design choice reflecting incomplete utilisation of total capacity.

A full quantitative comparison, including performance metrics such as NSE, is beyond the scope of this short contribution but is available in Gao et al. (2014), which analysed multiple catchments and demonstrated strong correspondence between inferred and observed storage dynamics.

3 RESULTS

Figure 2 top panel shows the Precipitation and Potential Evaporation daily time series at the Ettelbruck catchment in Luxembourg. The bottom panel shows the dynamic storage, starting from the beginning of the hydrological year (here September). The maximum storage deficit is around 150mm, which provides an estimate for S_{required}. Note that the storage deficit is reset to zero whenever the cumulative P exceeds the cumulative E.

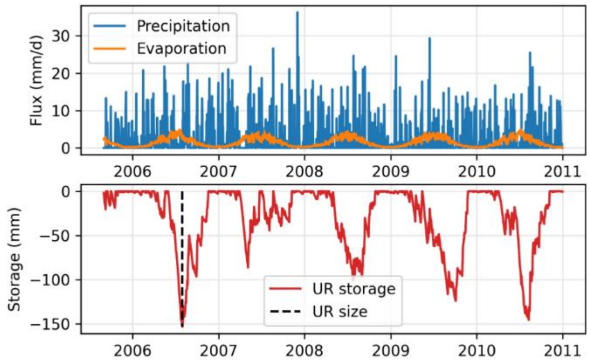

Figure 2. Upper panel: precipitation and evaporation at the Ettelbruck catchment in Luxembourg (2006–2011). Lower panel: Dynamic storage deficit calculated from cumulative fluxes, with a maximum of≈150 mm

Figure 3 show the simulation of the model for the entire hydrograph. One can see that the models capture behaviourally the threshold like response, with the discharge onset at the beginning of the wet season.

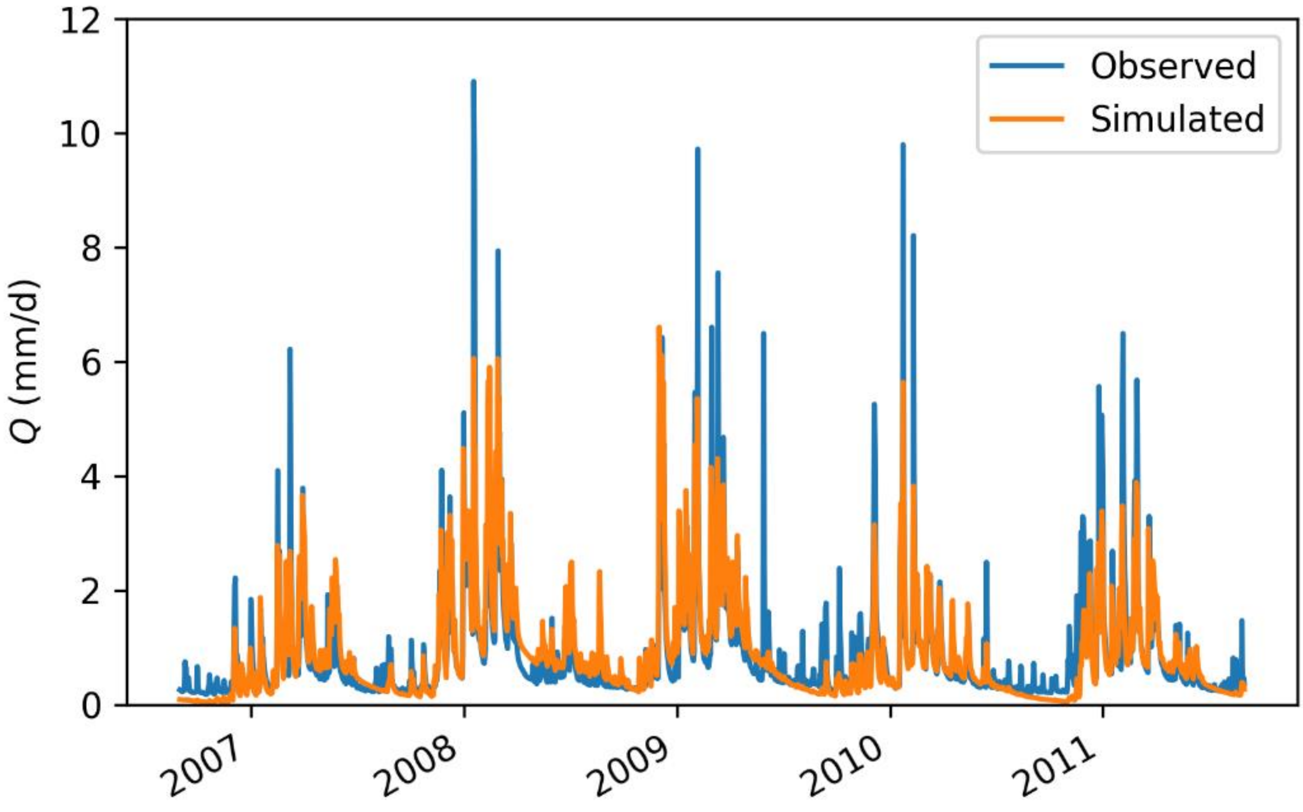

Figure 3. Simulated streamflow for the Ettelbruck catchment using parameters estimated directly from climatic inputs. The simulation captures the threshold-like onset of flow at the start of the wet season

4 DISCUSSION

How the rooting-zone water-storage capacity—the amount of water accessible to plants—varies spatially remains largely unknown and cannot be directly observed. From an ecosystem perspective, this capacity emerges from the co-evolution of vegetation and soil, as plants modify soil structure to balance water retention and drainage for survival. The ecosystem-based approach thus provides a simple yet physically grounded means of estimating this otherwise unobservable property. At larger scales, Stocker et al. (2023) derived global estimates of rooting-zone capacity, demonstrating how the concept scales from catchment to continental levels. Recently, this approach has been used to investigate the adaptation of ecosystems' root zones to climate change (Xi et al. 2025).

This approach compels a broadening of perspective—from traditional hydrological models, which primarily describe physical fluxes and storages, to ecohydrological frameworks that explicitly account for biological regulation and feedbacks between vegetation, soil, and climate. It highlights how ecosystems not only respond to hydrological conditions but actively shape them to sustain function and resilience under changing environmental constraints.

5 CONCLUSIONS

This work illustrates how an ecosystem-based perspective can complement traditional hydrological modeling by considering the role of vegetation in shaping soil hydraulic properties and regulating water storage. By linking simple reservoir-based representations with ecological reasoning, the approach offers a practical way to estimate rooting-zone water-storage capacity from climatic inputs. Although simplified, this framework provides insight into how vegetation and soil co-evolve to balance water retention and drainage under varying environmental conditions. Such integration of hydrological and ecological perspectives may support improved understanding of soil–plant–water interactions and their response to climate variability.

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