https://doi.org/10.5194/egusphere-2025-1927
Preprint. Discussion started: 12 June 2025

Soil physico-chemical indicators for ecosystem services: a focus on water regulation

Binyam Alemu Yosef[1], Angelo Basile[1,2], Antonio Coppola[3], Fabrizio Ungaro[4], and Marialaura Bancheri[1,2]

[1]Institute for Mediterranean Agricultural and Forestry Systems (ISAFOM), National Research Council (CNR), Piazzale E. Fermi, 1, Portici, NA 80055, Italy
[2]CRISP Research Center, Department of Agriculture, University of Napoli Federico II, Via Università, 100, Portici, NA 80055, Italy
[3]Department of Chemical and Geological Sciences, University of Cagliari, Via Università, 40, Cagliari 09124, Italy, Cagliari, Italy
[4]Institute of BioEconomy – National Research Council (IBE-CNR), Via Madonna del Piano 10, 50019 Sesto Fiorentino, Italy

Correspondence: Marialaura Bancheri (marialaura.bancheri@cnr.it)

Abstract. This study investigates the intricate relationship between soil properties and water-related processes, with a focus on their collective impact on ecosystem service provision, particularly water regulation. Conducted in three diverse regions Marchfeld (Austria), Bologna (North Italy) and Rmel (Tunisia), the research aims to identify key soil properties that influence water infiltration (INF), groundwater recharge (GWR), and crop water stress indexes (CWSI). Key soil characteristics such as saturated hydraulic conductivity (K_S), available water content (AWC), bulk density (BD), saturated water content (θ_s), organic matter (OM), clay content and soil depth were analyzed for their role in regulating water movement and the overall hydrological balance. Pairwise correlation and multiple linear regression analyses were used to assess the interactions among soil water balance processes and soil properties. The results reveal significant variations between regions in terms of the factors that control infiltration, groundwater recharge, and CWSI. For example, in Marchfeld infiltration showed a strong positive correlation with BD ($r = 0.74$, $p < 0.001$), while CWSI had the most significant negative correlation with soil depth ($r = -0.35$, $p < 0.001$). Futhermore, multiple linear regression models were developed to assess the relevance of the different soil properties and of their interactions on the components of the soil water balance. As an example, in Marchfeld, the model for infiltration ($r = 0.79$, $p < 0.001$) was highly predictive, incorporating Clay, OM and soil depth. These results emphasize the critical role of key soil properties K_S, AWC, BD, OM, clay content, θ_s and soil depth in controlling soil water processes. The study highlights the value of using these properties in predictive models to inform water management practices to optimize crop performance and soil conservation in different agricultural settings.

1 Introduction

Soil delivers a wide range of high-value functions, including food production, raw material supply, support for human activities, historical archiving, biodiversity conservation, organic carbon sequestration, and regulation of water and nutrient cycles (McBratney et al., 2017).

https://doi.org/10.5194/egusphere-2025-1927
Preprint. Discussion started: 12 June 2025

In fulfilling these functions, soils provide a variety of goods and services essential to human well-being and the advancement of sustainable socio-economic development, collectively known as "ecosystem services" (Costanza et al., 1997).

Despite soil's importance as a key component of terrestrial ecosystems, most studies - especially in the past - have focused on ecosystem services, such as provisioning, supporting, regulating, and cultural services, stemming from other ecosystem components, while placing little emphasis on soil itself (Costanza et al., 1997; MEA, 2005; Hewitt et al., 2015).

A decade ago, this represented the state of the art; however, significant progress has been made since then. Numerous projects and initiatives have emerged to highlight and deepen our understanding of the mechanisms driving the delivery of soil-based ecosystem services. Notable examples include the SERENA project (https://ejpsoil.eu/soil-research/serena), the SOB4ES project (https://www.sob4es.eu/), and the BENCHMARKS project (https://soilhealthbenchmarks.eu/) at the EU level, as well as the Global Soil Biodiversity Initiatives network (https://www.globalsoilbiodiversity.org/) at the global level.

More recently, emphasis has been placed on linking ecosystem services and soil functions with the state of soil health. For example, in Europe the *EU soil strategy for 2030* (SWD, 2021) 323 final - stated that "soils are healthy when they are in good chemical, biological, and physical condition and are able to continuously provide as many of the ecosystem services as possible". To achieve the goal of effectively evaluating soil health, there has been a notable increase in efforts to identify straightforward indicators and indices that can serve as proxies for soil processes, soil functions, and ecosystem services, thereby reflecting the overall health of soil in a simplified manner. Among the many studies on this topic, a few key bibliographic and review works include those by Bünemann et al. (2018); Rinot et al. (2019); Jian et al. (2020); Liu et al. (2020); Bagnall et al. (2023); Sellami and Terribile (2023).

However, soil is far more complex. The assumption (see Figure 1) that a single parameter or indicator can directly be linked to a soil process, function, and ecosystem service — and ultimately define soil health status — is optimistic at best, failing to account for the numerous interacting factors within the complex soil-water-plant system. A step forward in addressing soil's multi-functionality and variability requires quantifying multiple indicators and integrating them into a comprehensive index. However, as Lehmann et al. (2020) highlighted in their review of over 500 studies on soil health and quality, relatively few indices exist, with only five studies including a single soil health index. The limitation of inferring soil health solely from indicators (Figure 1) lies in overlooking the dynamic nature of soil, a complex time-dependent system (Lal, 2008). This is especially true for water-regulating services, where the dynamic component plays a critical role. In fact, the quantification and comprehensive study of water regulation services remain under explored, highlighting the need for further research into the role of soils in hydrological regulation. Here we provide examples of studies examining soil health in relation to water regulation services. Moebius-Clune et al. (2016) used wet aggregate stability and Available Water Capacity (AWC) as key indicators. Bagnall et al. (2022b) found that doubling soil organic carbon could nearly double the water storage capacity of soil. Another study by Bagnall et al. (2022a) tested several parameters—such as water-stable aggregate percentage, bulk density, permanent wilting point, field capacity (measured on both repacked and intact cores), saturated hydraulic conductivity, and soil organic carbon, revealing that field capacity measured on intact soil cores was the best indicator of soil physical health in relation to the water cycle. As part of the EU SERENA project under EJP Soil (https://ejpsoil.eu/soil-research/serena), information was collected on existing methods across 14 member states for evaluating soil-based ecosystem services. For

https://doi.org/10.5194/egusphere-2025-1927
Preprint. Discussion started: 12 June 2025

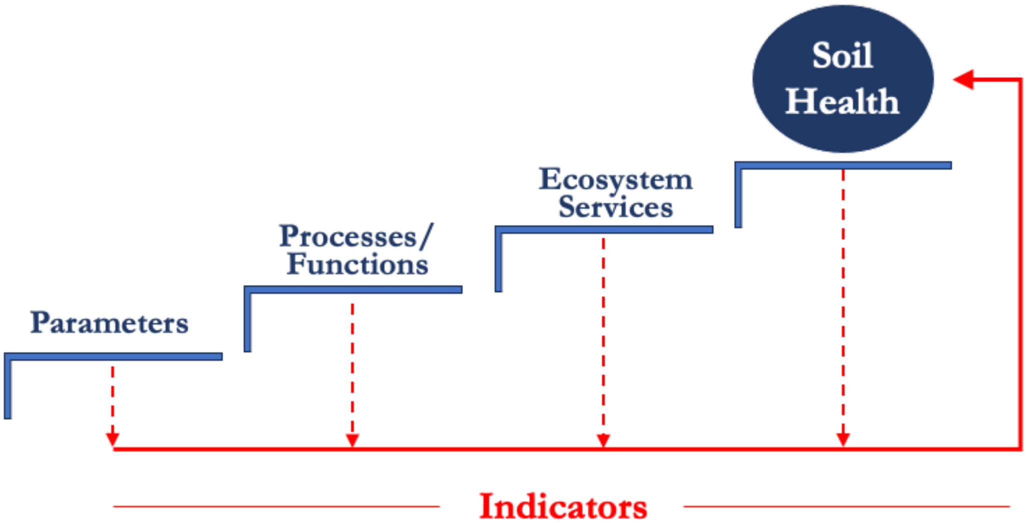

Figure 1. Schematic linkage of soil parameters, processes, functions, ecosystem services and indicators for soil health assessment

water regulation services (termed "hydrological control"), assessments primarily focused on AWC, followed by water drainage, evapotranspiration, runoff, and saturated hydraulic conductivity.

As previously highlighted, a substantial body of research investigates the relationships among indicators, processes, ecosystem services, and soil health. However, the extent to which an indicator represents a specific process is often assumed to be uniform across soils or derived from simplified schemes. Such schemes frequently overlook the vertical variability of soil properties—particularly hydrological characteristics—by presuming soil homogeneity. Furthermore, the climatic component plays a crucial role in driving the dynamic nature of soil processes, thereby influencing the parameters and indicators most relevant to each specific process. In conclusion, the impact of each indicator varies among soils and must be evaluated within the context of each soil's unique soil-plant-atmosphere continuum.

1.1 Aim

The knowledge gap addressed in this study concerns the extent to which two sets of indicators — simple/static versus complex/process-based/dynamic — align and provide coherent insights. Therefore, the aim of this work is to evaluate the efficacy of widely proposed physical and chemical soil parameters, namely, saturated hydraulic conductivity (K_S), available water content (AWC), bulk density (BD), organic matter content (OM), clay content, saturated water content (θ_s) and soil depth

https://doi.org/10.5194/egusphere-2025-1927
Preprint. Discussion started: 12 June 2025

(SD), as indicators and proxies for water-related soil functions and processes (the initial two steps in the staircase shown in Figure 1). Ultimately, this study evaluated how well these indicators reflect the ecosystem services provided by soils in terms of water regulation (the third step). The indicators are restricted to the upper soil horizon, consistent with the approach of most previous studies and projects, including the EU LUCAS database, which focus mainly on the topsoil layer. The analysis also considered the synergistic and interactive effects of these indicators. This evaluation used a process-based model, FLOWS (Coppola et al., 2024; Hassan et al., 2024), to simulate water flow within the soil-plant-atmosphere continuum across three distinct soil datasets, each characterized by different climatic conditions: from central Europe to the northern and southern Mediterranean regions.

2 Materials and Methods

2.1 Case studies

The process-bases FLOWS model was applied to three case studies representing distinct climate and soil's datasets, located in Austria, Italy and Tunisia (Figure 2).

Marchfeld region is located at the North-Eastern of Vienna, at a latitude of 48.20^0 N and a longitude of 16.72^0 E (Figure 2A). It covers an area of approximately 1000 km^2 and the climate can be classified as Temperate Continental Climate/Humid Continental Climate according to the Köppen classification (Geiger, 1954), with a mean annual precipitation of about 500–550 mm, an average temperature between 9 and 10^0 C and a mean annual reference potential evapotranspiration of about 800 mm. Geologically, the study area roughly coincides with the Quaternary alluvial plain in the central part of the Vienna Basin (Fusco et al., 2024), with a flat topography and an altitude within 160 - 180 meters a.s.l. The dominant soil types in Marchfeld are Chernozem and Para-Chernozem, Stagnic Phaeozem, Fluvisol and Anthrosol, characterized by humus-rich surface horizons and sandy deep horizons, followed by fluvial gravel from the former river bed of the Danube. Given the above conditions, the area is one of the primary sources of agricultural products in Austria, and winter wheat is one of the main cultivated crops.

Bologna province is located in Emilia-Romagna region (northeastern Italy), the study site lies at a latitude of 44.45^0 N and a longitude of 11.43^0 E (Figure 2B). The province of Bologna covers approximately 3703 km^2 and has a humid subtropical climate with a mean annual precipitation of approximately 644-1436 mm and an average temperature between 10.3 and 14.6 ^{0}C (reference period 1991-2015) and a mean annual reference evapotranspiration of approximately 1106 mm. The area, primarily dedicated to agriculture, extends south of the Po River, bordered by the Apennine mountain range to the south and the Adriatic Sea to the east. The climate of the Bologna province is categorized into seven climatic zones, referred to as BIC zones, based on the mean annual difference between precipitation (P) and reference evapotranspiration (ET). This classification system provides a detailed understanding of local climatic conditions. For more information, visit Arpae's BIC indicators page. Our study site is located within the second climatic zone (BIC2), characterized by a precipitation-evapotranspiration balance (P-ET) between -400 and -300 mm. The area extends approximately 60 km from north-east to south-west, running parallel to the Apennines chain, with a width varying between 6 and 12 km. It covers an area of approximately 632 km^2, with elevations ranging from 12 to 230 meters a.s.l. About 95% of the area is in the Bolognese Plain, where soil types reflect the age of the sediments

https://doi.org/10.5194/egusphere-2025-1927
Preprint. Discussion started: 12 June 2025

(i.e. Holocene vs. Pleistocene) and the differences in relief and geomorphology which characterize the typical pedolandscapes of the plain. Soils range from Vertisols in the depressions of the plain, to Fluvisols along the recent river banks, to Calcaric Cambisols in the levee areas, to ancient and weathered Chromic Luvisols along the Apennine border. The soils of the Bologna plain sustain intensive agricultural activities, which range, depending on local pedoclimatic conditions, from typical continental productions such as cereals and livestock farms, to Mediterranean crops (orchards, vineyards, vegetables) and cereals (Calzolari et al., 2016).

Rmel area is located in the North eastern part of Tunisia and it lies at a latitude of 36.37^0 N and a longitude of 10.25^0 E (Figure 2C). It covers an area of approximately 623 km^2. The Rmel climate can be classified as temperate climates, dry season and hot in the summer in the Köppen climate classification system, with the overall annual amount of precipitation is rather low and characterized by high irregularity (Jebari et al., 2016). The average rainfall is ranging from 350 to 600 mm. This area is characterized by semi-arid Mediterranean climate with mild, rainy winters and hot, dry summers with an average annual temperature of about 18.5 ^{0}C and a mean annual reference evapotranspiration of about 1193 mm. The landscape of the area, located in the hills that connect the mountain slopes to the lowlands, has an elevation ranging from 35 to 1188 meters a.s.l. The majority of the study area is under cereal cultivation, followed by olive plantations and pastures (Jarray et al., 2023). The soils in the region are predominantly of two types developed on calcareous rich parent materials: *Rendzinas* and *Brown calcareous soils* (Attia et al., 2004).

2.2 The FLOWS model

In the FLOWS model, the one-dimensional vertical transient water flow is simulated by numerically solving the Richards equation, using an implicit backward finite difference scheme with explicit linearization (Coppola et al., 2024; Hassan et al., 2024) (Eq.(1)):

$$C(h)\frac{\partial h}{\partial t} = \frac{\partial}{\partial z}\left(k(h)\frac{\partial h}{\partial z} - k(h)\right) - S_w(h) \tag{1}$$

where C(h) = dθ/dh $[L^{-1}]$ is the soil water capacity, θ $[-]$ is the volumetric water content, h $[L]$ is the soil water pressure head, t $[T]$ is time, z $[L]$ is the vertical coordinate being positive upward, and K(h) $[LT^{-1}]$ the hydraulic conductivity. The term $S_w(h)$ $[T^{-1}]$ is introduced for taking into account root water uptake.

The model discretizes the spatial flow field in a prescribed number of nodes (usually 100) of constant width (Δz). Time discretization starts with a prescribed initial time increment (Δt). This time increment is automatically adjusted at each time level according to the criteria proposed by Vogel (1987).

The overall schematic processes of water flow and solute transport simulated by FLOWS (see Figure 3):

2.2.1 Hydraulic properties

Richards' equation requires the water retention function, θ(h), and the hydraulic conductivity, k(h), function to be known. These functions interrelate pressure head, h , water content, θ, and hydraulic conductivity, K. Several water retention and hydraulic

https://doi.org/10.5194/egusphere-2025-1927
Preprint. Discussion started: 12 June 2025

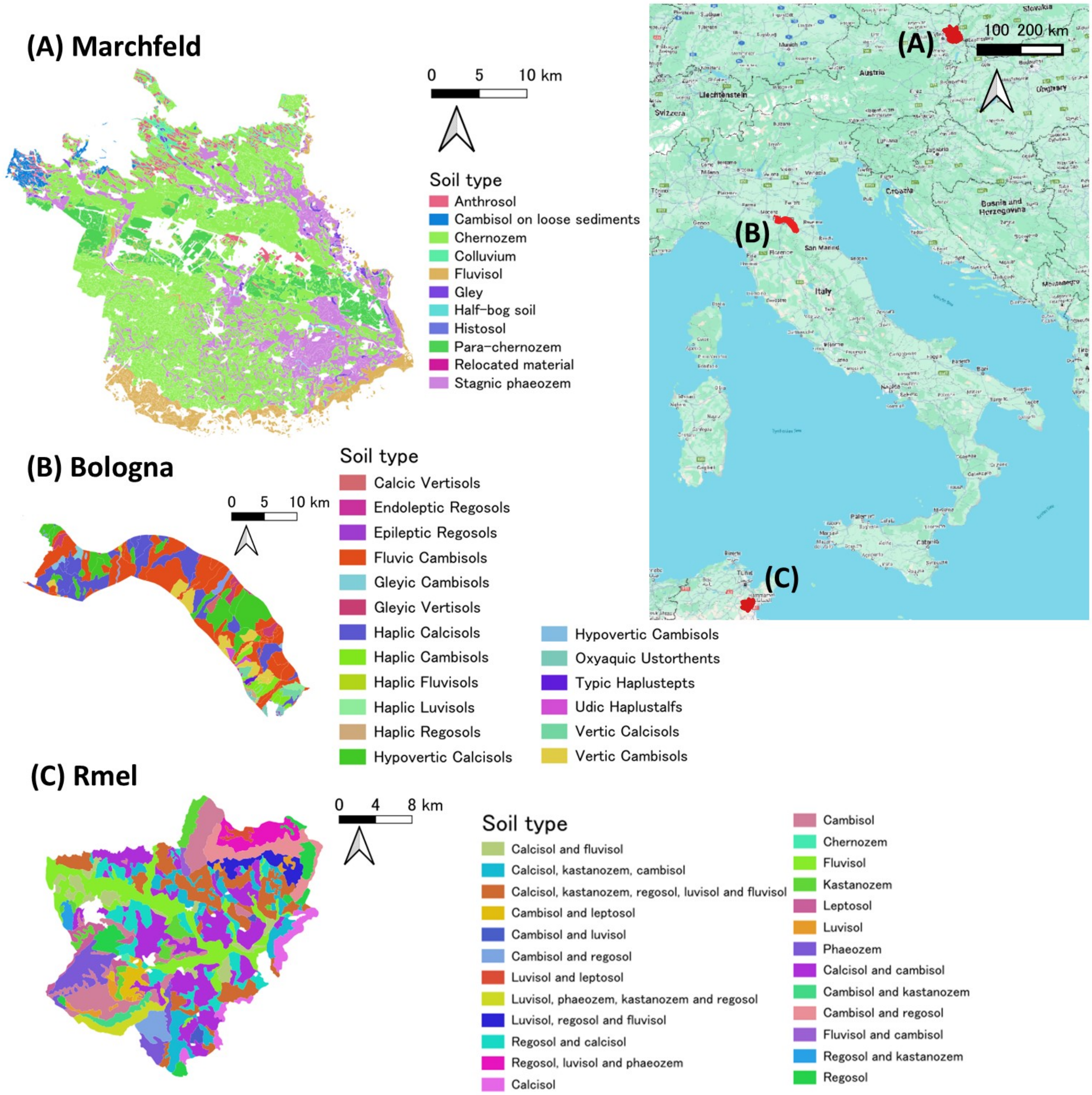

Figure 2. Marchfeld Region, Austria (A) (Fusco et al., 2024); Bologna, North-Italy (B) (ARPAE Emilia-Romagna, Soil maps from WebGIS portal: https://servizimoka.regione.emilia-romagna.it/mokaApp/apps/ped/index.html); Rmel, Tunisia (C) (LANDSUPPORT: https://www.landsupport.eu/dss-platform/); and the entire study areas map on the upper right corner (©Google Maps)

https://doi.org/10.5194/egusphere-2025-1927
Preprint. Discussion started: 12 June 2025

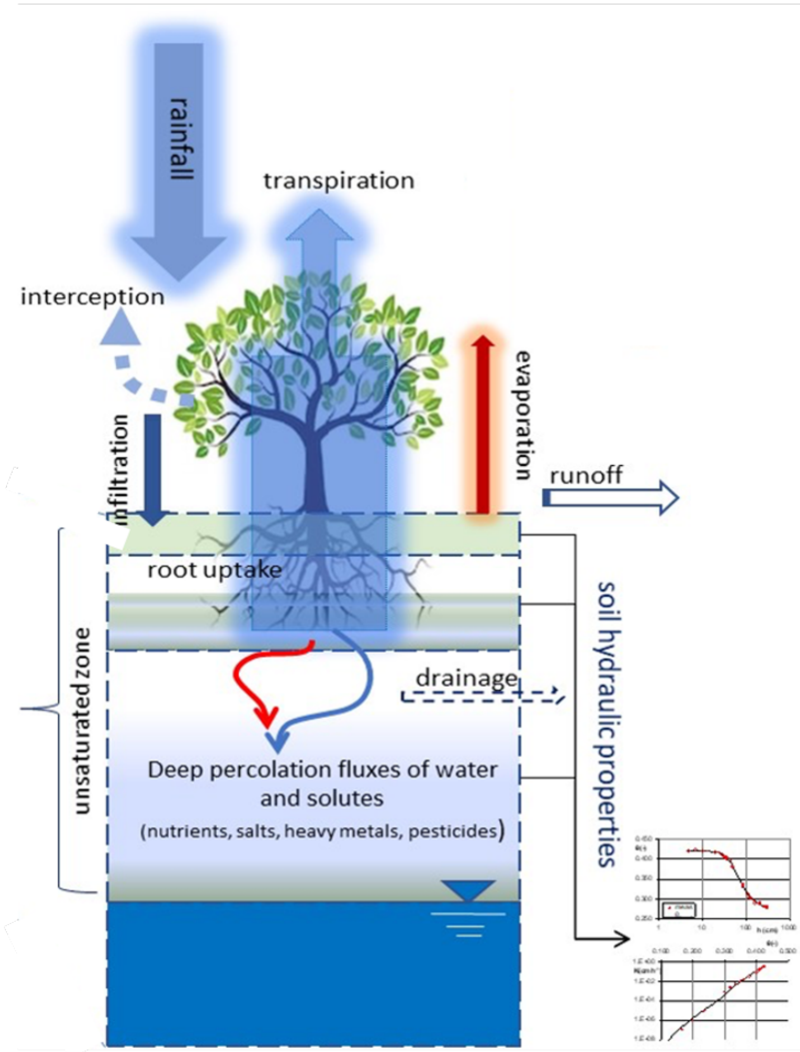

Figure 3. Water flow and solute transport processes simulated by FLOWS

conductivity functions can be selected in the model, for these simulations we assumed the van Genucthen-Mualem (VGM) equations (Van Genuchten, 1980):

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = [1 + |\alpha h|^n]^{-m} \tag{2}$$

$$K(\theta) = K_S S_e^{\tau} \left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2 \tag{3}$$

https://doi.org/10.5194/egusphere-2025-1927
Preprint. Discussion started: 12 June 2025

where S_e is effective saturation, h [L] is the pressure head, α $[L^{-1}]$ is related to the inverse of the air entry pressure head, n [-] and m [-] are shape parameters, with the constrain that m = 1 - 1/n, θ, θ_r [–] and θ_s [–] are the actual, the residual and the saturated water contents, respectively, K(θ) $[LT^{-1}]$ is the hydraulic conductivity function, K_S $[LT^{-1}]$ is the hydraulic conductivity at $\theta = \theta_s$ and τ is a parameter which accounts for the dependence of the tortuosity and the correlation factors on the water content.

2.2.2 Boundary and initial conditions for water flow

Flow rates and pressure heads, either constant or time-variable, can be used as the upper boundary condition. Similarly, gradients, pressure heads, or flow rates, whether constant or variable, can be applied at the bottom of the soil profile. In our simulations, daily flow rates (i.e., precipitation and potential evapotranspiration) from a representative climate year were implemented as top boundary conditions. A fixed unit gradient ($dh/dz = -1$) was applied as the bottom boundary condition.

The reference evapotranspiration (ET_0) was estimated by applying the Hargreaves formula (Hargreaves and Allen, 2003), while the potential crop evapotranspiration (ET_p) is calculated as $ET_p = K_c \cdot ET_0$, where K_c is the crop coefficient that varies with crop type, growth stage (Allen et al., 1998).

Finally, the initial conditions can be set as either pressure head or water content, which may be constant or vary with soil depth.

2.2.3 Vegetation parameters

The vegetation is simulated in a so-called static way, so the growth of the crop is not dynamically simulated by the model, but the user has to specify the stage of crop development by providing as input the evolution over time of the leaf area index, root depth, and crop coefficient as a function of the stage of development.

Furthermore, the code applies Beer's law (Ritchie, 1972) to separate potential evaporation and transpiration from potential evapotranspiration, as given by the equation $E_p = ET_p \cdot exp(-K_l \cdot LAI)$. This requires the crop-specific light extinction coefficient (K_l) and the Leaf Area Index (LAI).

The root water sink term, ($S_w(h)$), in Equation 1 is calculated in FLOWS according to a so-called macroscopic approach, frequently adopted in hydrologically oriented soil-plant-atmosphere continuum models for describing plant water uptake. According to the approach of Feddes et al. (1978), and neglecting the osmotic stress, it is calculated by the Eq.(4):

$$S_w(h) = \alpha(h) S_p \quad (4)$$

where α(h) is the crop-specific water reduction function that depends on the local water pressure head at a given depth (z) and S_p is the potential root uptake, assumed to be equal to the potential transpiration. The function $\alpha(h)$ is a piecewise linear function that represents a reduction factor for root water uptake (ranging from 0 to 1), with five stages of water uptake defined by four values of pressure head (h1 > h2 > h3 > h4). The model accounts for different root distribution shapes with depth, such as uniform, logistic, Prasad-type, etc. In our study, we applied the uniform root distribution function.

https://doi.org/10.5194/egusphere-2025-1927
Preprint. Discussion started: 12 June 2025

2.3 Input dataset for model simulations

Climate: For each case study, a representative median year was chosen, considering both precipitation and reference ET. This choice served two main objectives: i) to generalize the model results, ensuring that they are representative of the investigated area, and ii) to reduce the computational demand associated with solving the Richards equation for all the soils involved in the study.

The representative median year for the Marchfeld site, within the period from 1997 to 2016, was identified as the year spanning from October 2006 to September 2007, with an annual precipitation of 526 mm and a reference evapotranspiration of 952 mm. This year exhibited precipitation closest to the median value calculated for the 20-year dataset, making it a typical representation of the region's average precipitation pattern. For Bologna, the representative median year during the period from 1991 to 2022 was identified as the year spanning from October 2017 to September 2018, with an annual precipitation of 746 mm and a reference evapotranspiration of 1106 mm. This year closely matched the median precipitation value calculated for the 32-year dataset, reflecting typical precipitation conditions for the region. For Rmel, the representative median precipitation year during the period from 2008 to 2018 was identified as the year spanning from October 2009 to September 2010, with an annual precipitation of 410 mm and a reference evapotranspiration of 1193 mm. This year corresponds to the median value of the dataset, representing typical precipitation conditions for the region during the study period.

Soil: The soil characteristics included the percentages of sand, silt, clay and the soil organic matter content for each pedological horizon. These parameters were used as inputs in the HYPRES pedotransfer functions to predict soil hydraulic properties (bulk density [g cm^{-3}], θ_s [-], α [cm^{-1}], n [-], K_S [cm d^{-1}] and τ [-]) as shown in Table 1 (Wösten et al., 2001).

Crop: The vegetation module of the FLOWS model was parameterised specifically for durum wheat (*Triticum turgidum* subsp. *durum*) largely cultivated at the three sites. The light extinction coefficient was set to K_l=0.45. The crop coefficient (Kc) varies during the growing season and was obtained from sources from the literature (REF). The Leaf Area Index (LAI) was modeled using Growing Degree Days (GDD), applying a lognormal function (REF). The water stress coefficients of the Feddes model were set as follows: h_1=-1, h_2=-10, h_3^H=-500, h_3^L=-300, h_4=-8000, where the superscripts H and L for the H3 values refer to high (5 mm day $^{-1}$) and low (1 mm day $^{-1}$) potential evapotranspiration, respectively. Finally, the maximum rooting depth for durum wheat was set to 80 cm.

2.4 Ecosystem Services and Indicators

Water-related processes within the soil-plant-atmosphere system, such as infiltration, evapotranspiration, and drainage, are integral components of the hydrological cycle. These processes are primarily influenced by climate and soil hydrological properties. By simulating these processes, the FLOWS model provides outputs that enable the estimation of four key regulating ecosystem services:

- Runoff triggering (RUN): the contribution of the soil in separating the amount of water that infiltrates from the portion that flows externally, potentially generating runoff.

https://doi.org/10.5194/egusphere-2025-1927
Preprint. Discussion started: 12 June 2025

– Infiltration (INF): the soil's ability to regulate water entry, contributing to water regulation services.

– Groundwater recharge (GWR): the soil's capacity to conduct water downward and replenish groundwater, thereby supporting water regulation services.

– In addition the Crop Water Stress Index (CWSI) is considered as a proxy indicator for food provision ecosystem services, measuring the level of water stress experienced by crops. CWSI is calculated as (1 - T_{act}/T_{pot}) * 100, where T_{act} is actual transpiration and T_{pot} is potential transpiration.

These outputs were analysed to evaluate their interrelations with a groupf of key soil parameters which are commonly selected as indicators of ecosystem services. These indicators encompass saturated hydraulic conductivity (K_S), available water content (AWC), bulk density (BD), organic matter (OM), clay content (CLAY), saturated soil water content (θ_s) and soil depth (SD).

2.5 Statistical analysis

Various descriptive analysis tools and summary measures were used to explore and describe the data, as well as to visualize their distributions. To investigate the degree of correlation between ecosystem services and indicators (soil properties), we calculated the Pearson correlation using the *metan* package in R software (Olivoto and Barbin, 2020). In the text, we classify the degree of correlation (r) as follows: very weak (<0.2), weak (0.2–0.4), moderate (0.4–0.6), strong (0.6–0.8), and very strong (>0.8). Scatter-plots were generated using the *AgroR* package (Shimizu et al., 2022) and the *ggplot2* package (Wickham, 2016) in R.

In addition, stepwise multiple linear regression analyses were performed to identify linear relationships between selected ecosystem services and soil properties, utilizing the *olsrr* package in R (Hebbali, 2020). The stepwise selection method applied p-values to determine the most parsimonious model. The statistical significance of model parameters was assessed by performing an analysis of deviance (validated by F-tests) to compare a null model (no effect) with models that included one or more explanatory variables.

All statistical analyses and graphing were conducted using RStudio software, version 4.3.2 (R Core Team, 2023).

3 Results

This section is organized into four subsections to present the findings of the analysis across all three case study areas.

– Subsection 3.1 presents the soil data used in the simulations, highlighting the study area's diverse pedological characteristics. These data encompass critical physical and hydrological properties essential for modelling water-related processes in the soil-plant-atmosphere continuum.

– Subsection 3.2 discusses the impact of each individual process on the overall soil water balance, providing insights into how processes like infiltration, evaporation, plant uptake, and drainage contribute in each region.

https://doi.org/10.5194/egusphere-2025-1927
Preprint. Discussion started: 12 June 2025

– Subsection 3.3 evaluates the statistical relationship between individual soil indicators (e.g., saturated hydraulic conductivity, bulk density, and organic matter content) and each water-related process. This analysis aims to determine how well specific indicators can predict or represent particular processes.

– Subsection 3.4 explores the multivariate relationships between indicators and their influence on each water-related process. By examining these interactions, this analysis seeks to understand potential synergistic or antagonistic effects of indicator combinations on infiltration, groundwater recharge, and crop water stress index.

Each subsection provides detailed insights into the functioning and inter-dependencies of soil indicators and water processes, contributing to a comprehensive understanding of soil-water interactions in different environmental settings.

3.1 Soil profiles dataset

Table 1 presents a summary of the primary soil characteristics and hydraulic properties observed in the three study regions.

Variability in soil depth across the study areas reflects regional differences in soil profiles, which have significant implications for water-related processes such as infiltration and groundwater recharge. On average, Marchfeld and Bologna exhibit deeper soil profiles (approximately 76 cm) compared to Rmel, where the average soil depth is about 65 cm. Marchfeld exhibits the largest variability in soil depth, with a coefficient of variation (CV) of 75%, followed by Rmel (CV = 62%) and Bologna (CV = 44%).

The soils of Bologna are predominantly heavy, with clay and silt making up over 80% of the composition on average. This suggests a predominance of fine particles, which typically results in slower infiltration rates and higher water retention. Furthermore, the Bologna area exhibits the least variability in texture, with coefficients of variation (CV) for silt at 17% and clay at 24%. This low variability indicates a more homogeneous soil structure, which may lead to consistent hydrological behaviour across the region.

Soils in Rmel are different from the above cases, with a higher sand content averaging 45%. Sandy soils generally facilitate faster infiltration and lower water retention. However, the variability in textures is considerably higher in Rmel, with CV values for silt and clay ranging between 39% and 47%. This heterogeneity may contribute to more variable water-related processes and localized differences in soil behaviour. Textures variability in Marchfeld falls between that of Bologna and Rmel, with CV values also ranging in between the other two sites. This suggests a diverse soil structure, potentially leading to spatial differences in water movement and storage.

Variability in soil texture among the three study areas corresponds to significant differences in their hydraulic properties. The mean values of key soil hydraulic parameters—namely, saturated water content (θ_s), air-entry parameter (α), shape parameter (n), saturated hydraulic conductivity (K_s), and the pore connectivity/tortuosity factor (τ)—differed statistically significantly between the areas. The mean values and coefficients of variation of (θ_s) and α remain similar across the three areas. More pronounced differences are observed in the parameters n and K_s, both of which are critical for governing water flow in the soil. Higher values of n indicate steeper water retention curves, which imply greater and faster water release from the soil as matric potential decreases. Higher values of K_S signify faster water movement through the soil profile. These variations reflect

https://doi.org/10.5194/egusphere-2025-1927
Preprint. Discussion started: 12 June 2025

Table 1. Mean, minimum, maximum, standard deviation (st.d.) and coefficient of variation (CV) of the main soil characteristics of input dataset in the study areas of Marchfeld, Bologna and Rmel. The number of investigate soil profile (s.p.) is reported in parenthesis for each site.

		Soil depth (cm)	Sand (%)	Silt (%)	Clay (%)	Bulk density (g cm^{-3})	Organic matter (%)	θ_s (-)	α (cm^{-1})	n (-)	K_S (cm d^{-1})	τ (-)
Marchfeld (215 s.p.)	mean	75.9	36.4	45.5	18.1	1.49	1.5	0.42	0.03	1.22	24.6	-1.82
	min	15.0	1.8	8.0	1.2	0.97	0.2	0.32	0.002	1.12	4.23	-4.16
	max	200	90.1	80.1	53.0	1.72	19.1	0.68	0.20	1.62	98.9	2.98
	st.d.	56.6	22.4	16.9	9.9	0.11	1.9	0.04	0.02	0.09	16.4	1.54
	CV	75	62	37	55	7	127	10	67	7	67	-85
Bologna (73 s.p.)	mean	76.1	19.4	46.9	33.7	1.51	1.2	0.42	0.02	1.13	15.3	-3.59
	min	10.0	1.9	32.5	13.4	1.18	0.7	0.29	0.01	1.12	4.00	-5.68
	max	150	52.0	61.5	52.9	1.64	1.8	0.63	0.05	1.27	89.3	0.31
	st.d.	33.3	10.6	8.2	8.2	0.07	0.3	0.04	0.01	0.03	14.9	0.74
	CV	44	55	17	24	5	25	10	50	3	97	-21
Rmel (27 s.p.)	mean	64.8	44.8	27.9	27.3	1.43	1.6	0.43	0.04	1.19	28.2	-2.22
	min	10.0	13.4	6.3	4.6	1.10	0.4	0.34	0.01	1.12	3.68	-3.99
	max	190	81.9	51.6	52.8	1.64	7.0	0.56	0.09	1.43	100	1.40
	st.d.	40.1	20.6	10.9	12.7	0.13	1.4	0.05	0.02	0.08	20.7	1.34
	CV	62	46	39	47	9	88	12	50	7	73	-60

the influence of texture, with coarser soils (e.g., Rmel) generally exhibiting higher K_S (28 cm d^{-1}) values, allowing quicker infiltration and drainage, while finer soils (e.g., Bologna) tend to have lower (15 cm d^{-1}), retaining water for longer periods. As expected, the coefficients of variation (CVs) of K_S are notably high across the three study areas, reflecting the inherent variability of this property: Bologna CV=97%, Rmel CV=73% and Marchfeld CV=67%.

The stark contrast between the heavy, homogeneous soils of Bologna and the coarser, heterogeneous soils of Rmel underlines the importance of site-specific soil management strategies and response to climatic inputs.

3.2 Water balance components

Table 2 presents the results of the simulated water balance components, including infiltration, interception, drainage, runoff triggering, transpiration, and evaporation, calculated as mean values of all soil profiles in each region. These six processes collectively illustrate how precipitation is partitioned on average within each area. The data presented reflect the average behaviour of the area. Table 2 also includes the minimum and maximum values for each of the processes described above.

Overall, the terms of the water balance in the three study regions of Marchfeld, Bologna, and Rmel revealed significant differences, driven primarily by differences in the amounts of precipitation (Table 2) and the annual distributions. In fact, Bologna received the highest annual precipitation (745.90 mm), followed by Marchfeld (526.20 mm), and Rmel (410.80 mm), characterized by the lowest rainfall amount.

https://doi.org/10.5194/egusphere-2025-1927
Preprint. Discussion started: 12 June 2025

Table 2. Mean (coefficient of variation (%)) and relative share of the different components for the water balance with respect to the precipitation for interception, runoff and infiltration, and with respect to infiltration for transpiration, evaporation, and drainage of the annual values of each component of the water balance in the study areas of Marchfeld, Bologna, and Rmel.

Processes	Marchfeld	Bologna	Rmel
Precipitation (mm)	526.2	745.9	410.8
Interception (mm)	21.78	41.01	21.37
Interception/Precipitation (%)	4.14	5.50	5.20
Runoff (mm)	36.18 (99)	164.15 (45)	4.09 (236)
Runoff/Precipitation (%)	6.88	22.01	1.00
Infiltration (mm)	468.24 (8)	540.74 (14)	385.34 (2)
Infiltration/Precipitation (%)	88.99	72.49	93.80
Transpiration (mm)	126.4 (13)	223.49 (7)	171.35 (5)
Transpiration/Infiltration (%)	26.99	41.33	44.47
Evaporation (mm)	206.79 (5)	171.7 (0.2)	189.99 (6)
Evaporation/Infiltration (%)	44.16	31.75	49.30
Drainage (mm)	43.23 (85)	148.8 (33)	9.61 (67)
Drainage/Infiltration (%)	9.23	27.52	2.49
CWSI (%)	25.74 (37)	16.45 (34)	20.82 (20)

Mean interception losses were consistently low, ranging from 21.37 mm to 41.01 mm across the regions, indicating that canopy cover has a relatively small effect on the total water budget.

The mean surface runoff in Bologna was significant (164.15 mm), primarily due to the texture of the dominant soils in the area, which range from fine silty to silty clay loam. This soil texture is associated with low K_S, resulting in the activation of overland flow when rainfall exceeds the soil's infiltration capacity(Beven, 2004). The importance of this mechanism is evidenced by historical and recent flooding disasters in the Emilia-Romagna region (Arrighi and Domeneghetti, 2023). In contrast, Rmel exhibited negligible runoff (4.09 mm), which can be attributed to its low precipitation levels and rates, as well as its coarser soils. These soil characteristics enhance infiltration capacity, reducing surface runoff.

The infiltration of net precipitation, i.e., the total precipitation minus runoff and vegetation interception, is relatively high for Rmel (385.34 mm) and Marchfeld (468.24 mm), accounting for around 90% of the total precipitation. In contrast, it is lower for Bologna (540.74 mm), representing around 73% of the total precipitation. This discrepancy is due to runoff, which, in the latter case, removes a substantial portion of the precipitation.

https://doi.org/10.5194/egusphere-2025-1927
Preprint. Discussion started: 12 June 2025

Mean crop transpiration was higher in Bologna (223.49 mm) compared to Rmel (171.35 mm) and Marchfeld (126.40 mm). The latter exhibited the lowest values, primarily due to the lower temperatures in comparison to Bologna and Rmel. The mean evaporation is similar across the three case study (around 190 mm).

The average amount of water leaving the soil profile (i.e., drainage) was notably higher in Bologna (148.80 mm). This was primarily due to the significant precipitation levels, but also to the relative homogeneity of the soil horizons, which facilitate water flow. Indeed, it is well known that the greater the heterogeneity along the soil profile, the lower the water flow through these horizons (Matthews et al., 2004). In contrast, Rmel exhibited the lowest mean drainage (9.61 mm), likely due to the limited precipitation. The relatively low amount of rainfall and the high variability of soils in Marchfeld result in intermediate values for infiltration, runoff triggering, and drainage, falling between those observed in Bologna and Rmel.

As an example of how different soil types influence water partitioning processes, the pie chart in Figure 4 illustrates the distribution of infiltrated water among transpiration, evaporation, and drainage for three distinct soil types in the Marchfeld region, which displays the highest variability among the three study areas. These soils exhibit markedly different characteristics: the Para-chernozem is shallow (<50 cm), with a high sand content (>60%); the Fluvisol is considerably deeper (130 cm), characterized by a silty texture and a high organic matter content (OM = 4.6%); and the Stagnic Phaeozem is the deepest (200 cm), with an organic matter content of 2.7%.

The contribution of evaporation is nearly identical across the different soil types, with 48% for para-chernozem, 50% for Fluvisol, and 56% for stagnic phaeozem. This consistency suggests that evaporation is primarily driven by atmospheric demand. As the initial phase of the evaporation process is weather-controlled (Pearse et al., 1949), the soil's role in the process itself remains minimal, especially given the temporal distribution of precipitation.

This holds true for all the investigated sites, where the variability of the evaporation amounts among the investigated soils is low (the coefficient of variation ranges from 0.2 to 6%).

The percentage contribution of transpiration increases from Para-chernozem to Fluvisol and then to Stagnic Phaeozem, while drainage follows an inverse pattern. This behavior is predominantly controlled by variations in the pore size distribution both along individual soil profiles and among different soil types, which is reflected in their distinct hydraulic properties. For example, in Stagnic Phaeozem soil, the presence of a fine-textured subsurface horizon significantly impedes water movement through the soil profile, resulting in reduced drainage efficiency compared to Fluvisol and Para-chernozem. Consequently, Stagnic Phaeozem exhibits prolonged water retention, thus enhancing the availability of soil moisture for evapotranspiration over an extended period.

3.3 Interrelationship between soil indicators and ecosystem services

The Pearson correlation coefficients (r) between the seven soil indicators (K_S, AWC, BD, OM, CLAY, θ_S, and SD) and the four ecosystem services (RUN, INF, GWR, and CWSI) for Marchfeld, Bologna, and Rmel are summarized in Table 3. Asterisks denote significance levels: (*) for ($p < 0.05$), (**) for ($p < 0.01$), and (***) for ($p < 0.001$). These levels indicate varying degrees of statistical significance, with lower p-values showing stronger evidence against the null hypothesis.

https://doi.org/10.5194/egusphere-2025-1927
Preprint. Discussion started: 12 June 2025

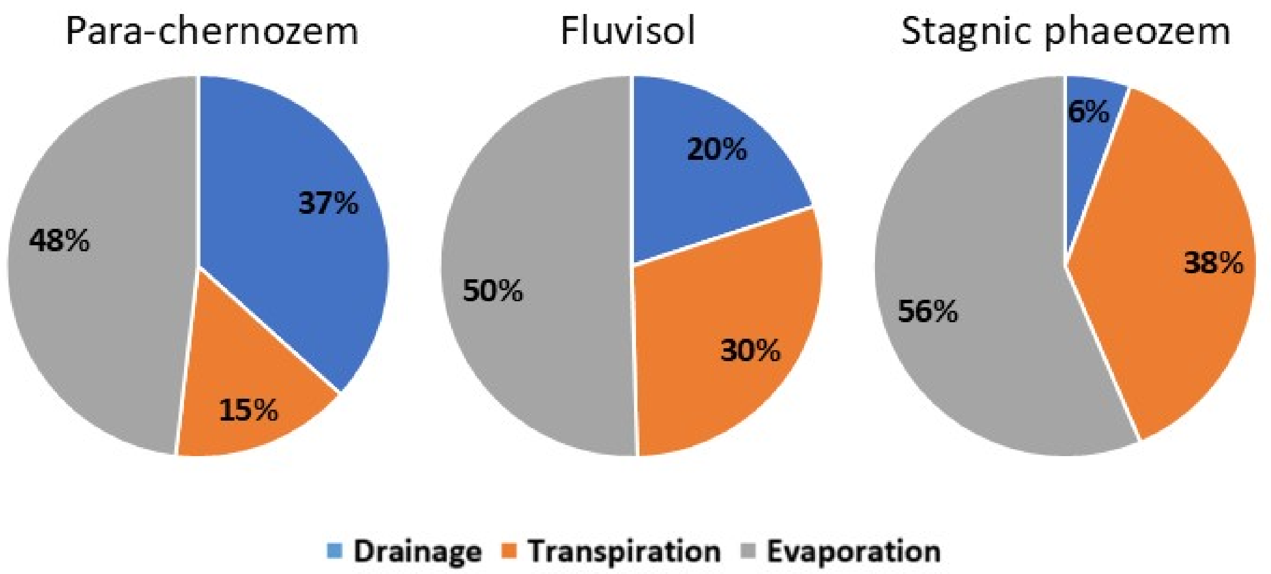

Figure 4. Percentage of infiltrated water distributed among three processes—transpiration, evaporation, and drainage—in the Marchfeld region for soil profiles Para-chernozem, Fluvisol, and Stagnic phaeozem

Soil depth (SD) shows moderate to weak correlations (from r = |0.19| up to r = |0.50|) across the three sites, except for GWR in Bologna, where the correlation is nil (r = -0.05). Firstly, it is worth noting that the correlations for RUN show the same value as INF. This holds for all the investigated parameters because the amount of infiltrated water is directly calculated as the difference between rainfall (which is constant for each area) and runoff. Therefore, the correlation coefficient is the same but with the opposite sign. In particular, INF/RUN showed weak correlations with SD (from r = |0.19| up to r = |0.35|), and a moderate negative correlation with GWR (r = -0.46 and r = -0.49 for Marchfeld and Rmel, respectively). These correlations are negative, as expected: the deeper the soil, the lower the flux of water below the soil bottom, and consequently, the lower the GWR. Finally, for CWSI, the correlation ranges from weak (r = -0.31) to moderate (r = -0.50), with negative values since deeper soils are associated with reduced crop stress.

Clay content (CLAY) exhibits the highest values among the seven indicators. INF is strongly negatively correlated in Marchfeld (r = -0.67) and Bologna (r = -0.66) and moderately negatively correlated in Rmel (r = -0.49). GWR shows a higher negative correlation only in Bologna (r = -0.69), while CWSI exhibits a moderate correlation in both Bologna and Rmel. However, the correlation coefficients have opposite signs: in Bologna, higher clay content is associated with increased

https://doi.org/10.5194/egusphere-2025-1927
Preprint. Discussion started: 12 June 2025

Table 3. Pearson correlation coefficients (r) between process of soil water balance and soil properties in Marchfeld, Bologna and Rmel. (INF = infiltration; GWR = groundwater recharge; RUN = Runoff; CWSI = crop water stress index (%); OM = organic matter; BD = bulk density; θ_s = saturated water content; K_s = saturated hydraulic conductivity; AWC = available water content)

		SD	CLAY	OM	BD	θ_S	K_S	AWC
Marchfeld	INF	0.27^{***}	-0.67^{***}	-0.57^{***}	0.74^{***}	-0.76^{***}	0.52^{***}	-0.12
	GWR	-0.46^{***}	-0.05	-0.09	0.09	-0.09	0.12	0.19^{**}
	RUN	-0.27^{***}	0.67^{***}	0.57^{***}	-0.74^{***}	0.76^{***}	-0.52^{***}	0.12
	CWSI	-0.35^{***}	-0.05	0.09	0.04	-0.05	0.20^{**}	-0.22^{**}
Bologna	INF	0.19	-0.66^{***}	-0.16	0.30^{**}	-0.42^{***}	0.38^{***}	0.35^{**}
	GWR	-0.05	-0.69^{***}	-0.06	0.49^{***}	-0.59^{***}	0.47^{***}	0.34^{**}
	RUN	-0.19	0.66^{***}	0.16	-0.30^{**}	0.42^{***}	-0.38^{***}	-0.35^{**}
	CWSI	-0.31^{**}	0.48^{***}	0.02	0.01	0.12	0.00	-0.57^{***}
Rmel	INF	0.35	-0.49^{**}	-0.75^{***}	0.67^{***}	-0.65^{***}	0.46^{*}	-0.39^{*}
	GWR	-0.49^{**}	0.13	0.21	-0.23	0.21	0.15	-0.06
	RUN	-0.35	0.49^{**}	0.75^{***}	-0.67^{***}	0.65^{***}	-0.46^{*}	0.39^{*}
	CWSI	-0.50^{**}	-0.51^{**}	-0.30	0.49^{**}	-0.53^{**}	0.38^{*}	-0.68^{***}

Note: Asterisks denote significance level (* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$).

stress, whereas in Rmel, clay content appears to reduce stress. This contrasting behavior in Rmel could be explained by its predominantly sandy soils, where an increase in clay acts as a structuring factor, enhancing soil water retention capacity and thereby reducing crop water stress.

Organic matter (OM) is negatively correlated with infiltration in Marchfeld (moderate, r = -0.57) and Rmel (strong, r = -0.75). All other correlations between organic matter and processes are weak.

Bulk density (BD) of the upper layer is strongly positively correlated with INF in the Marchfeld (r = 0.74) and Rmel (r = 0.67) case studies, showing a high level of significance (p < 0.001). In contrast, bulk density in Bologna exhibits only a weak linear correlation with infiltration. An analysis of the processes reveals that high bulk density values correspond to high sand content, which, on the one hand, reduces porosity but, on the other, increases K_S, primarily enhancing infiltration. As a result, positive correlations are observed. No clear pattern is observed for GWR and CWSI, although a moderate positive correlation is found for GWR at the Bologna site and for CWSI at the Rmel site.

Saturated soil water content (θ_S) exhibits a strong negative correlation with infiltration at the Marchfeld (r = -0.76) and Rmel (r = -0.65) sites, while in Bologna, the correlation is moderately negative (r = -0.42). A moderate negative correlation is also observed for GWR at the Bologna site and for CWSI at the Rmel site. The behavior of θ_S follows a similar correlation pattern to bulk density (BD) but with the opposite sign. This is expected, as the two indicators are closely related, given that θ_S is assumed to be equal to soil porosity.

https://doi.org/10.5194/egusphere-2025-1927
Preprint. Discussion started: 12 June 2025

Saturated hydraulic conductivity (K_S), despite being considered the best indicator for infiltration, shows a moderate positive correlation in Marchfeld (r = 0.52) and Rmel (r = 0.46) and a weak correlation in Bologna. The moderate positive correlation with GWR in Bologna (r = 0.47) suggests that, due to the reduced permeability of the entire profile, higher K_S values in the upper horizon lead to increased drainage at the bottom of the soil profile. PTFs often lead to a reduction in the variability of hydrological properties, particularly K_S. This effect arises because PTFs estimate K_S based on more readily available soil properties, such as texture, bulk density, and organic matter content, using empirical relationships or statistical models.

Available water capacity (AWC) with regard to INF, GWR and RUN, moderate to weak correlations were observed, with values ranging from -0.12 up to 0.39. Furthermore, in the case of INF, it is evident that the correlation in Bologna is weak and postive, whereas in Rmel it is weak but negative. This suggests that there is no consistent physical relationship between AWC and infiltration. Therefore, regardless of climate or soil type, the use of this indicator is not recommended for representing the ecosystem service of infiltration.

AWC shows a moderate correlation with CWSI in Bologna (r = -0.57) and a strong correlation in Rmel (r = -0.68), whereas a weaker correlation is observed in Marchfeld (r = -0.22). This variation in behaviour among the three sites can be attributed to differences in rainfall distribution. In Bologna and Rmel, the higher soil water storage capacity (higher AWC) allows intermittent rainfall to be effectively stored in the soil, thereby reducing crop water stress. In contrast, the more consistent rainfall distribution in Marchfeld prevents the onset of water stress, reducing the significance of soil water storage capacity in this region. Additionally, this steady rainfall pattern minimizes runoff, allowing most of the precipitation to infiltrate the soil and remain readily available for crop growth, regardless of the soil's storage capacity. Specifically, the soils in Marchfeld infiltrate 90% of the precipitation, compared to only 73% in Bologna, primarily due to Bologna's higher runoff (16.4 cm) relative to Marchfeld (3.6 cm).

3.4 Multivariate analysis of interrelations between soil indicators and ecosystem services

To deepen the analysis, we moved from a one-to-one single correlation between parameters and process to a multi-to-one regression approach. The fundamental principle of the stepwise regression procedure is to sequentially add or remove predictor variables from the model based on a p-value threshold of 0.05. This process continues iteratively until no further adjustments are statistically justified. Hence, in Table 4, the ranking of importance of the soil properties for each site and the four ecosystem services is provided, along with the correlation coefficient (r), the MAE and the corresponding p-value. A higher ranking indicates a greater contribution of the parameter to the process, thereby enhancing prediction accuracy.

The step-wise regression analysis included three variables (indicators): Soil depth, Clay content, and Organic matter content. The remaining four variables (θ_S, BD, K_S, and AWC) were excluded as they are dependent on the preceding ones. Specifically, BD, θ_S and K_S were derived from a pedotransfer function, which considers clay content and OM as input, among other parameters. Finally, AWC is also a function of soil depth.

In four out of nine possible cases, multiple regression did not yield any further improvement over simple linear regression. Specifically, in these cases — CWSI in Marchfeld, clay content for GWR in Bologna, organic matter for INF/RUN and soil depth for GWR in Rmel — the correlation coefficient was already at its maximum compared to the other variables, meaning that the results remained unchanged.

In three of the remaining six cases, the combination of clay content and soil depth emerges as the best predictor, with clay content being negatively correlated and soil depth being positively correlated. Specifically, at the Bologna site, multiple regression with INF/RUN exhibits a strong correlation (r = 0.70), with an average overestimation of approximately 4 cm. Additionally, the T-value for clay is around 8, whereas for soil depth, it is 2.8, indicating that clay has three-times level of confidence as a predictor. From a physical perspective, it is important then to highlight that these two variables do not contribute equally to the process. The Crop Water Stress Index (CWSI) is influenced by both clay content and Soil depth at the Bologna and Rmel sites. At the Bologna site, the correlation coefficient is moderate to strong (r = 0.60), with the Mean Absolute Error (MAE) approaching zero. At the Rmel site, a strong correlation is observed (r = 0.65) with an MAE of 2.3 cm. The T values indicate greater significance for the clay content (5.3) compared to the depth of the soil (-3.7) in Bologna, while in Rmel similar T values are observed (-2.6). Notably, despite the similar statistical metrics between Bologna and Rmel for CWSI, the variables impact the sites differently. At Rmel, both clay content and soil depth are negatively correlated with CWSI, suggesting that higher values of these variables correspond to reduced crop stress. In contrast, at Bologna, this negative correlation is observed for the only Soil depth variable. This discrepancy may be due to higher clay content leading to increased runoff and reduced water infiltration, thereby decreasing soil water availability for root uptake.

4 Discussion and Conclusions

This study's findings underscore the importance of understanding local soil and climatic variations to better manage water-related processes and ecosystem services. The differences among the Marchfeld, Bologna, and Rmel regions reveal how unique pedoclimatic conditions can shape hydrological behaviour and affect related ecosystem services. By examining these distinct regions, the study contributes valuable insights that could guide tailored approaches to soil and water management, ensuring more effective conservation and sustainable land use practices in various climatic zones.

To achieve the objectives of this research, which aims to evaluate the effectiveness of widely proposed physical and chemical indicators in accurately representing water-related soil functions and processes, as well as assessing how well these indicators reflect the ecosystem services provided by soils in water regulation, we seek to systematically advance beyond the scheme in Figure 1. In this context, the results of this study can be discussed as follows:

- The effective evaluation of widely proposed physical and chemical indicators in accurately representing water-related soil functions is not always a linear process; rather, it often requires progressive refinement driven by site-specific conditions. In this regard, Figure 1 could be more appropriately represented as a moving staircase, symbolizing a cyclical process of refinement. During this loop, parameters can be added or discarded based on the unique characteristics of each site.
- Some of the most commonly measured parameters did not show the expected correlation with the investigated processes, while others proved to be more relevant. A notable example is saturated hydraulic conductivity (K_S), which is often

https://doi.org/10.5194/egusphere-2025-1927
Preprint. Discussion started: 12 June 2025

Table 4. Statistics of multiple linear regression models predicting processes of soil water balance based on the interaction effect of soil properties in Marchfeld, Bologna and Rmel. (INF = infiltration; RUN = Runoff; GWR = groundwater recharge; CWSI = crop water stress index; OM = organic matter)

	Processes	Soil properties	r_p	r	MAE	p-value
Marchfeld	INF/RUN	Clay	0.67	0.79	1.70	<0.001
		OM	0.09			
		Soil depth	0.03			
	GWR	Soil depth	0.46	0.48	2.45	<0.001
		OM	0.02			
	CWSI	Soil depth	0.35	0.35	6.42	<0.001
Bologna	INF/RUN	Clay	0.66	0.70	4.22	<0.001
		Soil depth	0.04			
	GWR	Clay	0.69	0.69	2.89	<0.001
	CWSI	Clay	0.49	0.60	0.03	<0.001
		Soil depth	0.11			
Rmel	INF/RUN	OM	0.75	0.75	0.40	<0.001
	GWR	Soil depth	0.49	0.49	0.44	<0.01
	CWSI	Clay	0.51	0.65	2.30	<0.01
		Soil depth	0.14			

Note: MAE = Mean Absolute Error (cm); r_p = correlation between the individual soil properties and the model; r = overall correlation coefficient of the model.

chosen as the best predictor for infiltration rates and other water regulation ecosystem services. In the cases studied, K_S exhibited only moderate positive correlations with infiltration (r = 0.52 in Marchfeld and r = 0.46 in Rmel), and even weaker correlations in Bologna (r = 0.38), with values lower than those for clay content, θ_s, and bulk density. This finding is not entirely surprising, as the specialized literature on the effect of K_S on infiltration is contradictory. For instance, in a study examining the impact of soil structure on hydrological processes and the ranking of retention and conductivity curve parameters, Coppola et al. (2009) found that soil structure played a dominant role in aggregated soils. They concluded that K_S was not the most suitable indicator for capturing the effect of soil aggregation on hydraulic behaviour. On the other hand, Baritz et al. (2023), in their review of common soil health indicators to support policy decisions focusing on soil threats, selected K_S as the best indicator for soil compaction and related processes such as infiltration and runoff. Additionally, Calzolari et al. (2016), in evaluating eight soil ecosystem services based on spatially continuous data, used K_S as one of the indicator for water regulation ES along with air entry pressure; in both cases the

https://doi.org/10.5194/egusphere-2025-1927
Preprint. Discussion started: 12 June 2025

two parameters were derived from locally calibrated PTFs. Ultimately, a comprehensive analysis or meta-analysis of the relationship between K_S and infiltration/runoff across different soil and climate contexts is still lacking or incomplete. This gap in the literature highlights the need for further research to clarify the role of K_S and its effectiveness as an indicator for water-related soil functions.

- The use of Pedotransfer Functions (PTFs), despite their widespread application and, in many cases, being the only viable option, presents a limitation, as highlighted at the beginning of Section 3.4. Specifically, PTFs lead to: i) the smoothing of the spatial variability of soil characteristics, which is also observed in three case study areas presented in this work as can be seen from the values in Table 1, and ii) a consequent damping effect on the hydrological responses, which prevents a more detailed understanding of the underlying processes and of the soil parameters driving them. As a result, some derived parameters, such as bulk density, θ_S, K_S, and AWC, were necessarily excluded from the analysis.

- The complex interplay between meteorological variables and soil properties drives the water balance towards different components, depending on the variable spatial and temporal patterns and conditions. In this context, the Bologna site presents a particularly interesting case study, as the primary factor influencing water regulation is the asymmetrical distribution of rainfall throughout the year. Approximately 30 cm of rainfall occurs during February and March, accounting for nearly 40% of the total annual precipitation. As a result, the role of soil in water regulation is undeniably crucial, especially due to its ability to infiltrate water and facilitate its movement through groundwater recharge. However, the challenge at the landscape level extends beyond the vertical water balance; it is also shaped by lateral water movement processes. Subsurface lateral flow, in particular, plays a key role in redistributing water through the soil toward streams or rivers. This process is influenced by both landscape morphology and soil hydraulic properties. It becomes particularly important when a less permeable layer—such as a clay-rich or compacted soil—restricts vertical infiltration, redirecting water laterally along soil horizons (Li et al., 2014). This mechanism can increase the risk of downstream flooding, emphasizing the importance of understanding and managing soil-water interactions in flood-prone areas. In such cases, soil management becomes crucial for enhancing water regulation ecosystem services. Preventing soil compaction caused by intensive tillage and adopting minimum tillage practices can help reduce lateral flow while promoting groundwater recharge. Additionally, removing surface-compacted layers would improve the drainage of excess water through the existing artificial drainage network, further mitigating flood risks and enhancing overall water management.

Future improvements to the present work will involve conducting the same analysis but focusing exclusively on measured hydraulic properties. This approach will enhance the understanding of all water-related ecosystem services by providing more direct insights into the physical processes governing water movement and retention in soils.

Code and data availability. The code of the FLOWS model and data that support the findings of this study are available from the corresponding author, upon reasonable request.

https://doi.org/10.5194/egusphere-2025-1927
Preprint. Discussion started: 12 June 2025

Author contributions. **BAY:** Conceptualization, data curation, analysis, methodology, validation, visualization, writing original draft, writing review and editing. **AB:** Conceptualization, data curation, analysis, methodology, validation, visualization, writing review and editing. **AC:** Methodology, validation, writing review and editing. **MB:** Conceptualization, data curation, analysis, methodology, validation, visualization, writing review and editing. **FU:** Conceptualization, methodology, validation, writing review and editing.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. Part of the soil database (Marchfeld and RMEL regions) employed within the study was built during the EC H2020 LANDSUPPORT project, grant number 774234.

The Bologna database was built under the SERENA (Soil Ecosystem seRvices and soil threats modElling aNd mApping) EJP SOIL internal project. EJP SOIL has received funding from the European Union's Horizon 2020 research and innovation program: Grant agreement number 862695.

The research was funded by European Union's Horizon Europe research and innovation program, under Grant Agreement: 101091010, Project BENCHMARKS.

https://doi.org/10.5194/egusphere-2025-1927
Preprint. Discussion started: 12 June 2025

References

Allen, R. G., Pereira, L. S., Raes, D., Smith, M., et al.: Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56, FAO, Rome, 300, D05 109, 1998.

Arrighi, C. and Domeneghetti, A.: Brief communication: On the environmental impacts of 2023 flood in Emilia-Romagna (Italy), Natural Hazards and Earth System Sciences Discussions, 2023, 1–10, 2023.

Attia, R., Hamrouni, H., Agrebaoui, S., and Dridi, B.: Caractérisation et évaluation de l'érosion hydrique Bassin versant de Sbaihia (Zaghouan), Direction des Ressources en Sols.(Ministère de l'Agriculture et des Ressources Hydraulique-Tunisie), 2004.

Bagnall, Rieke, E., Morgan, C., Liptzin, D., Cappellazzi, S., and Honeycutt, C.: A minimum suite of soil health indicators for North American agriculture. Soil Secur 10: 100084, 2023.

Bagnall, D. K., Morgan, C. L., Bean, G. M., Liptzin, D., Cappellazzi, S. B., Cope, M., Greub, K. L., Rieke, E. L., Norris, C. E., Tracy, P. W., et al.: Selecting soil hydraulic properties as indicators of soil health: Measurement response to management and site characteristics, Soil Science Society of America Journal, 86, 1206–1226, 2022a.

Bagnall, D. K., Morgan, C. L., Cope, M., Bean, G. M., Cappellazzi, S., Greub, K., Liptzin, D., Norris, C. L., Rieke, E., Tracy, P., et al.: Carbon-sensitive pedotransfer functions for plant available water, Soil Science Society of America Journal, 86, 612–629, 2022b.

Baritz, R., Amelung, W., Antoni, V., Boardman, J., Hijbeek, R., Horn, R., Prokop, G., Römbke, J., Romkens, P., Steinhoff-Knopp, B., et al.: Soil monitoring in Europe–Indicators and thresholds for soil health assessments, Copenhagen: European Environment Agency. doi, 10, 956 606, 2023.

Beven, K.: Robert E. Horton's perceptual model of infiltration processes, Hydrological processes, 18, 3447–3460, 2004.

Bünemann, E. K., Bongiorno, G., Bai, Z., Creamer, R. E., De Deyn, G., De Goede, R., Fleskens, L., Geissen, V., Kuyper, T. W., Mäder, P., et al.: Soil quality–A critical review, Soil biology and biochemistry, 120, 105–125, 2018.

Calzolari, C., Ungaro, F., Filippi, N., Guermandi, M., Malucelli, F., Marchi, N., Staffilani, F., and Tarocco, P.: A methodological framework to assess the multiple contributions of soils to ecosystem services delivery at regional scale, Geoderma, 261, 190–203, 2016.

Coppola, A., Basile, A., Comegna, A., and Lamaddalena, N.: Monte Carlo analysis of field water flow comparing uni-and bimodal effective hydraulic parameters for structured soil, journal of Contaminant Hydrology, 104, 153–165, 2009.

Coppola, A., Zucaro, R., Baralla, S., Satta, M., Ruberto, M., Comegna, A., Dragonetti, G., and Hassan, S. B. M.: Monitoring and modelling fluxes of water and nutrients to surface drainage network from irrigated agricultural fields in a hydraulically Reclaimed Coastal Area, Ecohydrology, 17, e2723, 2024.

Costanza, R., d'Arge, R., De Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'neill, R. V., Paruelo, J., et al.: The value of the world's ecosystem services and natural capital, nature, 387, 253–260, 1997.

Feddes, R., Kowalik, P., and Zaradny, H.: Simulation of Field Water Use and Crop Yield, A Halsted Press book, Wiley, 1978.

Fusco, F., Allocca, V., Bancheri, M., Basile, A., Calcaterra, D., Coppola, A., Neuwirth, M., Puig-Sirera, À., Terribile, F., and De Vita, P.: A multi-method approach for assessing groundwater vulnerability of shallow aquifers in the Marchfeld region (Austria), Journal of Hydrology: Regional Studies, 54, 101 865, 2024.

Geiger, R.: Klassifikation der klimate nach W. Köppen, Landolt-Börnstein–Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, 3, 603–607, 1954.

Hargreaves, G. H. and Allen, R. G.: History and evaluation of Hargreaves evapotranspiration equation, Journal of irrigation and drainage engineering, 129, 53–63, 2003.

https://doi.org/10.5194/egusphere-2025-1927
Preprint. Discussion started: 12 June 2025

Hassan, S. B., Dragonetti, G., Comegna, A., Lamaddalena, N., and Coppola, A.: Analyzing the role of soil and vegetation spatial variability in modelling hydrological processes for irrigation optimization at large scale, Irrigation Science, 42, 249–267, 2024.

Hebbali, A.: olsrr: Tools for building OLS regression models, R package version 0.5, 3, 2020.

Hewitt, A., Dominati, E., Webb, T., and Cuthill, T.: Soil natural capital quantification by the stock adequacy method, Geoderma, 241, 107–114, 2015.

Jarray, F., Hermassi, T., Mechergui, M., Zucca, C., and Le, Q. B.: Long-Term Impact of Soil and Water Conservation Measures on Soil Erosion in a Tunisian Semi-Arid Watershed, Land, 12, 2023.

Jebari, S., Daly, H., Saidi, I., Ezzeddine, H., and Oussaifi, D.: Rmel river basin adaptation plan, Part I & II. Tunis, INRGREF & BeWater Publication, pp. 1–56, 2016.

Jian, J., Du, X., and Stewart, R. D.: A database for global soil health assessment, Scientific Data, 7, 16, 2020.

Lal, R.: Soils and sustainable agriculture. A review, Agronomy for Sustainable Development, 28, 57–64, 2008.

Lehmann, J., Bossio, D. A., Kögel-Knabner, I., and Rillig, M. C.: The concept and future prospects of soil health, Nature Reviews Earth & Environment, 1, 544–553, 2020.

Li, Y., Zhou, Q., Zhou, J., Zhang, G., Chen, C., and Wang, J.: Assimilating remote sensing information into a coupled hydrology-crop growth model to estimate regional maize yield in arid regions, Ecological modelling, 291, 15–27, 2014.

Liu, Y., Wu, K., and Zhao, R.: Bibliometric analysis of research on soil health from 1999 to 2018, Journal of Soils and Sediments, 20, 1513–1525, 2020.

Matthews, C., Braddock, R., and Sander, G.: Modeling flow through a one-dimensional multi-layered soil profile using the Method of Lines, Environmental Modeling & Assessment, 9, 103–113, 2004.

McBratney, A., Morgan, C. L., and Jarrett, L. E.: The value of soil's contributions to ecosystem services, Global soil security, pp. 227–235, 2017.

MEA: Millennium Ecosystem Assessment: Ecosystems and human well-being: Synthesis, Island Press, Washington, DC, 2005.

Moebius-Clune, B., Moebius-Clune, D., Gugino, B., Idowu, O., Schindelbeck, R., Ristow, A., van Es, H., Thies, J., Shayler, H., McBride, M., Kurtz, K., Wolfe, D., and Abawi, G.: Comprehensive assessment of soil health: The Cornell framework manual, Cornell University, 2016.

Olivoto, T. and Barbin, D. L. A.: metan: An R Package for Multi-Environment Trial Analysis, Methods in Ecology and Evolution, 11, 783–789, 2020.

Pearse, J., Oliver, T., and Newitt, D.: The mechanism of the drying of solids: Part I. The forces giving rise to movement of water in granular beds during drying, Trans. Inst. Chem. Eng.(London), 27, 1–8, 1949.

R Core Team, R. S.: R A language and environment for statistical computing, R Foundation for Statistical Computing, Vienna, Austria, 2023.

Rinot, O., Levy, G. J., Steinberger, Y., Svoray, T., and Eshel, G.: Soil health assessment: A critical review of current methodologies and a proposed new approach, Science of the Total Environment, 648, 1484–1491, 2019.

Ritchie, J. T.: Model for predicting evaporation from a row crop with incomplete cover, Water resources research, 8, 1204–1213, 1972.

Sellami, M. H. and Terribile, F.: Research Evolution on the Impact of Agronomic Practices on Soil Health from 1996 to 2021: A Bibliometric Analysis, Soil Systems, 7, 78, 2023.

Shimizu, G., Marubayashi, R., and Goncalves, L.: AgroR: Experimental statistics and graphics for agricultural sciences, R package version, 1, 2022.

https://doi.org/10.5194/egusphere-2025-1927
Preprint. Discussion started: 12 June 2025

SWD, . f.: EU Soil Strategy for 2030, Reaping the benefits of healthy soils for people, food, nature and climate, Commission Staff Working Document, p. 64, 2021.

Van Genuchten, M. T.: A closed-form equation for predicting the hydraulic conductivity of unsaturated soils, Soil Sci. Soc. Am. J., 44, 892–898, 1980.

Vogel, T.: SWM II - Numerical model of two-dimensional flow in a variably saturated porous medium., Tech. rep., Wageningen Agricultural University, 1987.

Wickham, H.: ggplot2: Elegant Graphics for Data Analysis, Springer-Verlag New York, New York, 2016.

Wösten, J., Pachepsky, Y. A., and Rawls, W.: Pedotransfer functions: bridging the gap between available basic soil data and missing soil hydraulic characteristics, Journal of hydrology, 251, 123–150, 2001.