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Comparing hydrological responses across catchments using a new soil water content metric

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Abstract

Soil water content (SWC) is a fundamental variable involved in several hydrological processes governing catchment functioning. Comparative analysis of hydrological processes in different catchments based on SWC data is therefore beneficial to infer driving factors of catchment response. Here, we explored the use of high-temporal resolution SWC data in three forested catchments (2.4–60 ha) in different European climates to characterize hydrological responses during wet and dry conditions. The investigated systems include Ressi, Italy, with a humid temperate climate, Weierbach, Luxembourg, with a semi-oceanic climate, and Can Vila, Spain, with a Mediterranean climate. We introduced a new SWC metric defined as the difference between seasonal mean SWC at a relatively shallow and a deep soil layer. The difference is classified in three distinct states: similar SWC between the two layers, higher SWC in the deeper layer, and higher SWC in the shallow layer. In the most humid site, Ressi, we frequently found similar SWC at the two soil depths which was associated with high runoff ratios. Despite similar precipitation amounts in Can Vila and Weierbach, SWC patterns were very different in both catchments. In Weierbach, SWC was similar across the entire soil profile during wet conditions, whereas evaporation of shallow water resulted in higher SWC in the deep soil layer during dry conditions. This led to high runoff ratios during wet conditions and low runoff ratios during dry conditions. In Can Vila, SWC was consistently higher in the deeper layer compared to the shallow layer, irrespective of the season, suggesting an important role of hydraulic redistribution and vertical water movement in this site. Our approach provides an easy and useful method to assess differences in hydrological behaviour solely based on SWC data. As similar datasets are increasingly collected and available, this opens the possibility for further analyses and comparisons in sites around the globe with contrasted physiographic and climate characteristics.

KEYWORDS
Can Vila, dry and wet conditions, forested catchment, hydrological states, rainfall runoff, Ressi, runoff ratio, soil moisture, Weierbach

1 | INTRODUCTION

Soil moisture, or soil water content (SWC), is a fundamental variable in hydrological systems influencing water fluxes at the land-atmosphere boundary, including energy balance, water budget, and vegetation transpiration. At the small catchment scale (<10 km^2), SWC often exerts a primary role on runoff generation processes, hillslope-stream connectivity, and streamflow response (e.g., Florian et al., 2020; Han et al., 2021; Matgen et al., 2012; Zuecco et al., 2019). Therefore, comparing hydrological processes in different catchments based on SWC data can be beneficial to infer driving factors of catchment response.

In small catchments, in-situ spatially distributed measurements of SWC at sub-hour resolutions are typically collected to investigate hydrological processes associated to SWC variability. The role of SWC on catchment response is frequently expressed in terms of the relation between antecedent SWC and the timing and magnitude of stormflow response. Previous work in both semi-arid catchments with mean annual precipitation <500 mm (Castillo et al., 2003; Schoener & Stone, 2019; Zhang et al., 2011) and in humid catchments with mean precipitation >1000 mm (Singh et al., 2021; Uber et al., 2018) demonstrated that high antecedent SWC is typically associated to large flow volumes, high runoff ratios, and short time lags in stormflow generation. Although the sensitiveness of the catchment response to antecedent SWC conditions varies with soil properties and vegetation cover, it has been shown that including antecedent SWC in models improves runoff predictions (Castillo et al., 2003; Schoener & Stone, 2019; Zhang et al., 2011). Quite often, the influence of SWC on runoff generation in small catchments with contrasting climates revealed a threshold behaviour between antecedent SWC and both surface flow, such as stormflow volume, peak streamflow, runoff ratios (Farrick & Branfireun, 2014; Meyles et al., 2003; Vreugdenhil et al., 2022), and subsurface flow, such as pipe flow and shallow groundwater level (Penna et al., 2011; Tromp-van Meerveld & McDonnell, 2006). This threshold behaviour is usually interpreted as a storage capacity deficit that must be filled and exceeded prior to triggering a significant streamflow response (Martínez-Carreras et al., 2016).

Climate (precipitation and temperature) controls SWC dynamics at the hillslope and catchment scales. Rainfall magnitude and intensity mediate the SWC-runoff response by increasing vertical connectivity and decreasing response time above a rainfall threshold across a wide range of forested ecosystems such as in the Loess Plateau in China (Ge et al., 2022) and in North Carolina, USA (Singh et al., 2021). SWC appears to play a key role in controlling the velocity of a wetting front, the development of preferential flow paths, and the time lag between the rainfall peak and the SWC peak (Singh et al., 2021), gradually homogenizing the response across locations. In fact, the variability in SWC is largest when soils are dry (Dymond et al., 2021; Penna et al., 2009). Air temperature mediates soil evaporation and vegetation transpiration and these processes regulate SWC (Seneviratne et al., 2010). High temperature during dry conditions is often associated with low SWC near the surface (Bourletsikas et al., 2023) driven by water evaporation and transpiration (Renner et al., 2016). In fact, in forested systems transpiration can be an important fraction of total evapotranspiration depending on atmospheric evaporative demand, soil water supply (e.g., SWC), and vegetation cycles (Lagergren & Lindroth, 2002; Xu et al., 2022).

For better understanding the role of SWC on runoff generation processes, several studies have analysed SWC variability in different catchments or hillslope positions, and at multiple depths across the soil profile. Observations of SWC dynamics at different soil depths are often used to infer preferential flow—relatively rapid water movement through the soil that bypasses part of the soil matrix (Hendrickx & Flury, 2001) and its relation to runoff generation (Demand et al., 2019; Zhang et al., 2022). SWC data from several locations have been used to develop hydrological signatures for understanding catchment-scale soil moisture dynamics and runoff response in various land uses (Araki et al., 2022). Scaife et al. (2020) used SWC at different depths in several locations along the hillslope in two small forested catchments in the Coweeta Hydrologic Laboratory, North Carolina, USA. They found that SWC data coupled with groundwater measurements supplemented threshold analyses of quickflow by acting as additional indicators of runoff mechanisms. Particularly, they observed that the degree of coupling between soil moisture and groundwater and their relative response during storms varied across the study catchments and was associated with runoff generation processes characteristic of the hillslope or the catchment (Scaife et al., 2020). Zhang et al. (2021) used SWC measurements from four soil profiles across two hillslopes in a subtropical catchment in China. They identified subsurface flow as the main contributor to flood generation and a SWC-regulated shift from slow to rapid runoff. SWC and precipitation depth mediated the lateral-connectivity from hillslopes to streams responsible for the occurrence of high stormflow amounts (Zhang et al., 2021).

No comparative study has investigated and compared differences in SWC between shallow and deep soil layers among distinct catchments across a variety of climates. We hypothesize that the analysis of SWC at different soil depths during contrasting moisture conditions can serve as an indicator of runoff generation mechanisms at the hillslope and catchment scale and can be adopted as a metric to comparatively assess catchment hydrological response to meteorological forcing. For testing this hypothesis, we rely on the seasonal variability in SWC hillslope-scale patterns at shallow and deeper layers in three small, forested catchments (<1 km^2) under contrasting climatic conditions in Luxembourg, Italy, and Spain. More specifically, we address the following research questions:

i. How do the differences in SWC between shallow and deep soil layers vary with moisture conditions in time and among sites in three forested catchments?
ii. How can the differences in SWC between shallow and deep soil layers be used as a metric to infer hydrological processes in these catchments?

2 | METHODS

2.1 | Study areas

We used data collected from 2017 to 2021 in three experimental catchments located in Luxemburg, Italy, and Spain. The three catchments are forested but characterized by contrasting climate and terrain (Table 1). The climate in the 0.45 km^2 Weierbach catchment, Luxembourg (49°49′38" N, 5° 47′44″ E, Figure 1) is semi-oceanic with mean annual precipitation of 898 mm and mean air temperature of 8.7°C. Catchment elevation ranges from 422 to 512 m a.s.l and is underlain by Devonian schist and phyllite (Hissler et al., 2021). The soils in the Weierbach reach up to 70 cm depth and consist of Siltic, sceletic Cambisol (loamy) (Moragues-Quiroga et al., 2017). More details about this catchment can be found in several previous studies (Antonelli et al., 2020; Glaser et al., 2019; Gourdol et al., 2021; Hissler et al., 2021; Juilleret et al., 2016; Martínez-Carreras et al., 2016; Wrede et al., 2015).

The climate in the 0.024 km^2 Ressi catchment, Italy (45°47′11.8″ N, 11°15′54.1″ E, Figure 1) is humid temperate with a

TABLE 1 Main characteristics of the three study catchments.

Catchment	Size (km^2)	Elevation (m.a.s.l)	Mean soil depth (m)	Mean annual precipitation 2017–2021 (mm)	Mean daily temperature 2017–2021 (°C)	Vegetation
Weierbach	0.45	422–512	0.7	898	8.7	Oak, beech, spruce, and Douglas fir
Ressi	0.02	598–721	2	2119	10.2	Beech, chestnut, maple, hazel, hornbeam, and ash
Can Vila	0.60	1100–1700	1	918	10.3	Scots pine forests and residual oak trees

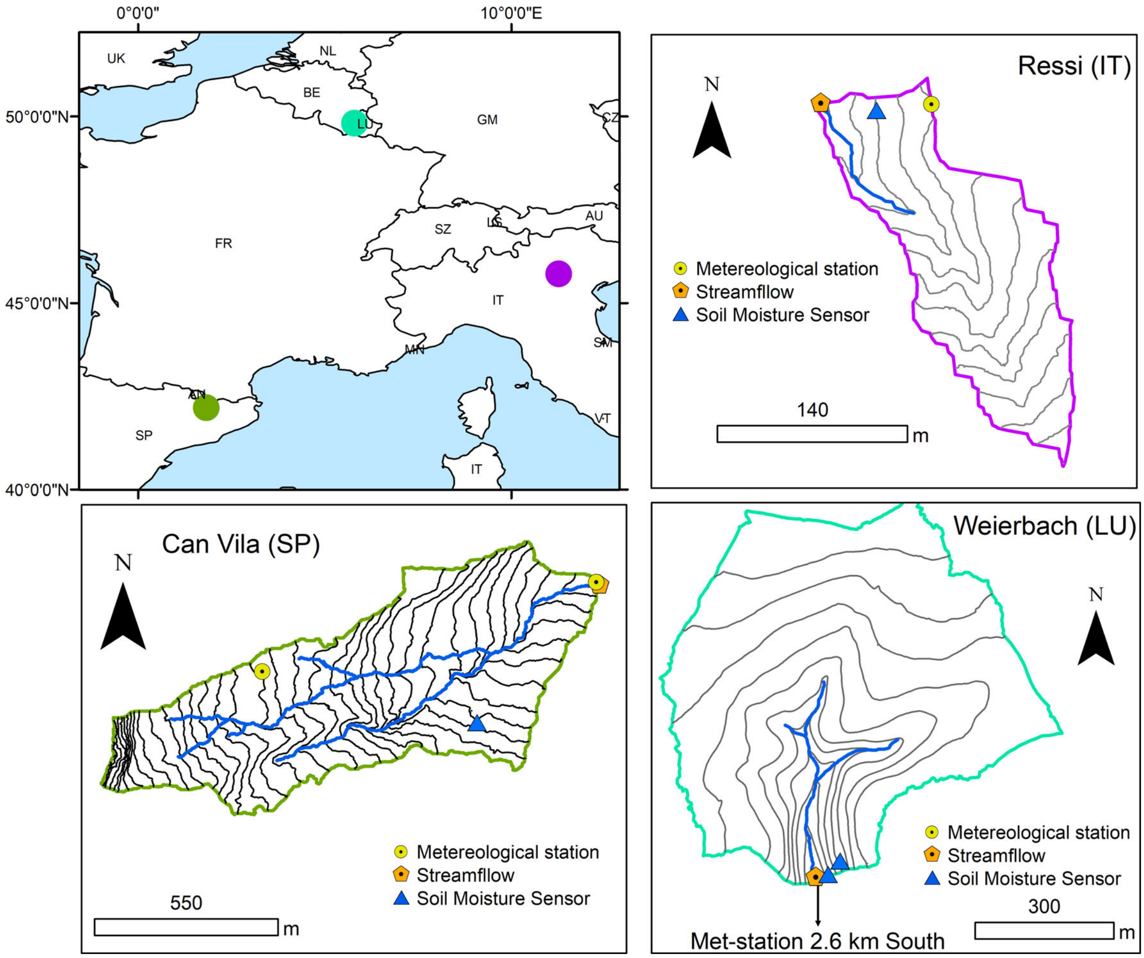

FIGURE 1 Location of the three study catchments: Weierbach in Luxembourg (LU), Ressi in Italy (IT), and Can Vila in Spain (SP). In each map we indicated the location of the sensors considered to monitor streamflow, meteorological conditions, and soil moisture.

mean annual precipitation of 2119 mm and mean annual temperature of 10.2°C. Catchment elevation ranges from 598 to 721 m a.s.l and it is underlain by rhyolites and dacites from Triassic volcanic extrusions (Sedea et al., 1986). The soil is classified as Cambisol. Soil texture in the top 10 cm is sandy clay loam and in the deeper layers is sandy clay (Penna et al., 2015). More details about the Ressi catchment and the hydrometeorological monitoring can be found in Zuecco et al. (2021).

The 0.60 km^2 Can Vila catchment, Spain, (42°12′12″ N, 1°49′3″ E, Figure 1) has a humid temperate climate with mean annual precipitation of 918 mm and mean annual temperature of 10.3°C. Catchment elevation ranges from 1100 to 1700 m a.s.l and the area is underlain by red clayey smectite-rich mudrocks. The soils in Can Vila are silty-loam in texture with depths of 0.5 m to a few meters (Molina et al., 2019) that vary greatly, depending on lithology, geomorphology, and terracing. More details about this catchment can be found in Llorens et al. (2018).

2.2 | Data record and analysis

We compiled four years (2017–2021) of high-resolution hydrometric data in all three catchments including precipitation, streamflow, air temperature, and SWC recorded at two depths. The SWC sensors were located both in relatively shallow and deep soil layers on hillslopes of the study catchments. In the Weierbach catchment, the SWC sensors were located at 10 and 40 cm, in the Ressi catchment at 15 and 45 cm, and in the Can Vila catchment at 0–30 cm and 30–60 cm. In Weierbach, SWC was recorded with Campbell CS 650 SWC Reflectometers (Campbell Scientific, Logan, Utah, USA) (Hissler et al., 2021); in Ressi, SWC was measured with 10HS Frequency Domain Reflectometry probes (METER Group, Inc., USA) (Zuecco et al., 2021) and in Can Vila SWC was measured with 30-cm long Time Domain Reflectometry probes installed vertically in a profile.

To contextualize the results, we summarized monthly hydrometric data in terms of mean precipitation amount, mean precipitation intensity, and mean runoff at the catchment outlet. We then compared SWC distributions at two different soil depths across sites and conditions (dry or wet) using a Kruskal–Wallis test (Kruskal & Wallis, 1952) with Bonferroni correction (Bonferroni, 1936) to avoid Type I error. The SWC data were used to derive a metric for comparing and describing the catchments' hydrologic behaviour. We computed the SWC difference between the deep (D) and the shallow (S) soil layers and then classified SWC records in three distinct states (Figure 2): when the SWC was similar between the two depths (S ~ D), when the deep SWC was higher than the shallow SWC (D > S), and when the shallow SWC was higher than the deep SWC (S > D). The threshold to differentiate the states was defined as 10% of the maximum difference between deep and shallow SWC across all available data in every site (Figure S1).

We quantified the fraction of time in each of the SWC states (Figure 2) using the entire record and splitting the data by SWC condition (i.e., dry and wet). Wet and dry conditions were defined based on

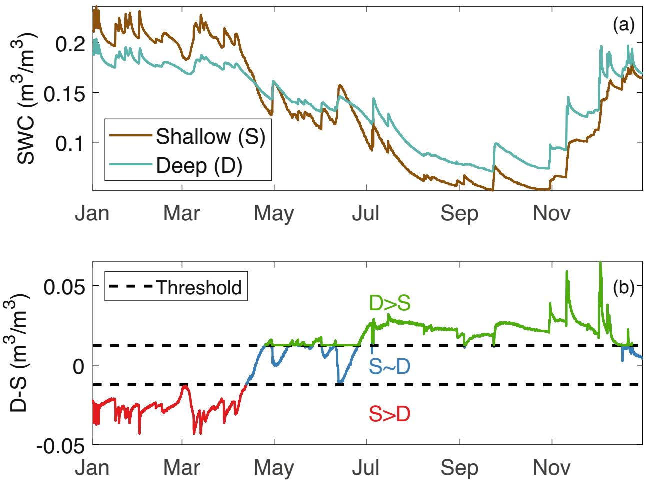

FIGURE 2 (a) Example of annual variability in soil water content (SWC) at the shallow (S) and deeper (D) soil depths and (b) SWC difference between the two soil depths (D-S). Three SWC states were identified: D > S (green); S > D (red); S ~ D (blue). The threshold was defined as 10% of the maximum difference between deep and shallow SWC across all data (Figure S1). The data displayed in this example are from the Weierbach in 2018.

the 2017–2021 SWC distribution in the shallow layer: instances below the 50th percentile of SWC were considered dry and instances above the 50th percentile of SWC were considered wet (Blume et al., 2009). We also quantified hydrologic metrics over the duration of each SWC state, including total precipitation, total runoff at the catchment outlet, catchment runoff ratio (total runoff/total precipitation), and mean air temperature.

3 | RESULTS

3.1 | Precipitation and streamflow characterization

Hydrometric information for the three study sites indicated similar patterns in precipitation intensity and contrasting patterns in the monthly distribution of precipitation and runoff (Figure S2). While in all catchments the mean monthly rainfall intensity was highest in the summer months, precipitation intensity rates were different across sites. In the Weierbach catchment mean monthly precipitation intensity varied between 1.5 and 7.4 mm/h; in the Ressi catchment, precipitation intensity was 1.6 to 3 times larger than in the Weierbach catchment varying between 4 and 11.6 mm/h; and in the Can Vila catchment precipitation intensity reached intermediate values between the Weierbach and the Ressi catchments varying between 3.2 and 8.1 mm/h (Figure S2). In the Weierbach, the months with the highest mean precipitation were December, January, and October, and the months with the highest runoff at the catchment outlet span from December to February (Figure S2). In Ressi, most precipitation was received in the October–December period and in the April–May period, and most of the mean monthly runoff at the catchment outlet

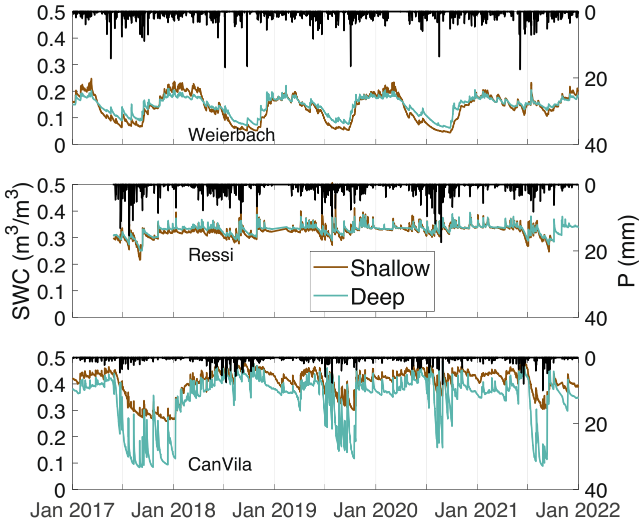

FIGURE 3 Time series of 5-min precipitation and soil water content (SWC) in the shallow (S) and deep (D) soil layers measured between 2017 and 2021 in the three study catchments.

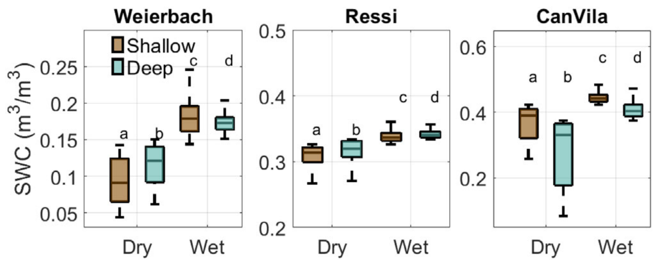

FIGURE 4 Box plots of the soil water content (SWC) at shallow and deep soil layers considering all data collected from 2017 to 2021 in the three study catchments. Data collected were assigned to dry and wet conditions based on SWC distribution measured in the shallow soil layer at each site: instances below the 50th percentile of SWC were considered dry and instances above the 50th percentile of SWC were considered wet. The letters above the bars (a–d) indicate significance of differences between the medians (Kruskal–Wallis test). All *p*-values were equal to zero. The top and bottom of each box indicate the 25th and 75th percentiles of the distribution and the middle line inside the box represents the median value. Lines extending out of the box correspond to the maximum and minimum values. Outliers were omitted.

occurred in November–December, and in April–May (Figure S2). In contrast to both Ressi and Weierbach precipitation in Can Vila was low in December–January and highest in October and April–June. In this catchment, the highest mean monthly runoff at the outlet occurred in November and February–June (Figure S2).

The compiled time series of SWC data illustrated a large variability across sites (Figure 3). For example, SWC values in the Weierbach and Can Vila catchments displayed strong seasonality with higher values consistently occurring in the winter and lower values consistently occurring in summer. Note that SWC values in deeper soil layers were more responsive to rainfall events at the Can Vila catchment during summer than at the Weierbach catchment. In contrast, SWC values in the Ressi catchment showed no clear seasonal pattern, with high SWC values occurring every month of the year.

3.2 | Soil water content distributions

The SWC distribution across the three investigated catchments illustrates large differences between the systems. In the Weierbach, the SWC range was the lowest, i.e., 0.21 m^3/m^3 (0.04–0.25 m^3/m^3). In the Ressi catchment, the range was 0.29 m^3/m^3 (0.21–0.51 m^3/m^3), while the range was the largest in the Can Vila catchment with 0.41 m^3/m^3 (0.08–0.49 m^3/m^3). SWC variability was marked across wet and dry conditions in both shallow and deep locations in all studied sites. In the Weierbach, shallow soil layer SWC was higher than in the deep layer during the wet season and lower during the dry season. In contrast, in Can Vila, shallow soil layer SWC was higher during both the wet and the dry season. In Ressi, shallow SWC was higher during the wet conditions and lower in dry conditions, with very small differences between the two soil depths (Figure 4).

3.3 | Distributions of soil water content states during the 2017–2021 period

The proportion of the analysed record classified into each SWC state (Figure 2) varied greatly across sites. In the Weierbach, 17% of the time the shallow SWC was higher than the SWC in the deep soil layer, 45% of the time the deep SWC was higher than the shallow SWC, while 39% of the time SWC was similar at the two depths (Figure 5). In the Ressi catchment, 84% of the time SWC was similar at the two depths, 14% of the time the deep layer had higher SWC than the shallow one, and only 2% of the time SWC was higher in the shallow layer than in the deep one. In the Can Vila catchment, 79% of the time SWC was higher in the shallow soil layer than in the deep layer, 21% of the time SWC was similar at the two soil depths, and a very small fraction of the record (<0.3%) SWC has higher in the deep soil layer (Figure 5).

The temporal occurrence of the different hydrological states was different between the three sites. In Weierbach, the S ~ D state occurred primarily in fall and spring with over 65% of the occurrences recorded in March and May, as well as between October and December (Figure 6). In contrast, the S ~ D state in the Ressi catchment occurred between 67% and 89% of the time in every month. In the Can Vila catchment, the S ~ D state occurred primarily in summer, with 48% of the occurrences between June and August. The S > D state primarily occurred in the winter months in Weierbach with over 90% between December and March. In contrast, this state was more frequent in summer for the Ressi catchment, with 65% of the occurrences happening between June and September. In the Can Vila catchment, the S > D state occurred primarily between June and October with 65% of the occurrences.

SWC differences between shallow and deep layers were characterized by a strong variability between dry and wet conditions in the

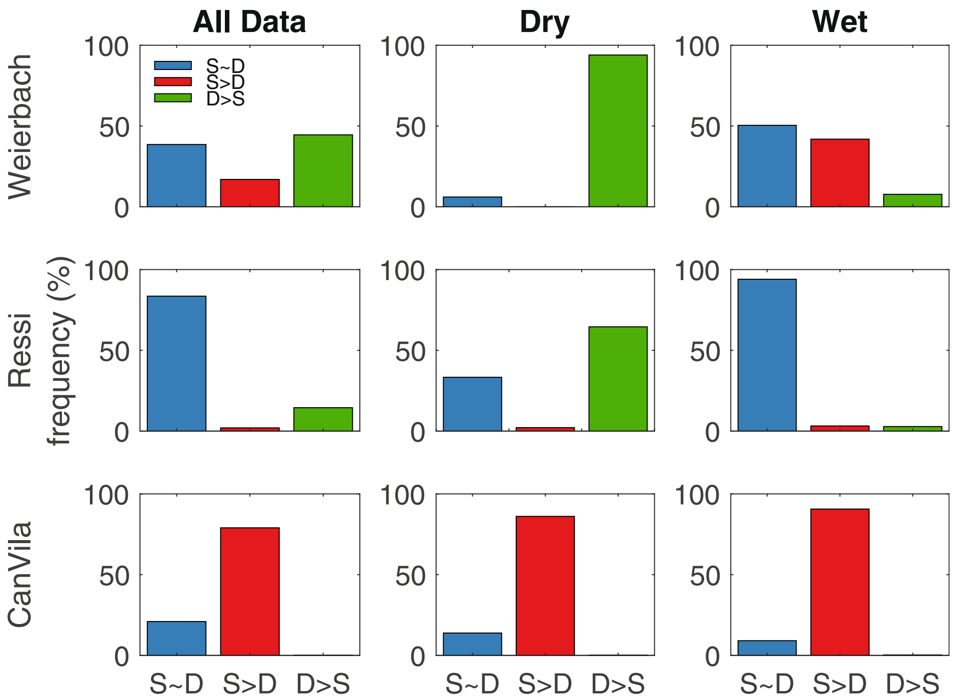

FIGURE 5 Frequency of soil moisture states (see Figure 2) at the three sites considering all data together, data collected in dry conditions, and data collected in wet conditions only. Data collected during dry and wet conditions were defined based on the 2017–2021 full database of the soil water content (SWC) distribution in the shallow layer per site: instances below the 50th percentile of SWC were considered dry and instances above the 50th percentile of SWC were considered wet.

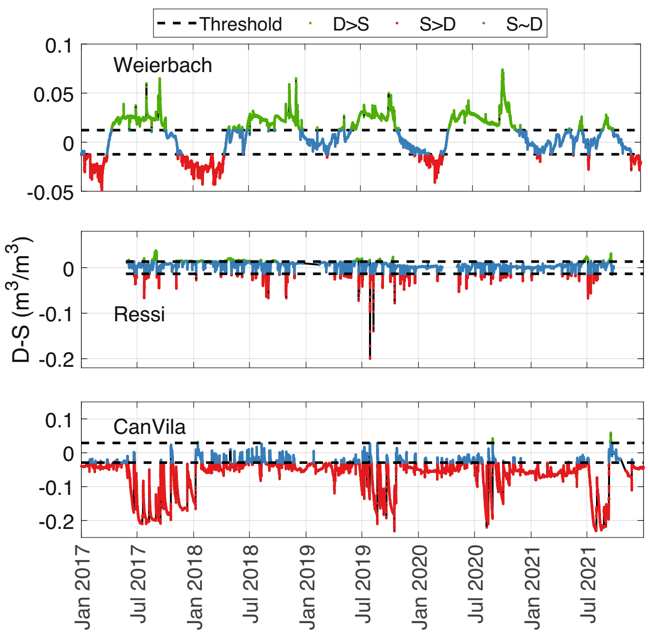

FIGURE 6 Difference between deep (D) and shallow (S) soil water content (SWC) at the three study sites. Three soil moisture states based on the difference between deep (D) and shallow (S) soil water content (SWC); Figures 2 and S1) at the three study sites: D > S (green), S > D (red) and S-D (blue).

Weierbach and Ressi catchments (Figure 5). In Weierbach, during most of the dry period (94% of the time) SWC was higher in the deep soil layer than in the shallow one. However, during the wet period, SWC was primarily similar between the two depths (50%) or higher in the shallow layer (42%) (Figure 5). In Ressi, SWC in the dry season was mostly higher in the deep soil layer (65%) while in the wet season 94% of the time SWC was similar at both soil depths (Figure 5). In Can Vila, SWC states were relatively similar across wet and dry conditions. SWC was higher in the shallow soil layer than in the deep one most of the time in both dry and wet conditions (86% during dry and 90% during wet conditions). Much less frequent was the state in which SWC was similar at both depths (14% of the time in the dry condition and 10% of the time in the wet condition). Frequency of SWC was never higher in the deep soil layer (Figure 5). The strong seasonality of the SWC states in Weierbach is also evident when looking at the distributions of SWC states across the year. In Weierbach, during wet months (December–March, Figure S2) SWC was either similar between the two depths or higher in the shallow layer (Figure S3). Higher SWC in the deep layer was common during the summer months (June–August) (Figure S3) which had lower precipitation (Figure S2). In Ressi, monthly SWC indicates the prevalence of similar SWC between the two depths (Figure S3) while in Can Vila monthly SWC indicates the prevalence of higher SWC in the shallow soil layer (Figure S3).

3.4 | Precipitation and runoff during each SWC state

In the Weierbach catchment, almost one third of the precipitation (35%) was received when deep SWC was comparable to shallow SWC. About 43% of the precipitation was received when the deep SWC was higher than the shallow SWC. The remaining 22% was received when the shallow SWC was higher than the deep SWC. Large fractions of runoff at the catchment outlet were delivered primarily when SWC was similar between soil depths (53%) and when the SWC was higher in the shallow depth (43%). Only 4% of the runoff at the outlet was delivered when the deep SWC was higher than the shallow SWC. In the Ressi catchment, most of the precipitation (74%) and most of the runoff (89%) were associated with states in which SWC was similar at the two depths. In this site, 21% of the precipitation was received when SWC was higher in the shallow soil layer than in the deep one with 4% of the runoff occurring in this state. Little precipitation (5%) and runoff (7%) were related to states in which SWC was higher in the deep layer than in the shallow one. In the Can Vila catchment, most of the precipitation (56%) and runoff at the outlet (52%) occurred when SWC was higher in the shallow layer than the deep one. In this site, 43% of the precipitation was received when the deep SWC and the shallow SWC were similar with 48% of the runoff occurring also under this state. Very little precipitation (<1%) with no associated runoff was associated with states in which SWC was higher in the deep soil layer than in the shallow one (Table S1).

Despite the highlighted differences across the study sites, the fraction of runoff at the catchment outlet (Q) per each hydrologic state and the associated runoff ratio (Q/P) varied with the fraction of time characterized by similar SWC in the deep and shallow soil layers (S ~ D). The fraction of runoff increased with the fraction of time SWC was in the S ~ D state for the all-time series (i.e., all data, dry and wet conditions) (Figure 7a). Similarly, the runoff ratios increased with the fraction of time SWC was in the S ~ D state (Figure 7b).

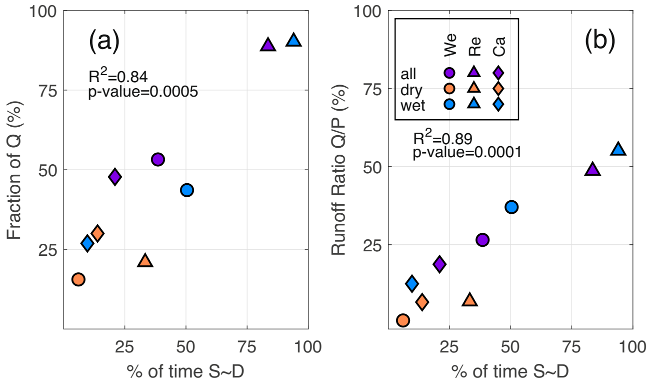

FIGURE 7 Relationship between the fraction of time soil water content (SWC) was similar at the two soil depths (S ~ D) considering all data, data collected during dry and wet conditions and (a) the fraction of runoff (Q) (runoff divided by total runoff at the catchment outlet) delivered during this state and (b) the runoff ratio (Q/P) (total runoff delivered during this state divided by total precipitation). Shapes of the markers correspond to the three catchments: Weierbach (We), Ressi (Re) and Can Vila (Ca).

Runoff is also presented as a function of SWC for the three states in each catchment (Figure 8). In the Weierbach and Ressi catchments, a typical threshold effect between SWCm (i.e., SWC in the shallow soil layer normalized by its mean) and runoff was evident, whereas the threshold relation was more confused in Can Vila. Particularly, in the Weierbach, a clear pattern in the threshold effect during the three states was observed, with the value of the SWCm threshold increasing from the D > S state to the S ~ D, and up to the S > D state. When D > S, a state that typically occurred in summer (Figure 6), the threshold effect was limited and runoff production was reduced as well, whereas during the S ~ D and S > D states higher runoff was produced, and the threshold effect was evident. In the Ressi catchment, the value of the SWCm threshold was quite similar for all three states, but the highest runoff was only produced during the S ~ D state (the state that was more frequent, see Figure 5). In the Can Vila catchment, the threshold effect was less evident but, similarly to the Ressi catchment, the highest values of runoff were reached during the S ~ D state.

4 | DISCUSSION

4.1 | Soil water content variability across three catchments

Our results highlight a wide variability in SWC across the investigated sites, which are located in diverse climatic conditions. This offers a nice opportunity to highlight the effects of climate on SWC. Precipitation characteristics such as depth and intensity have been shown to influence SWC dynamics (Demand et al., 2019; Tymchak & Torres, 2007; Wiekenkamp et al., 2016; Wilson et al., 2004) and given that temperature influences evapotranspiration, it, in turn, exerts a control in SWC (Hasselquist et al., 2018; Schaap et al., 1997). Temporal variability in SWC reflected differences in climate (precipitation and temperature) across the three sites (Figure 4). SWC varied the least in the Ressi catchment, which is the most humid site (i.e., with the highest annual precipitation amount). Conversely, SWC varied the

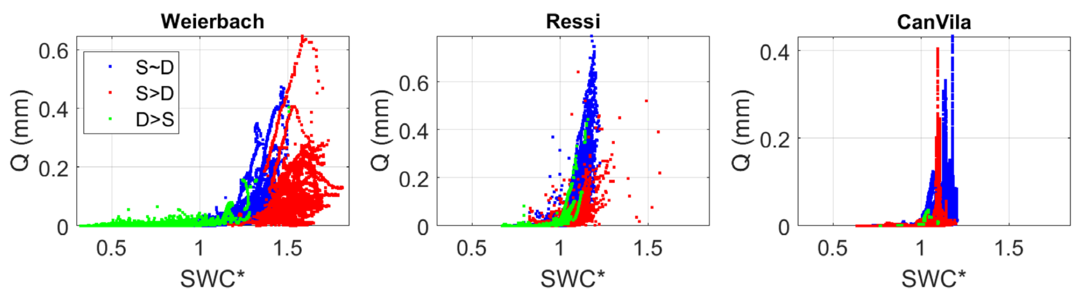

FIGURE 8 Relation between soil water content (SWC) in the shallow soil layer normalized by its mean (SWCm) and stream runoff (Q) in each of the three studied catchments for the entire observation period. Markers are colour-coded according to the three SWC states (see Figure 2).

most in Can Vila, which is the driest site. In this sense, SWC reflects the meteorological forcing of the investigated sites. However, specific differences in the frequency of the three hydrological states (S ~ D, S > D, D > S, Figures 5 and 6) among the three sites suggest the effect of other controls in addition to climate forcing. For instance, in the Ressi and Weierbach catchments, SWC was higher in the lower soil layer during the dry period, and higher SWC was observed in the upper soil layer in the wet period (Figure 4). This reflects the D > S state (in green in Figures 5 and 6) observed almost exclusively in summer in these two catchments as a likely effect of soil water evaporation and tree transpiration (Bourletsikas et al., 2023; Gwak & Kim, 2017; Jia et al., 2016). Particularly, the more marked seasonality of the D > S state in the Weierbach catchment compared to the Ressi catchment (Figure 6) might be related to the occurrence of more intense summer rainfall events in Ressi, typical of the humid temperate climate, that disrupt the D > S state (Figure S2A). Conversely, in Can Vila, SWC was higher near the soil surface and lower in the deeper soil layer both in the dry and in the wet periods (Figure 4), and the D > S state never occurred (Figures 5 and 6). This situation could be related to the presence of pines with deep root apparatuses that can, on the one hand, access deep soil water in addition to the shallower one and, on the other hand, also enhance vertical hydraulic redistribution of water (Espeleta et al., 2004; Pinos et al., 2022; Skubel et al., 2017; Warren et al., 2008; Wei et al., 2022). Importantly, from a process perspective, the large occurrence of the S > D state suggests that vertical movements of soil water dominate in Can Vila and are responsible for efficient groundwater recharge observed during and immediately after rainfall events (Sprenger et al., 2019).

4.2 | Soil water content state as a metric to characterize hydrologic states and processes

Our analysis shows different precipitation depth and runoff values between the three soil moisture states in the three study catchments, indicating a large variability in SWC under different hydrological regimes. However, when considering all catchments together, we identified a consistent pattern in the relation between the fraction of time SWC was similar at the two soil depths (S ~ D) and both the fraction of runoff and the runoff ratio (Figure 7). This pattern suggests that during the S ~ D state, SWC at the shallow and deep layers was likely high and close to saturation, therefore increasing hydraulic conductivity and facilitating subsurface runoff generation, hillslope-stream connectivity and subsequent rapid delivery of water to the stream, and high runoff and runoff ratio values, as often observed in catchments characterized by various climates and land cover (e.g., James & Roulet, 2009; Muñoz-Villers & McDonnell, 2013; Penna et al., 2011; Schoener & Stone, 2019). More specifically, for the Ressi catchment, the largest fractions of time when shallow and deep SWC were similar (S ~ D) were associated with high runoff fraction values and high runoff ratios. This was particularly evident during wet conditions, in agreement with previous observations on the flashy response of this humid catchment (Penna et al., 2015; Zuecco et al., 2016). On the contrary, in the Can Vila catchment, the fraction of time during which S ~ D was small (less than 25%), the associated runoff values and runoff ratios were also small, even during wet conditions (Figure 7 and Table S1). Indeed, in this catchment, SWC in the shallow layer was higher than SWC in the deep layer for most of the time (Figure 6, bottom panel). This observation, as mentioned in Section 4.1, indicates significant moisture depletion from the deep layers and suggests the predominance of vertical drainage. This process explains the reactive response of groundwater previously documented in the Can Vila catchment and the large fraction of young water in groundwater (Sprenger et al., 2019). Therefore, the new, simple metric we introduced in this work was able to detect and highlight different hydrological behaviours in various catchments and to explain hydrological processes previously not so well understood. The largest difference in the relation between the fraction of time during which SWC was similar at the two soil depths and the fraction of runoff and the runoff ratio between dry and wet conditions was observed for the Weierbach catchment (Figure 8). In this site, low-intensity precipitation rather evenly distributed throughout the year (Figure S2) combined with large evapotranspiration fluxes during the summer and tree transpiration of shallow water results in very low flow during dry conditions (Fabiani et al., 2022; Hissler et al., 2021). This situation reflects well the low runoff values and runoff ratios observed during dry conditions which were associated with very infrequent occurrence of the S ~ D state (Figure 7).

The largest stream runoff in the three catchments was generated when a certain SWC threshold was exceeded (Figure 8). However, this condition was reached under different moisture states in each site. In the Ressi catchment, this threshold occurred mostly during the S ~ D state, while in the Weierbach and Can Vila catchments the threshold was associated with the S ~ D and the S > D states. These observations are consistent with Figure 7. The D > S state was mostly associated with dry conditions (i.e., below the SWC threshold) for all three catchments, indicating lower SWC in the shallow soil layer compared to the deep soil layer, mostly occurring during summer. This is likely due to the combined effect of high solar radiation and tree transpiration fluxes that result in low streamflow. The larger range in the relation between SWCm and stream runoff observed in the Weierbach catchment compared to the Ressi and especially to the Can Vila catchments may reflect site-specific soil characteristics in the three catchments. Although this threshold relation has been observed in many other catchments under different climatic conditions (recent examples are Chittolina et al., 2023; Qazi, 2020; Scaife et al., 2020; Zhao et al., 2020), this is the first time that this behaviour has been associated with different SWC states that underly distinct hydrological processes.

5 | CONCLUSIONS

The comparative understanding of runoff processes in catchments characterized by different climatic forcing, land cover, and physiography is still a challenge in current hydrological research. In this work, we introduced a novel, simple but powerful metric based on the difference between soil water content (SWC) in shallow and deep soil layers to investigate the hydrological response of three small, forested catchments in Europe featuring contrasting properties. The new metric proved to be effective in distinguishing three hydrological states and the main distinct catchment behaviours associated with them. A variable frequency of the three hydrological states in the three sites revealed a different control of the climatic forcing on each catchment's response. Specifically, this metric was able to explain the variance of runoff ratios. Sites with a large occurrence of times during which SWC was similar at the two soil depths consistently had higher runoff ratios compared to catchments that had a low occurrence of this state and low runoff ratios. Moreover, the SWC metric helped to better explain hydrological processes previously not entirely understood, as in the case of the site with Mediterranean climate where the dominance of vertical soil drainage responsible for groundwater recharge was assessed. The application of this metric in these three forested catchments in Europe revealed new behaviours and laid the basis for future analyses. Further comparative tests should be conducted in sites featuring other climates and vegetation cover to assess the full potential of this approach for characterizing a catchment's hydrological response.

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DATA AVAILABILITY STATEMENT

Weirbach data are available at: https://zenodo.org/record/4537700#.YinObBDMI-R. Ressi data are available at: https://osf.io/n24dg/. Can Vila data are available at http://hdl.handle.net/10261/335494.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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