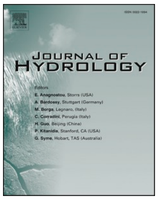
Journal of Hydrology 639 (2024) 131642

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol



Research papers

Seasonal meteorological forcing controls runoff generation at multiple scales in a Mediterranean forested mountain catchment

M. Macchioli Grande[a,b,*], K. Kaffas[c,d], M. Verdone[c], M. Borga[e], C. Cocozza[c], A. Dani[c], A. Errico[c], G. Fabiani[c,f], L. Gourdol[f], J. Klaus[g], F.S. Manca di Villahermosa[c], C. Massari[h], I. Murgia[c], L. Pfister[f,i], F. Preti[c], C. Segura[j], C. Tailliez[f], P. Trucchi[c], G. Zuecco[e,k], D. Penna[c,h,j]

[a] *Regional Centre of Scientific Research and Technological Transfer of La Rioja (CRILAR), National Scientific and Technical Research Council, Anillaco, La Rioja, Argentina*
[b] *Institute of Geology and Natural Resources, Centre of Research and Innovative Technologies, National University of La Rioja, Argentina*
[c] *Department of Agriculture, Food, Environment and Forestry, University of Florence, Italy*
[d] *Department of Science, Roma Tre University, Rome, Italy*
[e] *Department of Land, Environment, Agriculture and Forestry, University of Padova, Italy*
[f] *Department of Environmental Research and Innovation, Luxembourg Institute of Science and Technology (LIST), Luxembourg*
[g] *Department of Geography, University of Bonn, Germany*
[h] *Research Institute of the Geo–Hydrological Protection, National Research Council, Italy*
[i] *Faculty of Science, Technology and Medicine, University of Luxembourg, Luxembourg*
[j] *Oregon State University, Forest Engineering Resources and Management Department, Corvallis, USA*
[k] *Department of Chemical Sciences, University of Padova, Italy*

ARTICLE INFO

Keywords:
Streamflow response
Hydrograph separation
Time lags
Nested spatial scales
Electrical conductivity
Soil moisture

ABSTRACT

Understanding hydrological processes during dry periods in Mediterranean mountain catchments is critical due to the increasing frequency of drought episodes. In this work, we aimed at characterizing the effect of the seasonal variability of meteorological forcing on the hydrological response of a small mountain forested catchment in the Mediterranean region. We analyzed the hydrological response and its timing based on hydrometric and electrical conductivity (EC) data for a year in the nested (0.31–2 km^2) Re della Pietra catchment, in Central Italy. We used a soil moisture-based metric to distinguish between wet and dry periods and performed EC-based hydrograph separations during these two periods. The results revealed the important role of seasonality as a meteorological forcing affecting soil moisture, groundwater, streamflow response, and stream event water fractions. Wet and dry periods were distinctly characterized by different streamflow, soil moisture, and groundwater responses. Event water fractions in streamflow also highlight the relevance of the seasonality in the meteorological forcing on runoff generation. Particularly, at the rainfall-runoff event scale, the combination of antecedent soil moisture and precipitation depth controlled the non-linear response of streamflow, groundwater, and different event water fractions in the wet and dry periods.

Stream stages and event water fractions also varied across nested spatial scales. Antecedent moisture conditions triggered a faster streamflow response due to higher connectivity along the hillslope in the wet period, with higher event water fractions in the upper sub-catchments (25 %) compared to the lower sub-catchments (15 %). Conversely, in the dry period, higher event water fractions were registered at the outlet (11 %) than at the headwaters (7 %). Time lags between peak flows observed across the nested catchment showed a complex pattern, suggesting the interaction of multiple factors controlling the timing of streamflow peaks in the study area. These findings contributed to improve our mechanistic insights into the elusive seasonal hydrological patterns observed in Mediterranean mountain forested catchments.

---

* Corresponding author at: Department of Geology, University of Chile, Santiago, Chile.
E-mail address: mmacchioli@ing.uchile.cl (M. Macchioli Grande).

https://doi.org/10.1016/j.jhydrol.2024.131642
Received 31 July 2023; Received in revised form 19 June 2024; Accepted 20 June 2024

1. Introduction

The hydrological functioning of catchments is influenced by complex interactions between meteorological forcing, geomorphological features, soil properties, geology, vegetation cover, and land use (Bracken and Croke, 2007; Llorens et al., 2018; Wei et al., 2020; Birch et al., 2021; Massari et al., 2023). Despite the body of literature investigating the main controls on catchment hydrological response, our understanding of how runoff generation changes between dry and wet periods and across multiple spatial scales is still limited. Particularly, two processes that are related to the mechanistic fundamentals of runoff generation in mountain catchments are (i) the role of antecedent moisture conditions in controlling streamflow and groundwater response under dry and wet conditions, and (ii) the change in event water fractions in streamflow (the proportion of water input to the catchment, i.e., rainfall or snowmelt) compared to pre-event water fractions (i.e., water stored in the catchment prior to the rainfall or snowmelt event) across nested catchments. Although these processes can be case-sensitive depending on factors like climate and physiographic properties of the study area, their characterization is essential for a detailed understanding of rainfall-runoff dynamics at the catchment scale (Ries et al., 2017; Wei et al., 2020).

Previous studies have addressed the influence of antecedent soil moisture and storm characteristics on streamflow, shallow groundwater response, and event water contributions in mountain forested catchments. Llorens et al. (2018) reported extensive monitoring for 30 years at the Vallcebre experimental catchment, a small partly forested mountain catchment in the Catalan Pre-Pyrenees, northeastern Spain. The authors stressed the combined effect of antecedent moisture conditions, precipitation depth and intensity, and forest cover on the catchment hydrological response. Detty and McGuire (2010) identified hydrologic connectivity as a key control for catchment runoff response in a small, forested catchment in New Hampshire, USA. They showed that seasonal variations of hydrologic connectivity were related to dynamics in evapotranspiration, soil moisture storage, and groundwater recharge. Scaife and Band (2017) reported stormflow threshold behavior influenced by antecedent soil moisture and gross precipitation at forested mountain catchments of the Coweeta Hydrologic Laboratory, North Carolina, USA, finding differences between the dormant and the growing season. Thresholds in stormflow generation were also identified in a humid forested catchment in China, revealing the importance of antecedent conditions on the swift changes from slow to rapid runoff response (Zhang et al., 2021).

Hydrological processes in Mediterranean catchments, in particular, are affected by the strong seasonality in the meteorological forcing (i.e., alternance between a wet period in fall/winter and a dry period in spring/summer) and are thus extremely sensitive to drought episodes which are increasing both in frequency and severity (Giorgi and Lionello, 2008; Vasiliades and Loukas, 2009; Sellami et al., 2016; Massari et al., 2022). Nanda and Safeeq (2023) analyzed 129 rainfall-runoff events in Mediterranean headwater catchments in California (USA) and showed that runoff was eventually triggered when the total wetness (storage plus precipitation) exceeded specific thresholds. Their analysis also indicated that storage was higher at the downslope than at the upslope position, yielding higher runoff values. Dymond et al. (2021) studied water movement and storage on a forested Mediterranean slope. They observed that near-stream locations (riparian and footslope) were the wettest during the wet period, as well as ridges, with similar contents at 15, 35, and 100 cm of depth. However, during the dry period, soil moisture exhibited high variability among all depths and topographic positions, with higher influence of local factors, plant water use, soil texture, and climatic forcing.

The analysis of event water contribution provides insight into runoff response to precipitation in catchments (Buttle, 1994; Pellerin et al., 2008), and allows process identification when studying the seasonal differences in the contributions of various sources to streamflow (e.g., Penna et al., 2015). Event and pre-event water fractions at the rainfall-runoff event scale or at seasonal, annual, or multiannual time scales are typically computed through tracer-based (e.g., stable isotopes of hydrogen and oxygen, or electrical conductivity) hydrograph separation techniques (Klaus and McDonnell, 2013). Hydrograph separation analysis in a partially forested mountain headwater catchment in Switzerland revealed that pre-event water fractions were mainly controlled by rainfall amount with a limited influence of antecedent moisture conditions (Fischer et al., 2017). On the contrary, von Freyberg et al. (2018) found unclear relationships between antecedent moisture and storm characteristics and event or pre-event water contributions in another steep mountain forested catchment in Switzerland. Two- and three-component hydrograph separation was also performed in a small, forested catchment in the Italian Pre-Alps, revealing a strong seasonality in runoff generation (Penna et al., 2015). Summer streamflow was mainly generated through direct channel precipitation and saturation overland flow from the riparian zone. In contrast, fall and winter streamflow was predominantly fed by groundwater and hillslope soil water contributions. Mosquera et al. (2018) compared the use of different tracers in hydrograph separation in the catchments of the Mediterranean HJ Andrews Experimental Forest (Oregon, USA), but did not address specific seasonal hydrological responses.

In addition to quantifying the role of antecedent soil moisture and threshold behaviors on runoff generation, and event fraction contributions to streamflow, the analysis of stream response timing across nested spatial scales can provide valuable insights into possible changes in hydrological processes controlling discharge with increasing catchment size. However, studies focusing on this aspect performed in forested mountain catchments with Mediterranean climates remain scarce. McGlynn et al. (2004) studied the streamflow response in micro- and small-scale mountain forested catchments at Maimai (<1–280 ha) in New Zealand. These authors did not observe any consistent pattern of new water contribution with increasing catchment area, but their findings revealed an increment of time lag responses with increasing catchment size. For small (7–147 ha) forested catchments in Québec, Canada, event water contributions were found to be unrelated to catchment size but dependent on rainfall intensity and storm size, with higher event water transit time with increasing areas (Segura et al., 2012). Contrarily, Guastini et al. (2019) observed an overall decreasing trend of specific streamflow and runoff coefficients moving from a small grassland catchment to larger forested catchments (0.14–109 km^2) in the Dolomites, in northern Italy. However, they did not find any distinct relationship between lag times and catchment scales, suggesting interactions of multiple factors on response times.

The literature inspection reported above clearly reveals that only few studies have been carried out on the role of antecedent moisture conditions on catchment response during dry and wet periods, and on changes in event water fractions and timing of stream response across spatial scales. Most importantly, no studies have been conducted on these aspects in Mediterranean mountain forested catchments. To fill these knowledge gaps on the role of antecedent conditions on hydrological processes in meteorological contrasting periods, and on runoff volume timing across multiple spatial scales, we conducted a study based on hydrometeorological and tracer data collected in the small forested and nested Re della Pietra catchment, in the Apennine mountains, Central Italy. This catchment can be considered representative of Mediterranean mountain forested catchments due to its physiographic and climatic characteristics, thus making it an ideal setting for investigating seasonal patterns in hydrological responses. We aim to achieve a better mechanistic understanding of how the seasonal variability of the meteorological forcing affects the hydrological response at the headwater catchment scale, and between different spatial scales. In particular, we addressed the following questions:

i) How do antecedent moisture conditions control streamflow and shallow groundwater response during dry and wet periods?

ii) How do event water fractions and timing of stream response change with increasing spatial scales?

2. Study area

The Re della Pietra is a 2 km^2 experimental forested catchment located in the Tuscan Apennines, Central Italy (Fig. 1a). The area is part of the International Model Forest network (https://imfn.net/) and is managed by the local Forest Service. The climate is temperate Mediterranean with wet (approximately October–May) and dry (approximately June–September) periods. The average annual precipitation depth is 1316 mm (1992–2022) based on data available from a weather station located at 1005 m a.s.l. (12 km south from the catchment) and operated by the Regional Hydrological Service. The year 2021, which covers most of the data collected for this study, was characterized by an annual precipitation of 1212 mm, i.e., slightly less than the long-term average. Therefore, the study period can be considered representative of the long-term hydrometeorological conditions in the study area. Average monthly temperatures vary from 2 °C in January to 20 °C in August, and the average annual temperature is 10.5 °C, according to data from the aforementioned weather station. Elevations range from 634 to 1320 m a.s.l., the average slope (from headwater to outlet) is 27.5°, and the stream channel is approximately 3000 m long. The catchment geology consists of sandstones corresponding to the Late Oligocene – Early Miocene Macigno Formation (Amendola et al., 2016). The soil is well drained and typically deeper than 50–80 cm, as assessed by spatially distributed knocking pole measurements. Soil texture in the upper headwater portion of the catchment was determined through the analysis of 11 soil samples collected in March 2021 at 0–20 cm (four samples), 20–40 cm (four samples), and 40–60 cm (three samples) close to the soil moisture sensors (see Section 3.1). Sand content in the 11 samples ranged between 57 and 76 %, and clay content between 4 and 11 %. Soil texture in all samples resulted in sandy loam, according to the USDA (1999) classification. The catchment area is predominantly covered by forests (>95 %), dominated by beech trees (*Fagus sylvatica*), oaks (*Quercus cerris*), and conifers (*Pseudotsuga menziesii* and *Pinus nigra*).

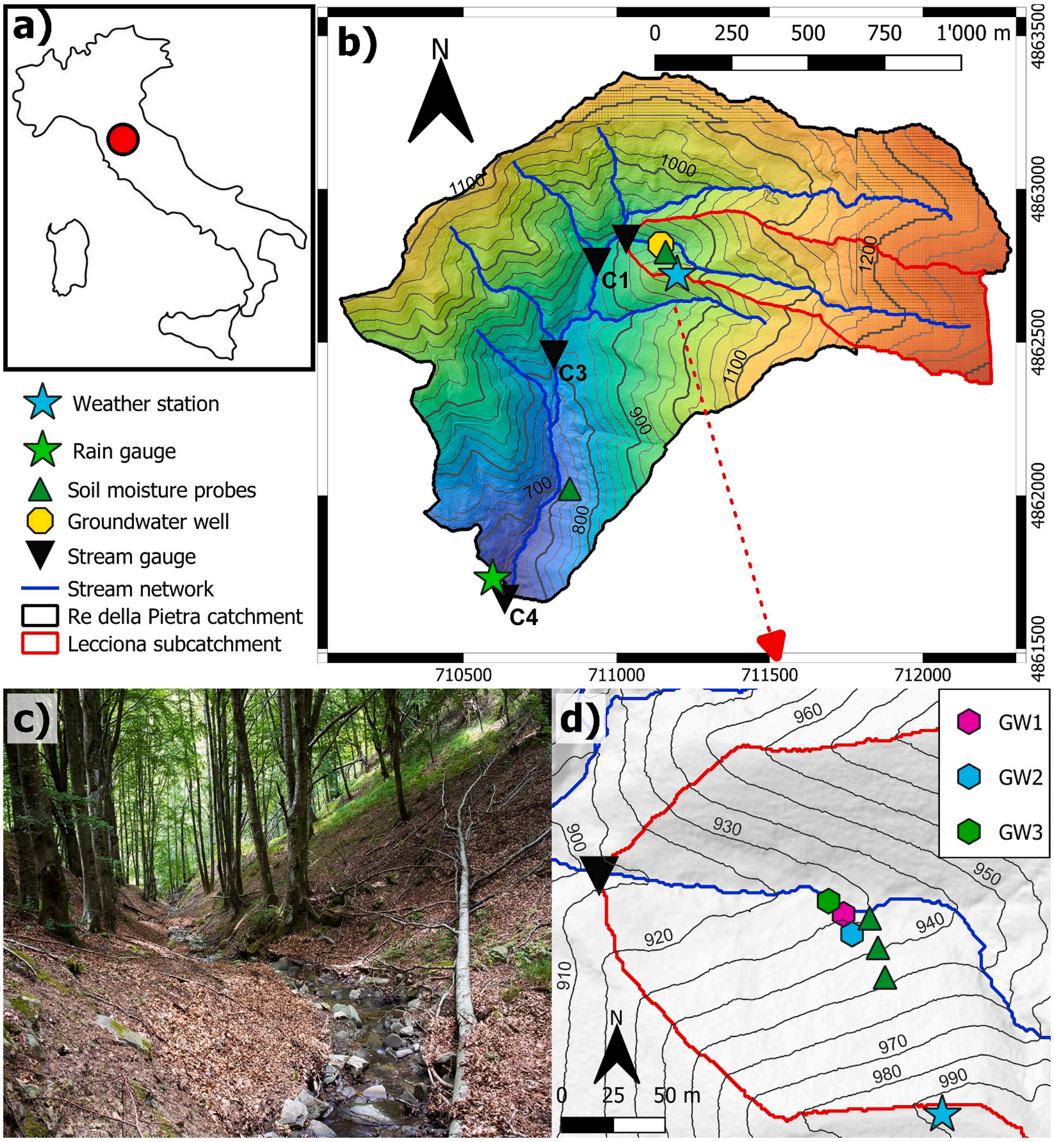


Fig. 1. A) Study area in the Tuscan Apennines (Italy). b) Map of the Re della Pietra experimental catchment, showing the position of the monitoring instruments (stream and rain gauges, groundwater wells, weather stations, and soil moisture probes. c) Field picture of the Lecciona sub-catchment. d) Detailed map of the Lecciona sub-catchment, showing the location of the instruments, including the weather station, the soil moisture probes, the three groundwater wells (GW1, GW2, and GW3), and the stream gauge.

3. Materials and methods

3.1. Hydrometeorological measurements

Hydrometeorological data were collected during one calendar year, from 19 January 2021 to 20 January 2022. Four sub-catchments, from the headwater to the outlet, were selected to investigate the hydrological response across nested scales (Fig. 1b). The sub-catchments drain 0.31–2 km^2, with average slopes varying between 23.2 and 27.5°, and stream lengths ranging from 1357 to 3001 m (Table 1). Most of the instruments were installed in the Lecciona sub-catchment, in the headwater portion of the Re della Pietra. A representative field picture of the Lecciona stream is shown in Fig. 1c. A weather station installed in a forest clearing near the boundary of the Lecciona sub-catchment at 991 m a.s.l. (Fig. 1d) records precipitation depth, air temperature, air humidity, solar radiation, wind speed, and wind direction at a 10-minute time step (reported precision for precipitation of 0.2 mm). Precipitation depth and air temperature were also recorded in another tree-free area at the outlet (C4) of the Re della Pietra catchment, at 634 m a.s.l. (Fig. 1b). Given their different elevations and the small size of the Re della Pietra catchment, the two rain gauges were deemed representative of the precipitation amount in the study area. Because of a two-week technical malfunction of the weather station at Lecciona, data from the rain gauge at C4 were used to fill in the gaps.

Stream stage, water temperature, and water electrical conductivity (EC) data were recorded at a 10-min interval by a CTD (conductivity, temperature, depth, with precisions of ± 0.5 % μS/cm, ± 0.3 °C, and ± 0.05 % mm, respectively) probe at Lecciona, C1, and C4, whereas at C3 only the stream stage was registered (reported precision of ± 0.05 % mm). At the Lecciona sub-catchment, a sharp crested weir with a composite triangular-rectangular shape was built to convert stream stage data into streamflow. The equations for the sharp crested weir were validated through multiple discharge measurements carried out using the salt dilution method under different hydrological conditions.

Soil moisture was measured as volumetric water content by six probes installed in the Lecciona sub-catchment and recorded at a 10-min interval (Fig. 1d). The probes were installed in a transect along the hillslope, in three positions separated by 5 m each: the riparian area at the bottom of the hillslope, the lower part of the hillslope, where a gentle break in slope was evident, and in the middle part of the hillslope. In each position, two probes were installed, one at 15 cm and another at 35 cm depth. The raw values of the probes were converted into volumetric water content (m^3/m^3) by applying a standard calibration for mineral soils suggested by the manufacturer (reported precision: 0.03 m^3/m^3). Soil moisture data among the three hillslope positions (riparian, low-slope, and mid-slope) were averaged by depth (15 and 35 cm) to assess the effect of soil moisture at the hillslope scale on the catchment hydrological response.

The influence of antecedent soil moisture conditions on the hydrological response was evaluated by computing the antecedent soil moisture index (ASI, Haga et al., 2005) given in Eq. (1):

$$ASI = \theta \times D \tag{1}$$

where θ is the volumetric soil moisture content at a given depth (m^3/m^3), and D is the installation depth (m). ASI was calculated based on soil moisture values recorded over one hour before the beginning of a precipitation event and averaged between the two depths and hillslope positions.

Pressure transducers measured groundwater levels in the Lecciona sub-catchment at a 15-min interval in three wells (reported precision is ± 0.05 mm). Two wells (GW1 and GW3) were located in the riparian zone, and a third one (GW2) was located at the foot of the hillslope (Fig. 1d).

3.2. Separation between wet and dry periods

We used the soil moisture-based metric proposed by Segura et al. (2023) to distinguish between wet and dry periods. First, we computed the hillslope spatial average soil moisture, i.e., among the three hillslope positions. Next, we determined the difference between the hillslope-average soil moisture at 35 and 15 cm depths. Upward positive peaks indicate that soil moisture at 35 cm is higher and responds earlier to precipitation than soil moisture at 15 cm, and were assigned to the wet period, while downward negative peaks indicate that soil moisture at 35 cm is lower and responds later than at 15 cm, and were assigned to the dry period (Fig. 2).

3.3. EC-based hydrograph separation

We used a tracer-based hydrograph separation approach to estimate the contribution of water originated from precipitation events ("event water") and the contribution of water already stored in the catchment ("pre-event water") to total streamflow. The latter is assumed to be a mixture of soil water and groundwater (Sklash and Farvolden, 1979; Laudon and Slaymaker, 1997; Penna et al., 2015). We used EC as a tracer in the hydrograph separations due to its simplicity in data acquisition and the high-resolution recording (e.g. Pellerin et al., 2008; Mosquera et al., 2018; Lazo et al., 2023). Hydrograph separation was performed i) at the yearly time scale at the stream gauges in Lecciona, C1, and C4; and ii) at the rainfall-runoff time scale during selected events in Lecciona only (see Section 3.4). At the yearly time scale, EC might behave as a non-conservative tracer due to dilution (during high flow) and concentration (during low flow) effects, resulting in non-stationary values of the pre-event water end-member signature over time, which is one of the prerequisites of the two-component hydrograph separation technique (Buttle, 1994). In our case, we found a slight differences in the EC signature during baseflow conditions, between the wet and the dry periods, being 1, <1, and 13 μS/cm for Lecciona, C1, and C4 respectively (Fig. S1).

Therefore, we applied EC-based hydrograph separation for wet and dry periods separately, identifying the pre-event water EC signature as the highest EC values measured in each stream section during base flow conditions. Because of its short duration, the seasonal dilution/concentration effect becomes negligible at the time scale of rainfall and runoff events, and EC can be considered a conservative tracer (Birch et al., 2021). In this case, the EC signature of pre-event water was identified as the highest EC value one hour before the event onset or during the initial phase of the event (Penna et al., 2016; Buttle, 1994). For both approaches (annual and event scale hydrograph separation), the EC of event water was represented by the average EC from precipitation water monthly collected by an evaporation-free sampler installed

Table 1
General characteristics of the Re della Pietra (RdP) catchment at different spatial scales.

Sub-catchment name	Size (km^2)	Elevation range (m asl)	Average slope (°)	Main stream length (m)*	Main tree species
Lecciona	0.31	913–1313	23.2	1357	*F. sylvatica*
RdP at C1	0.99	873–1320	23.6	1554	*F. sylvatica*
RdP at C3	1.34	815–1320	24.9	1994	*F. sylvatica* – Mixed deciduous forest
RdP at C4	2.00	634–1320	27.5	3001	*F. sylvatica* – Mixed deciduous forest

[2] *stream length was defined as the length of the channel measured in GIS environment from a digital elevation model (1x1 m, except in the upper part of the catchment where only 10x10 m^2 resolution was available).

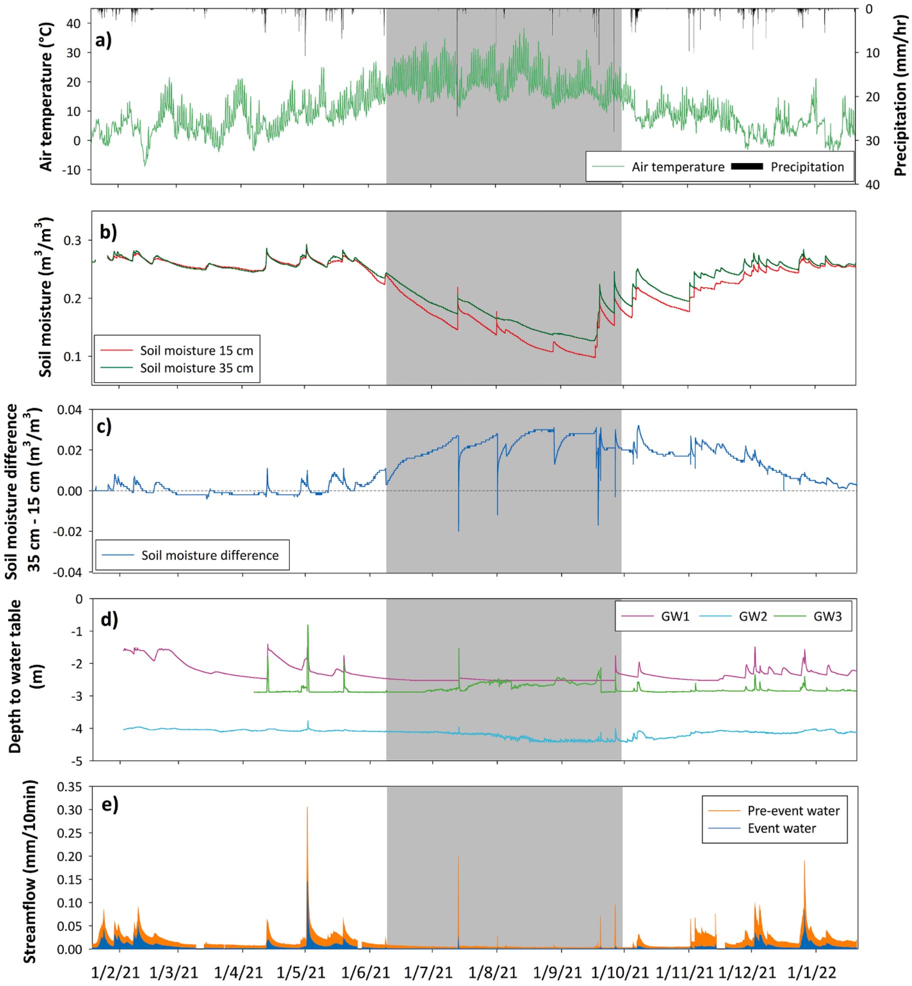


Fig. 2. Time series of hydrometeorological variables in the Lecciona sub-catchment. The grey shaded area shows the dry period as defined by the soil moisture-based metric (described in Section 3.2). a) Precipitation and hourly air temperature registered by the weather station. b) Spatial average (among the three hillslope positions) soil moisture at 15 and 35 cm. c) Difference between average soil moisture at 35 cm and 15 cm. d) Groundwater level in the three wells. e) Event and pre-event water in streamflow at the Lecciona sub-catchment.

close to the weather station.

The hydrograph separation was carried out employing the following equation:

$$f_e = \frac{C_s - C_p}{C_e - C_p} \tag{2}$$

where f_e is the event water fraction, C_s is the electrical conductivity of stream water, C_e is the electrical conductivity of precipitation, and C_p is the electrical conductivity of pre-event water.

3.4. *Identification of precipitation-runoff events and time-lag analysis*

Precipitation-runoff events were defined as events with a precipitation depth > 1 mm, which yielded a streamflow response > 0.01 mm/10 min. Based on these criteria, 34 events were identified during the study period in the Lecciona sub-catchment (Table S1). At the event scale, the distinction between baseflow and stormflow was performed using the constant-k method (Blume et al., 2007). The recession constant k was calculated at the time t of the event, and the time when this value remains constant marks the end of the event (Eq. (3)):

$$k = \frac{dQ}{dt} \times \frac{1}{Q(t)} \tag{3}$$

where Q is the streamflow, and t is the time.

A time-lag analysis was conducted to assess the hydrological response time at each spatial scale (i.e., the time of the peak streamflow) from the Lecciona stream gauge to the outlet at C4. Stream stages at a 10-min time step were normalized to the highest value for comparability purposes. The time difference between the start of the event (Q_0) and the time at peak flow (Q_p) was computed at each stream section. Additionally, time lag differences in the peak streamflow (Q_p) occurrence between stream sections at different locations of the Re della Pietra catchment were also calculated.

To address the possible influence of the catchment shape on the timing of peak streamflow response, the Gravelius index (Gravelius, 1914; Bendjoudi and Hubert, 2002) was calculated for each sub-catchment (Bendjoudi and Hubert, 2002; Zemzami et al., 2013). The Gravelius index is the ratio of the catchment perimeter to the circumference of a circle with an area equal to that of the given catchment. The higher the index, the more elongated the catchment shape, while conversely, the closer the index to 1, the more rounded the catchment shape.

4. Results

4.1. *Seasonal hydrological responses in the Lecciona sub-catchment*

The strong seasonality characterizing the meteorological forcing in the study area was eventually reflected in the hydrological response of the Lecciona sub-catchment (Fig. 2). The soil moisture-based metric (Section 3.2) clearly identifies two distinct periods characterized by different precipitation depths and hydrological conditions (Table 2). Dominating positive values with upward peaks in the time series of the soil moisture difference are associated to periods with high precipitation depth, high and coupled soil moisture at both depths, and large streamflow, typical of winter, early spring, and late fall conditions. On the contrary, dominating downward peaks mainly reaching negative values of soil moisture difference coincide with spells characterized by low precipitation, low and decoupled soil moisture between the two soil depths, and low streamflow, typical of late spring and summer conditions (Fig. 2). This clear pattern allowed us to use the soil moisture difference between the two depths to distinguish between wet periods (i.e., periods with mainly upward peaks) and dry periods (i.e., periods with mainly downward peaks) in the time series. During the wet period, event precipitation depth ranged between 1.5 and 72 mm with low to moderate intensity (from 1.9 to 10.8 mm/h), while during the dry period, there were fewer events but with higher precipitation intensity (from 5.4 to 28.0 mm/h) (Table S1).

Reflecting the seasonal intermittency of precipitation, soil moisture varied considerably during the wet than during the dry period, with a significant decreasing trend during rainless periods and fewer responses (Fig. 2a). Soil moisture probes recorded comparable moisture content at 15 cm and 35 cm during the first part of the wet period, namely from January until the first week of June. They displayed different water content for the entire duration of the dry period (Fig. 2b), resulting in a coupling (matching) and decoupling (separation) behavior during the wet and dry periods, respectively. After the dry period (late September), there was again a converging trend which lasted until mid-late December, when soil moisture at the two depths exhibited similar values again.

The water table also showed a certain degree of seasonal variability (Fig. 2d). Even though GW3 and GW1 wells are both located on a relatively flat area (14°) in the riparian zone, 1 and 3 m away from the Lecciona stream, respectively, they displayed noticeably different patterns. The groundwater level was most responsive at GW3, with a flashy response to precipitation with high peaks throughout the study period. The frequency and the magnitude of the peaks were consistent with the frequency and the magnitude of the major storm events. While showing a similar pattern during rainy periods, GW1 was almost unresponsive to even the largest precipitation events when these were preceded by periods with very little or no precipitation. This behavior was evident for the entire dry period, where the groundwater level was relatively stable with a slightly declining rate, but also during wet periods with long inter-storm times. It is worth noticing, however, that GW1 was highly responsive in the second part of the wet period (October 2021 onwards), resulting in higher peaks than GW3. GW2 is located at the footslope at a slightly higher altitude, 12 m from the stream, with a local slope of 26°. It had the deepest water table (1–2 m deeper than the other two wells) and displayed peaks of very low magnitude compared to GW1.

A clear seasonality in the Lecciona streamflow was evident as well (Fig. 2e), with streamflow being highly responsive to precipitation in the wet period and with very few but extreme responses in the dry period. This seasonal behavior was further characterized by longer recession times in the wet period in contrast with the dry period, which exhibited quick responses with very steep recessions. The highest peak in the dry period (13 July 2021) occurred after a prolonged period of dry conditions and was accompanied by a sharp peak in soil moisture (Fig. 2). Interestingly, the three following events —not preceded by a prolonged rainless spell— with higher precipitation depths in the dry period (1 and 28 August 2021, and 18–19 September 2021) resulted in lower streamflow. Pre-event water was dominant in the hydrograph throughout the year. However, proportionally larger fractions of event water were observed during the wet period (Fig. 2e and Table 3).

Table 2

Average and standard deviation (SD) of the measured hydrometeorological variables in the wet (254 days, from 19 January 2021 to 7 June 2021 and from 27 September 2021 to 20 January 2022) and the dry period (111 days, from 8 June 2021 to 26 September 2021) in the Lecciona sub-catchment.

Cumulative precipitation depth (mm)	Wet period 1128.1 Average	SD	Dry period 152.4 Average	SD
Air temperature (°C)	6.9	5.6	19.9	5.2
Soil moisture at 15 cm (m^3/m^3)	0.238	0.045	0.151	0.036
Soil moisture at 35 cm (m^3/m^3)	0.245	0.042	0.173	0.031
Streamflow at Lecciona (mm/10 min)	0.026	0.023	0.006	0.003
Groundwater level — GW1 (m)	−2.22	0.27	−2.51	0.03
Groundwater level — GW2 (m)	−4.11	0.09	−4.25	0.12
Groundwater level — GW3 (m)	−2.84	0.12	−2.71	0.14
Event water fraction (dimensionless)	0.25	0.12	0.07	0.05

4.2. *Soil moisture and precipitation controls on seasonal hydrological response*

The effect of 15 and 35 cm soil moisture on streamflow revealed contrasting behaviors in the wet and dry periods (Fig. 3). During the wet period, streamflow increased at soil moisture approximately at 0.25 m^3/m^3 for both depths, resulting in a non-linear behavior (Fig. 3a, b). An earlier —but lower in magnitude— rise of streamflow with instant peaks occurred at soil moisture values between 0.20 and 0.25 m^3/m^3, likely due to a large storm event in the wet period between the end of April and the beginning of May (28 April 2021, Event 7, Table S1). Conversely, during the dry period, there was little effect of soil moisture on streamflow generation, with an abrupt peaking of streamflow for soil moisture values around 0.20 m^3/m^3 for both depths, corresponding to the intense storm events in mid-July and late September (Fig. 3a, b; events 14 (13 July 2021) and 21 (26 September 2021), Table S1). The relation between soil moisture at the two depths and event water fraction was characterized by a marked non-linearity, especially in the dry period (Fig. 3c and 3d). Event water fractions varied greatly during the wet period but showed an overall increasing trend with instant peaks between soil moisture values of 0.17 and 0.25 m^3/m^3 at 15 cm depth (Fig. 3c), while a more rapid increase was observed for soil moisture values between 0.23 and 0.24 m^3/m^3 at 35 cm depth (Fig. 3d). A higher increment in event water fractions was observed for soil moisture values ranging between 0.26 and 0.28 m^3/m^3 at 15 cm depth, and between 0.27 and 0.29 m^3/m^3 at 35 cm depth.

A clear non-linear behavior was observed in the relation between ASI and stormflow, with high stormflow values recorded only during wet conditions with ASI $>$ 60 mm. However, some events had ASI $>$ 60 mm but low stormflow values (Fig. 4a). The addition of precipitation depth to ASI led to a threshold behaviour with a linear increase of stormflow with ASI + P above 80 mm (Fig. 4b). ASI + P also showed a linear relation with stormflow for the dry period events (inset in Fig. 4b). Antecedent soil moisture conditions at 15 and 35 cm, especially with the addition of precipitation depth, also influenced the maximum event water fraction during both dry and wet periods (Fig. 4c and 4d). Events in the dry and wet periods were quite well grouped in two different clusters in both cases, but it is interesting to notice that the maximum event water fraction increased with increasing ASI + P at an overall higher rate in the dry season compared to the wet season.

Table 3

Average and standard deviation (SD) of event water fraction (dimensionless) at Lecciona, C1, and C4 for the wet and dry period.

Stream gauge	Wet period Average	SD	Dry period Average	SD
Lecciona	0.25	0.12	0.07	0.05
C1	0.23	0.10	0.10	0.04
C4	0.15	0.11	0.11	0.07

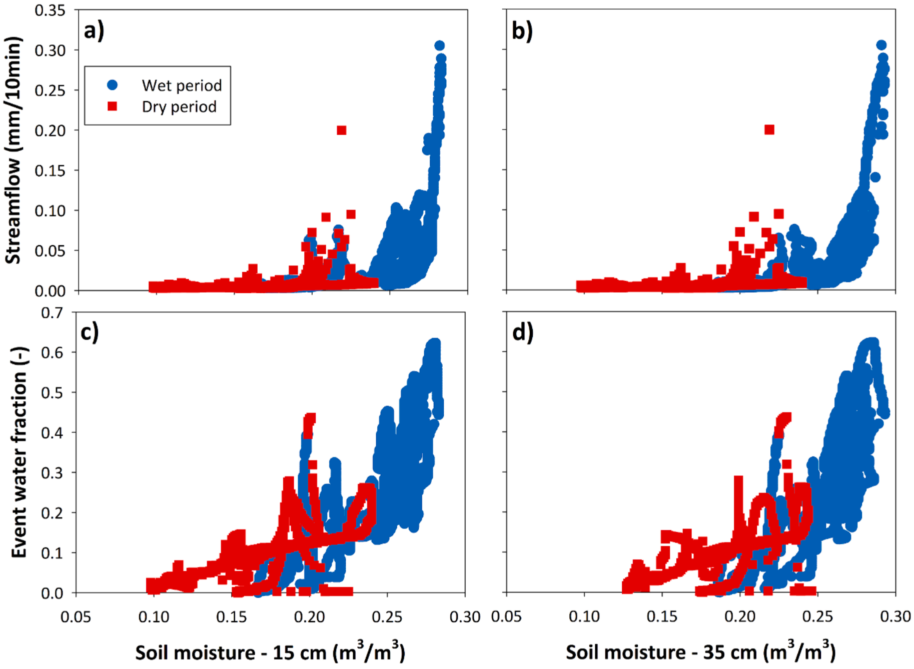


Fig. 3. Non-linear behavior between hillslope-averaged soil moisture and streamflow (panels a and b) and event water fraction (panels c and d) at Lecciona sub-catchment.

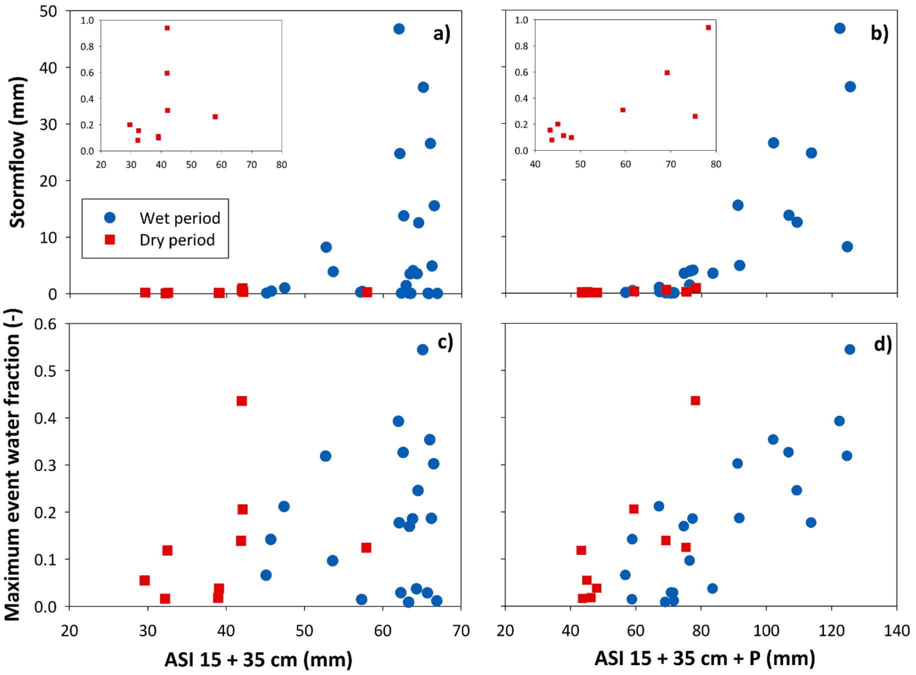


Fig. 4. Relations between a) the 15–35 cm-averaged antecedent soil moisture index (ASI) and stormflow; b) the sum of the 15–35 cm-averaged ASI and precipitation depth and stormflow; c) the 15–35 cm-averaged ASI and maximum event water fraction; d) the sum of the 15–35 cm-averaged ASI and precipitation depth and maximum event water fraction. The insets in panel a) and b) refer to the red points shown in the same panel and plotted on an expanded y scale.

Water table peaks in GW1 were unrelated to ASI during the dry period (Fig. 5a). During the wet period, GW1 peaks showed a threshold response with marked increases above 60 mm in ASI (Fig. 5a). For the dry period, this behavior was in perfect agreement with the GW time series (Fig. 2d), i.e., the water level at GW1 remained stable even during large rainwater inputs. The only exception to this pattern was observed for two events indicated by red and blue arrows, which correspond to the highest precipitation events in the dry and wet periods. Specifically, a precipitation event of 36.3 mm and ASI slightly above 40 mm in the dry period (19 September 2021, event 21, Table S1) was responsible for a water table rise up to ~ 1.8 m from the soil surface, while 72 mm (highest precipitation event of the entire study period; 6 October 2021, event 24, Table S1) with ~ 53 mm ASI resulted in a rise of water table up to ~ 2 m from the soil surface. Excluding these two events, the vertical rise of GW1 peaks for ASI values in the 62–67 mm range indicates a threshold behavior of GW1 peaks' response to ASI during the wet period.

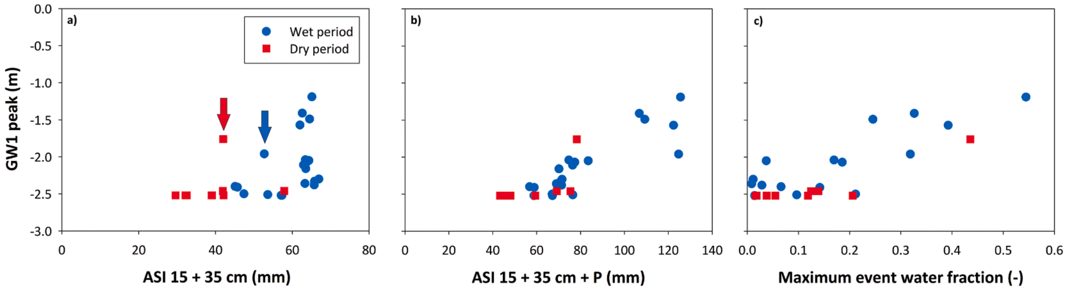


Fig. 5. Relationships at the event scale between a) ASI, b) ASI + P, and c) maximum event water fraction, and water table peaks at GW1 well. The red and blue arrows in panel a) indicate two events in the dry (19 September 2021) and wet (6 October 2021) periods, respectively, which deviate from the overall threshold behavior.

Adding precipitation to ASI (Fig. 5b) eliminated this threshold behavior in the wet period, generating a linear relation between ASI + P and GW1 peaks, with a slight dispersion for ASI + P above 100 mm. The situation in the dry period was almost identical. A linear relationship was also observed between the maximum event water fraction and the water table peaks at GW1 in the dry period (Fig. 5c). Interestingly, during the dry period, a streamflow response was not coupled with a groundwater response, and a corresponding increase of GW1 peaks did not accompany the rise of the maximum event water fraction in streamflow.

4.3. *Streamflow response across multiple spatial scales*

Stream stages at C1, C3, and C4, and streamflow at Lecciona displayed seasonal patterns, with moderate to high peaks and long recessions in the wet period and smaller and flashy responses in the dry period (Fig. 6a). Event water fractions at Lecciona and C1 were very similar (Fig. 6b). However, the event water fraction was often higher at Lecciona during the wet period, while the event water fraction was regularly higher at C1 during the dry period (Table 3). The event water fraction at C4 varied more widely than in C1 and Lecciona, being noticeably lower during the wet season (before May) and noticeably higher from mid-May onwards and for most of the dry season. Between October 2021 and January 2022, the event water fractions in C4 fluctuated differently than in Lecciona and C1, remaining generally lower (Fig. 6b).

The timing of stream response was variable across the catchment (Fig. 7). Positive values indicate that the upstream stream gauge peaked earlier than the downstream one, and negative values indicate the opposite. From Lecciona to C1, C3, and C4, the time lags consistently increase with greater differences in each sub-catchment's drainage area and stream length. Conversely, the small catchment area between C1 and C3 is counterbalanced by the long stream segment, which shifts the median value higher despite the high variability (long lower whisker). However, the relationships between stream length and catchment size with time lags are disrupted when considering C3-C4 and C1-C4 (Fig. 7).

5. Discussion

5.1. *Effect of antecedent conditions on streamflow and groundwater response in wet and dry periods*

The Lecciona sub-catchment showed a clear seasonal response to

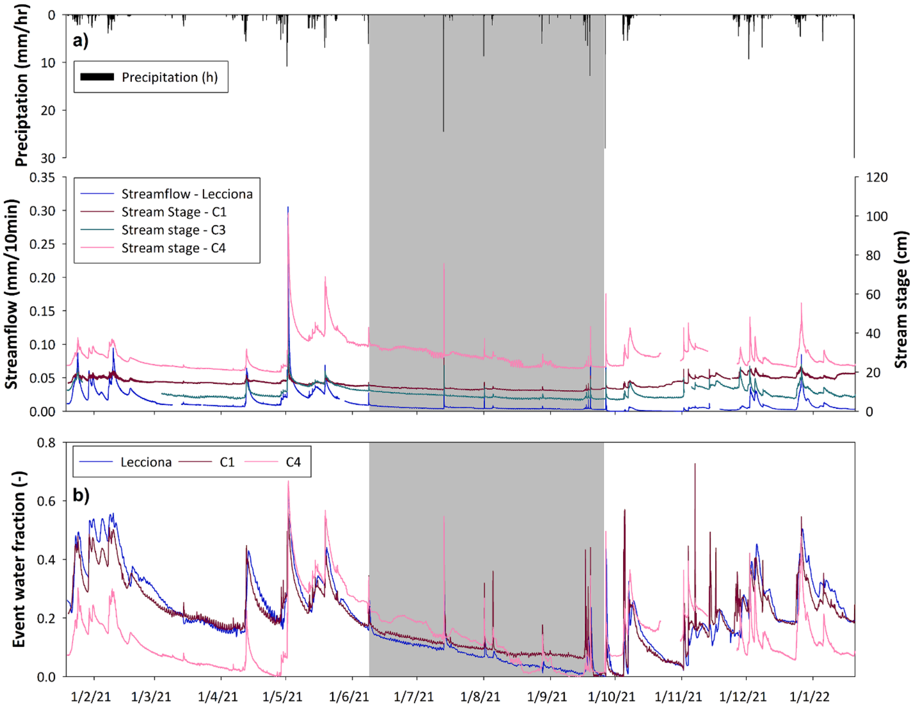


Fig. 6. a) Time series of precipitation, Lecciona streamflow, and stream stage at C1, C3 and C4. b) EC-based time series of event water fraction at Lecciona, C1, and C4. Weighted average precipitation of the two rain gauges is shown. The grey shaded area marks the dry season. Note that the water level sensors at C1, C3, and C4 were installed at different depths, therefore the reported stage values cannot be directly compared.

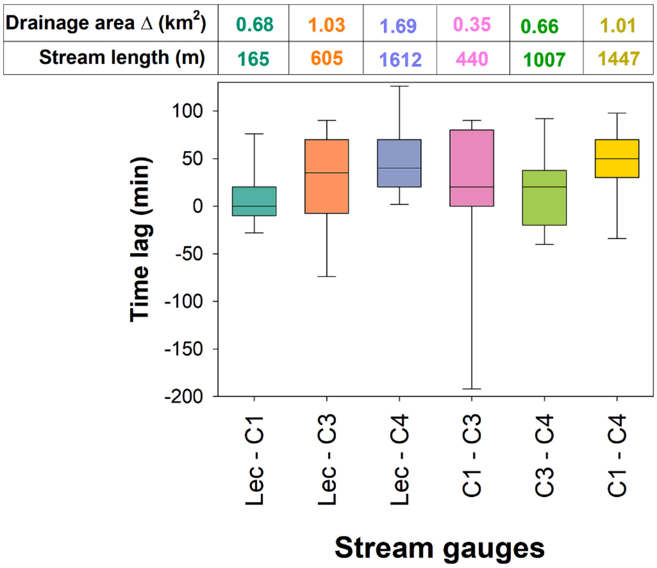


Fig. 7. Peak response timing (i.e., difference between the time of peak stage in two stream gauges) across spatial scales (Lecciona, C1, C3, and C4). The symbol "Δ" indicates the difference between the areas of the compared sub-catchments. Stream length was computed based on the digital elevation model of the catchment and refers to the length of the stream between the two stream gauges indicated below each boxplot. The boxplots represent the first and third quartiles, the horizontal lines depict the median value of each dataset and the whiskers the 5–95% confidence interval.

antecedent conditions during the studied period. The soil moisture difference between the measured depths allowed us to define temporal boundaries for dry and wet periods. Soil moisture responded quickly and had similar content at the two depths during the wet period (Fig. 2b). By contrast, soil moisture was decoupled between the two depths during the dry period, with higher values in the deeper soil, although with a responsive topsoil. The lower soil moisture content at 15 cm depth compared to the 35 cm depth observed during the dry period (Fig. 2b) could be due to the high evaporative demand on the soil surface and preferential tree water use in the shallower soil compared to the deeper layer (Fabiani et al., 2023). Although no soil-specific calibration was applied to our soil moisture probes, and therefore the results should be interpreted with some caution, the decoupling of soil moisture at 15 and 35 cm depths in the Lecciona sub-catchment was similar to the decoupling observed in the forested Weierbach catchment for soil moisture measured at 10 and 40 cm depths (Segura et al., 2023). On the contrary, our results differ with the opposite decoupling dynamics observed for the Mediterranean mountain Can Vila catchment, where soil moisture was often higher in the shallow soil layer than in the deep layer (Segura et al., 2023). The disagreement between our results and those found for the Can Vila catchment suggests that different soil characteristics and water uptake by vegetation (that may lead to a marked vertical hydraulic redistribution of soil water) can affect soil moisture dynamics at different depths together with climatic characteristics.

Similar findings were presented by Dymond et al. (2021) for a Mediterranean forested catchment in Northern California, where soil moisture manifested a clear seasonality. During the wet period soil moisture was more similar between 15, 30, and 100 cm depths at all topographic positions, while the soil layer at 30 cm maintained a uniform higher water content than the layer at 15 cm in most hillslope positions throughout the dry period, thus evidencing a higher variability among depths. Studying the dependence of soil respiration's temperature on soil moisture in a Mediterranean riparian forest Northeast in Spain, Chang et al. (2014) found that during dry conditions, the soil at 5 cm depth suffered a 45–63 % reduction of water content when the soil at 30 cm depth only 14–35 %. Penna et al. (2015) documented a seasonal variability in the mountain forested Ressi catchment in Northern Italy, with higher precipitation depth, soil moisture, and streamflow in wet periods characterized by slow recessions and moderately high peak flows, compared to dry periods, which showed a flashy response, with quick recessions, and high peak flows. Other forested catchments showed a similar seasonal response (Fenicia et al., 2014; Douinot et al., 2022).

The non-linear relation between antecedent soil moisture and streamflow at Lecciona was more evident in the wet than in the dry period, likely due to the upper soil moisture limit that bounded further soil moisture increase (Fig. 3a, b). Previous work reported non-linear threshold effects in the relation between antecedent soil moisture and streamflow in forested catchments as a result of the activation of gravity-driven subsurface flow that connects hillslope to the streams (Penna et al., 2015; Zhang et al., 2021). In particular, Zhang et al. (2021) reported two distinct thresholds in a forested humid catchment in China, documenting a shift from a slow response with unsaturated soil water storage to a fast response with gravity-driven water movement through the soil along the hillslope reaching the stream. This behaviour is also in agreement with the "fill-and-spill" conceptual model (McDonnell et al., 2021), which proposes that only when storage reaches its critical level (fill), interconnection occurs, and outflow pathways activate (spill). However, as far as we know, our study is the first to document the distinct behavior of the antecedent soil moisture-streamflow relation in seasonally different dry and wet periods.

The effect of seasonality on streamflow generation was also evident in the relation between antecedent conditions, obtained by combining antecedent soil moisture and event precipitation (ASI + P), and stormflow (Fig. 4). During the dry period, when soil moisture was low, and during short events, the amount of stormflow in relation to precipitation depth was low, and relations between stormflow and ASI were weak (Fig. 4a). However, the linear response of stormflow to ASI + P for the events in the dry period suggests that the effect of precipitation depth became critical in producing stormflow when antecedent moisture conditions were low (Fig. 4b). This basically stresses the important role of intense summer thunderstorms in generating runoff in this small catchment. Nevertheless, high stormflow values were always reached when wet soil and storm events were long (Fig. 4b). This observation agrees with the study of von Freyberg et al. (2018), which stresses the importance of controlling antecedent moisture conditions on streamflow and storm characteristics (precipitation depth and duration) in forested mountain catchments. The key role of wet antecedent conditions on streamflow generation was observed in other forested and not forested mountain catchments (e.g., Penna et al., 2011; Farrick and Branfireum, 2014; Wei et al., 2020). However, the distinct effect of seasonality on this behavior is shown here for the first time.

Antecedent soil moisture (ASI), and especially the combination of soil moisture and precipitation depth (ASI + P), had a clear effect on maximum event water fraction (Fig. 4c, d). This agrees with the findings by Fischer et al. (2017), who observed that event water contribution correlated positively to precipitation depth in a wet mountain and partially forested catchment in Switzerland, and with McGlynn et al. (2004), who showed increasing event water fractions with increasing antecedent moisture conditions in a forested catchment in New Zealand. In the Lecciona sub-catchment, non-linear behavior seemed to be controlled by antecedent soil moisture conditions combined with precipitation depth, suggesting the important role of hillslope-stream connectivity in delivering event water to the stream and in generating runoff (Fig. 4). Interestingly, the linear relation between ASI + P and maximum event water fractions was valid for events in both dry and wet periods. This new outcome can be valuable in understanding seasonal hydrological response in small catchments.

Groundwater in the Lecciona sub-catchment showed a different behavior in the riparian area, where the groundwater level was more responsive at GW3, closer to the stream (approximately 1 m distance) than GW1 (Fig. 2d). Additionally, a vertical increase of GW1 peaks above 62 mm of ASI (Fig. 5a) revealed a threshold behavior of GW1 response to antecedent moisture conditions during the wet period, while below that range of values, a considerable amount of rainfall would be necessary to elevate the water table. Noticeably, the groundwater level at the footslope was lower compared to the other two wells and not very responsive to precipitation (Fig. 2d). Despite the relatively small number of wells, which require some caution in the data interpretation, the observed response could imply less infiltration and more lateral flow at the hillslope, conducting water downwards and recharging the riparian zone. This process could be more effective in the wet period, when shorter transit times and larger connectivity between the riparian zone and the stream may control the event water fraction, particularly at the headwaters (Blume and van Meerveld, 2015; Nanda and Safeeq, 2023; Zuecco et al., 2019).

5.2. *Event water fractions and streamflow timing at different spatial scales*

A seasonal response was observed across all studied spatial scales in the Re della Pietra catchment. Stream stages were higher during the wet period than in the dry period, except at the outlet (C4), where the opposite was observed. Moreover, stream stages increased across spatial scales, from the Lecciona sub-catchment to the outlet of the Re della Pietra. Streamflow was dominated by pre-event water at all spatial scales (85 % on a yearly average), and event water contributions were smaller than pre-event water contributions (Fig. 2e and 6, and Table 3). Similar event water fractions were reported by Laudon et al. (2007) for a forested catchment in Sweden, while Dusek and Vogel (2018) reported pre-event water contribution comprising hillslope preferential flow of 52–84 % (i.e., event water fractions of 16–48 %) in a mountain forested catchment.

In our study area, event water fractions varied seasonally and within spatial scales, with decreasing event water contribution with increasing drainage area in the wet period (being Lecciona and C1 more similar). Conversely, during the dry period the opposite behavior was observed (in which C1 and C4 were more similar). Wetter antecedent conditions could help to mobilize pre-event water rather than the fast transmission of event water (von Freyberg et al., 2018), and thus could explain the overall prevalence of pre-event water on streamflow. Nevertheless, event water contribution showed both seasonal and spatial variations (Fig. 6b). The average event water fractions calculated for Lecciona and C1 sub-catchments were higher in the wet period (24 and 23 %, respectively) than in the dry period (8 and 10 %), whereas event water fractions at C4 were lower in the wet period (10 %) than in the dry period (28 %).

Blume et al. (2007), James and Roulet (2009), and Penna et al. (2015) reported for small forested catchments a similar behavior to that observed at C4, with higher event water fractions occurring during the dry period and with dry antecedent conditions. This could result from shallow-subsurface stormflow (which drives a fast delivery of event water as quick flow) and catchment geomorphology (James and Roulet, 2009). Direct channel precipitation and overland flow could be favored at the outlet by its lower topographic position, increasing event water fraction, as Muñoz-Villers and McDonnell (2012) suggested. Although we have no evidence, litter cover (pretty thick in the lower hillslope position of the Lecciona sub-catchment) may also play a role in overland flow paths, as in other steep mountain catchments (Douinot et al., 2022).

Considering that a large drainage area favors lateral connectivity between the stream and upper hillslopes (Zhang et al., 2021), a wetter and highly connected hillslope to the stream during the wet period can explain the greater pre-event water fraction at C4, compared to Lecciona and C1. Thus, large areas integrate more lateral flow (McGlynn et al., 2004), which controls higher pre-event water fraction and higher stream stage at the outlet. In wetter conditions, there might be a larger contribution of the hillslope and riparian zones (i.e., greater pre-event water contribution, Fig. 6), meaning higher hydrological hillslope-riparian-stream connectivity (Zuecco et al., 2019). Therefore, the different seasonal response at multiple spatial scales in the Re della Pietra catchment seems to be controlled by catchment size, topography, and differences in soil transmissivity and antecedent conditions, as also observed by Shanley et al. (2002) for steep, partly forested catchments in the North-Eastern USA.

Other forested catchments also exhibited a seasonal pattern in hillslope-stream hydrological connectivity. For instance, Detty and McGuire (2010) and Bonanno et al. (2021) described hillslopes hydrologically disconnected from the main channel during the dry period, and connected during the wet period in mountain forested catchments. Similarly, at the Re della Pietra catchment, the response of shallow groundwater and soil moisture drives these seasonal variations, controlled by antecedent conditions and soil/bedrock characteristics. The underlying bedrock consists of fractured sandstones below the soil, which promotes both vertical percolation and lateral subsurface flow within the hillslope at the soil–bedrock interface. Moreover, soil moisture response in the riparian area could control the higher event water fraction at Lecciona in the wet period, characterized by longer events and greater precipitation depths. By contrast, with increasing catchment size, higher connectivity during the wet period, which integrates lateral flow from a larger area, could lead to the decreasing event water contribution in the wet period. During the dry period, dry antecedent conditions, coupled with the presence of a hydrophobic litter cover and a bedrock of fractured sandstone draining a larger area, could lead to quick flows (Douinot et al., 2022), thus augmenting both the event water fraction and the stream stage with increasing catchment size.

The analysis of time lags of peak flow between multiple scales reveals a relatively complex pattern. On the one hand, the median time lag of peaks between Lecciona and C1, C3, and C4 increased with decreasing average catchment slope (Table 1), contrary to what was expected (Overton, 1971; Amiri et al., 2019). On the other hand, poor relations between time lags and catchment slope were found in other nested catchments with fractured geological settings (Penna et al., 2017). Further, the median time lag of peaks between all the stream gauges showed a consistent pattern of increasing lag times with increasing drainage area only in the upper part of the catchment, as observed elsewhere (McGlynn et al., 2004; Penna et al., 2017). Conversely, the relation between size and stream network and time lags weakened for the lower part of the catchment. The more elongated shape of the Lecciona sub-catchment, with a higher Gravelius index (Table 4), suggests that in the headwaters of the Re della Pietra, travel times are mainly a function of the stream length. The more rounded shape and more developed dendritic stream patterns of the other sub-catchments, in addition to catchment size and longer hillslopes, might lead to longer travel times (Bergstrom et al., 2016; van Meerveld et al., 2019).

Considering these results, the time lags between spatial scales appear to be controlled by time-variant hillslope hydrological connectivity, antecedent conditions, catchment size and shape, likely overlapping with soil properties and geology (Shanley et al., 2002; Haga et al., 2005; McGlynn et al., 2004). This combination of factors results in the large variability in streamflow peak time lags from upper headwater catchments to the outlet. Guastini et al. (2019) also reported a complex pattern in Alpine nested catchments, with an overall decrease in runoff coefficients and specific streamflow with increasing catchment area. In their case, however, a change in spring time was associated with a high

Table 4
Gravelius index calculated for the four sub-catchments of the Re della Pietra catchment.

	Size (km^2)	Perimeter (km)	Gravelius index (−)
Lecciona	0.31	3.89	1.95
C1	0.99	6.10	1.72
C3	1.34	7.06	1.71
C4	2.00	9.22	1.83

snowmelt contribution to streamflow, which is missing in our case. The presented results thus suggest that more detailed studies are necessary to understand the interplay of different factors in the resulting time lags of peak response at different spatial scales.

6. Conclusions

Analyzing the dataset collected in the Re della Pietra experimental catchment improved the mechanistic fundamentals of seasonal hydrological patterns observed during dry and wet conditions across multiple spatial scales. These patterns revealed new findings on the effect of the seasonal meteorological forcings on streamflow generation and the event water contributions during both wet and dry periods, which are still missing in Mediterranean mountain forested catchments. This is a first attempt to understand how runoff response propagates across multiple spatial scales in small, forested catchments – therefore integrating both temporal and spatial variability in hydrological processes.

Our findings highlighted different soil moisture behaviors in shallow and deeper layers as a function of the overall catchment wetness. Antecedent soil moisture and its seasonality, often in combination with precipitation depth, control in a non-linear way streamflow generation and the fraction of event water delivered to the stream, ensuring groundwater response and subsurface hydrological connectivity under wet conditions. Streamflow peaks propagate downstream following a consistent spatial pattern only in the upper part of the catchment, mainly reflecting the catchment structure, indicating that more complex and interacting processes govern the timing of the hydrological response across multiple spatial scales, even in such a small catchment. Further investigations over a longer period in this and other mountain forested catchments are required to corroborate our conclusions and better understand the hydrology of climate change-sensitive Mediterranean catchments.

Funding

This study was supported by the research projects: “WATer mixing in the critical ZONe: observations and predictions under environmental changes – WATZON” (call PRIN 2017, code: 2017SL7ABC), funded by the Italian Ministry of University and Research (MIUR); “Unravelling interactions between WATER and carbon cycles during drought and their impact on water resources and forest and grassland ecosySTEMs in the Mediterranean climate – WATERSTEM” (call PRIN 2020, code: 20202WF53Z), funded by the Italian Ministry of University and research (MIUR); Hydrological Controls on Carbonate-mediated CO_2 Consumption – Hydro4C (call PRIN 2022, code 2022PFNNRS), funded by the European Union – Next Generation EU; “Carbon and water cycles interactions during drought and their impact on WAter and ForEst Resources in the Mediterranean region –WAFER” funded by the Italian National research Council (Consiglio Nazionale delle Ricerche – CNR); “Space-time patterns of tree water uptake at hillslopes with contrasting climate and geology- STEP-UP” (code: AFR/STEP-UP ID 12546983), funded by the Fonds National de la Recherche Luxembourg; and “A new interdisciplinary approach to advance understanding of sediment and large wood TRANSport in FORested Mountain catchments – TRANSFORM” (call D.R. n. 328 on 11/03/2022, code: CUP B55F21007810001) funded by Next Generation EU and the University of Florence. MMG acknowledges a grant awarded by the National program for brief research internships abroad for postdoctoral students of the National Scientific and Technical Research Council of Argentina (Consejo Nacional de Investigaciones Científicas y Técnicas – CONICET), and a research project awarded by the National Agency of Research and Development of Chile (call FONDECYT POSTDOCTORADO 2022, code: 3220318, Agencia Nacional de Investigación y Desarrollo – ANID).

CRediT authorship contribution statement

M. Macchioli Grande: Writing – review & editing, Writing – original draft, Visualization, Data curation, Conceptualization. **K. Kaffas:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Conceptualization. **M. Verdone:** Writing – review & editing, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **M. Borga:** Writing – review & editing, Methodology, Investigation. **C. Cocozza:** Writing – review & editing, Methodology, Investigation. **A. Dani:** Writing – review & editing, Methodology, Investigation. **A. Errico:** Writing – review & editing, Methodology, Investigation. **G. Fabiani:** Writing – review & editing, Methodology, Investigation. **L. Gourdol:** Writing – review & editing, Methodology, Investigation. **J. Klaus:** Writing – review & editing, Funding acquisition, Conceptualization. **F.S. Manca di Villahermosa:** Writing – review & editing, Methodology, Investigation, Data curation. **C. Massari:** Writing – review & editing, Funding acquisition, Conceptualization. **I. Murgia:** Writing – review & editing, Methodology, Investigation, Data curation. **L. Pfister:** Writing – review & editing, Funding acquisition. **F. Preti:** Writing – review & editing, Methodology, Investigation. **C. Segura:** Writing – review & editing, Conceptualization. **C. Tailliez:** Writing – review & editing, Methodology, Investigation. **P. Trucchi:** Writing – review & editing, Methodology, Investigation. **G. Zuecco:** Writing – review & editing, Funding acquisition, Conceptualization. **D. Penna:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

The authors thank the local Forest Service (Unione Comuni Valdarno e Valdisieve) for their logistical support that allowed the development of the Re della Pietra experimental catchment. The authors also extend their thanks to Dr. Ilaria Zorzi and to many undergraduate students who contributed to field work. The dataset is available upon request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2024.131642.

References

Amendola, U., Perri, F., Critelli, S., Monaco, P., Cirilli, S., Trecci, T., Rettori, R., 2016. Composition and provenance of the Macigno Formation (Late Oligocene - Early Miocene) in the Trasimeno Lake area (northern Apennines). Mar. Pet. Geol. 69, 146–167. https://doi.org/10.1016/j.marpetgeo.2015.10.019.

Amiri, B.J., Gao, J., Fohrer, N., Adamowski, J., Huang, J., 2019. Examining lag time using the landscape, pedoscape and lithoscape metrics of catchments. Ecol. Ind. 105, 36–46. https://doi.org/10.1016/j.ecolind.2019.03.050.

Bendjoudi, H., Hubert, P., 2002. The Gravelius compactness coefficient: critical analysis of a shape index for drainage basins. Hydrol. Sci. J. 47, 921–930. https://doi.org/10.1080/02626660209493000.

Bergstrom, A., McGlynn, B., Mallard, J., Covino, T., 2016. Watershed structural influences on the distributions of stream network water and solute travel times under baseflow conditions. Hydrol. Process. 30, 2671–2685. https://doi.org/10.1002/hyp.10792.

Birch, A., Stallard, R., Barnard, H., 2021. Precipitation characteristics and land cover control wet season runoff source and rainfall partitioning in three humid tropical catchments in Central Panama. Water Resour. Res. 57(2), e2020WR028058 https://doi.org/10.1029/2020WR028058.

Blume, T., van Meerveld, H.J., 2015. From hillslope to stream: methods to investigate subsurface connectivity. Wires Water 2, 177–198. https://doi.org/10.1002/wat2.1071.

Blume, T., Zehe, E., Bronstert, A., 2007. Rainfall-runoff response, event-based runoff coefficients and hydrograph separation. Hydrol. Sci. J. 52, 843–862. https://doi.org/10.1623/hysj.52.5.843.

Bonanno, E., Blöschl, G., Klaus, J., 2021. Flow directions of stream-groundwater exchange in a headwater catchment during the hydrologic year. Hydrol. Process. 35 (8), e14310.

Bracken, L.J., Croke, J., 2007. The concept of hydrological connectivity and its contribution to understanding runoff dominated geomorphic systems. Hydrol. Process. 21, 1749–1763. https://doi.org/10.1002/hyp.6313.

Buttle, J.M., 1994. Isotope hydrograph separations and rapid delivery of pre-event water from drainage basins. Prog. Phys. Geogr. 18, 16–41. https://doi.org/10.1177/030913339401800102.

Chang, C.T., Sabaté, S., Sperlich, D., Poblador, S., Sabater, F., Gracia, C., 2014. Does soil moisture overrule temperature dependence of soil respiration in Mediterranean riparian forests? Biogeosciences 11 (21), 6173–6185. https://doi.org/10.5194/bg-11-6173-2014.

Detty, J.M., McGuire, K.J., 2010. Topographic controls on shallow groundwater dynamics: implications of hydrologic connectivity between hillslopes and riparian zones in a till mantled catchment. Hydrol. Process. 24 (16), 2222–2236. https://doi.org/10.1002/hyp.7656.

Douinot, A., Iffly, J.F., Tailliez, C., Meisch, C., Pfister, L., 2022. Flood patterns in a catchment with mixed bedrock geology: causes for flashy runoff contributions during storm events. Hydrol. Earth Syst. Sci. 26, 5185–5206. https://doi.org/10.5194/hess-26-5185-2022.

Dusek, J., Vogel, T., 2018. Hillslope hydrograph separation: The effects of variable isotopic signatures and hydrodynamic mixing in macroporous soil. J. Hydrol. 563, 446–459. https://doi.org/10.1016/j.jhydrol.2018.05.054.

Dymond, S.F., Wagenbrenner, J.W., Keppeler, E.T., Bladon, K.D., 2021. Dynamic hillslope soil moisture in a Mediterranean montane watershed. Water Resour. Res. 57 (11), e2020WR029170 https://doi.org/10.1029/2020WR029170.

Fabiani, G., Klaus, J., Penna, D., 2023. Contrasting water use strategies of beech trees along two hillslopes with different slope and climate. Hydrology and Earth System Sciences Discussions (preprint). https://doi.org/10.5194/hess-2023-225, in review.

Farrick, K.K., Branfireum, B.A., 2014. Soil water storage, rainfall and runoff relationships in a tropical dry forest catchment. Water Resour. Res. 50, 9236–9250. https://doi.org/10.1002/2014WR016045.

Fenicia, F., Kavetski, D., Savenije, H.H.G., Clark, M.P., Schopus, G., Pfister, L., Freer, J., 2014. Catchment properties, function, and conceptual model representation: Is there a correspondence? Hydrol. Process. 28, 2451–2467. https://doi.org/10.1002/hyp.9726.

Fischer, B.M.C., Stähli, M., Seibert, J., 2017. Pre-event water contributions to runoff events of different magnitude in pre-alpine headwaters. Hydrol. Res. 48, 58. https://doi.org/10.2166/nh.2016.176.

Giorgi, F., Lionello, P., 2008. Climate change projections for the Mediterranean region. Global Planet. Change 63, 90–104. https://doi.org/10.1016/j.gloplacha.2007.09.005.

Gravelius, H., 1914. Rivers, in: "Compendium in Hydrology", 1 (in German). Göschen, Berlin, Germany.

Guastini, E., Zuecco, G., Errico, A., Castelli, G., Bresci, E., Preti, F., Penna, D., 2019. How does streamflow response vary with spatial scale? Analysis of controls in three nested Alpine catchments. J. Hydrol. 570, 705–718. https://doi.org/10.1016/j.jhydrol.2019.01.022.

Haga, H., Matsumoto, Y., Matsutani, J., Fujita, M., Nishida, K., Sakamoto, Y., 2005. Flow paths, rainfall properties, and antecedent soil moisture controlling lags to peak discharge in a granitic unchanneled catchment. Water Resources Research 41, W12410. https://doi.org/10.1029/2005WR004236.

James, A.L., Roulet, N.T., 2009. Antecedent moisture conditions and catchment morphology as controls on spatial patterns of runoff generation in small forest catchments. J. Hydrol. 377, 351–366. https://doi.org/10.1016/j.jhydrol.2009.08.039.

Klaus, J., McDonnell, J., 2013. Hydrograph separation using stable isotopes: Review and evaluation. J. Hydrol. 505, 47–64. https://doi.org/10.1016/j.jhydrol.2013.09.006.

Laudon, H., Slaymaker, O., 1997. Hydrograph separation using stable isotopes, silica and electrical conductivity: an alpine example. J. Hydrol. 201, 82–101. https://doi.org/10.1016/S0022-1694(97)00030-9.

Laudon, H., Sjöblom, V., Buffam, I., Seibert, J., Mörth, M., 2007. The role of catchment scale and landscape characteristics for runoff generation of boreal streams. J. Hydrol. 344, 198–209. https://doi.org/10.1016/j.jhydrol.2007.07.010.

Lazo, P.X., Mosquera, G.M., Cárdenas, I., Segura, C., Crespo, P., 2023. Flow partitioning modelling using high-resolution electrical conductivity data during variable flow conditions in a tropical montane catchment. J. Hydrol. 617, 128898 https://doi.org/10.1016/j.jhydrol.2022.128898.

Llorens, P., Gallart, F., Cayuela, C., Roig-Planasdemunt, M., Casellas, E., Molina, A.J., Moreno de las Heras, M., Bertran, E., Sánchez-Costa, E., Latron, J., 2018. What have we learnt about Mediterranean catchment hydrology? 30 years observing hydrological processes in the Vallcebre research catchments. Geographical Research Letters 44, 475–502. https://doi.org/10.18172/cig.3432.

Massari, C., Avanzi, F., Bruno, G., Gabellani, S., Penna, D., Camici, S., 2022. Evaporation enhancement drives the European water-budget deficit during multi-year droughts. Hydrol. Earth Syst. Sci. 26 (6), 1527–1543. https://doi.org/10.5194/hess-26-1527-2022.

Massari, C., Pellet, V., Tramblay, Y., Crow, W.T., Gründemann, G.J., Hascoetf, T., Penna, D., Modanesi, S., Brocca, L., Camici, S., Marra, F., 2023. On the relation between antecedent basin conditions and runoff coefficient for European floods. J. Hydrol. 625 (B), 130012 https://doi.org/10.1016/j.jhydrol.2023.130012.

McDonnell, J.J., Spence, C., Karran, D., van Meerveld, H.J., Harman, C., 2021. Fill-and-Spill: A Process Description of Runoff Generation at the Scale of the Beholder. Water Resour. Res. 57, e2020WR027514 https://doi.org/10.1029/2020WR027514.

McGlynn, B.L., McDonnell, J.J., Seibert, J., Kendall, C., 2004. Scale effects on headwater catchment runoff timing, flow sources, and groundwater-streamflow relations. Water Resour. Res. 40, 1–14. https://doi.org/10.1029/2003WR002494.

Mosquera, G., Segura, C., Crespo, P., Mosquera, G.M., Segura, C., Crespo, P., 2018. Flow Partitioning Modelling Using High-Resolution Isotopic and Electrical Conductivity Data. Water 10, 904. https://doi.org/10.3390/w10070904.

Muñoz-Villers, L.E., McDonnell, J.J., 2012. Runoff generation in a steep, tropical montane cloud forest catchment on permeable volcanic substrate. Water Resour. Res. 48 (9) https://doi.org/10.1029/2011WR011316.

Nanda, A., Safeeq, M., 2023. Threshold controlling runoff generation mechanisms in Mediterranean headwater catchments. J. Hydrol. 620, 129532 https://doi.org/10.1016/j.jhydrol.2023.129532.

Overton, D.E., 1971. Estimation of surface water lag time from the kinematic wave equations. J. Am. Water Resour. Assoc. 71038 https://doi.org/10.1111/j.1752-1688.1971.tb05776.x.

Pellerin, B.A., Wollheim, W.M., Feng, X., Vörösmarty, C.J., 2008. The application of electrical conductivity as a tracer for hydrograph separation in urban catchments. Hydrol. Process. 22, 181–1818. https://doi.org/10.1002/hyp.6786.

Penna, D., Tromp Van-Meerveld, H.J., Gobbi, A., Borga, M., Dalla Fontana, G., 2011. The influence of soil moisture on threshold runoff generation processes in an alpine headwater catchment. Hydrol. Earth Syst. Sci. 15, 689–702. https://doi.org/10.5194/hess-15-689-2011.

Penna, D., van Meerveld, H.J., Oliviero, O., Zuecco, G., Assendelft, R.S., Dalla Fontana, G., Borga, M., 2015. Seasonal changes in runoff generation in a small forested mountain catchment. Hydrol. Process. 29 (8), 2027–2042. https://doi.org/10.1002/hyp.10347.

Penna, D., van Meerveld, H.J., Zuecco, G., Dalla Fontana, G., Borga, M., 2016. Hydrological response of an Alpine catchment to rainfall and snowmelt events. J. Hydrol. 537, 382–397. https://doi.org/10.1016/j.jhydrol.2016.03.040.

Penna, D., Zuecco, G., Crema, S., Trevisani, S., Cavalli, M., Pianezzola, L., Marchi, L., Borga, M., 2017. Response time and water origin in a steep nested catchment in the Italian Dolomites. Hydrological Processes 31, 768–782. https://doi.org/10.1002/hyp.11050.

Ries, F., Schmidt, S., Sauter, M., Lange, J., 2017. Controls on runoff generation along a steep climatic gradient in the Eastern Mediterranean. J. Hydrol.: Reg. Stud. 9, 18–33. https://doi.org/10.1016/j.ejrh.2016.11.001.

Scaife, C.I., Band, L.E., 2017. Nonstationarity in threshold response of stormflow in southern Appalachian headwater catchments. Water Resour. Res. 53, 6579–6596. https://doi.org/10.1002/2017WR020376.

Segura, C., James, A.L., Lazzati, D., Roulet, N.T., 2012. Scaling relationships for event water contributions and transit times in small-forested catchments in Eastern Quebec. Water Resour. Res. 48, W07502. https://doi.org/10.1029/2012WR011890.

Segura, C., Penna, D., Borga, M., Hissler, C., Iffly, J.F., Klaus, J., Latron, J., Llorens, P., Marchina, C., Martínez-Carreras, N., Pfister, L., Zuecco, G., 2023. Comparing hydrological responses across catchments using a new soil water content metric. Hydrol. Process. 37 (10), e15010.

Sellami, H., Benabdallah, S., La Jeunesse, I., Vanclooster, M., 2016. Quantifying hydrological responses of small Mediterranean catchments under climate change projections. Sci. Total Environ. 543, 924–936. https://doi.org/10.1016/j.scitotenv.2015.07.006.

Shanley, J.B., Kendall, C., Smith, T.E., Wolock, D.M., McDonnell, J.J., 2002. Controls on old and new water contributions to stream flow at some nested catchments in Vermont, USA. Hydrol. Process. 16, 589–609. https://doi.org/10.1002/hyp.312.

Sklash, M.G., Farvolden, R.N., 1979. Role of groundwater in storm runoff. J. Hydrol. 43 (1–4), 45–65. https://doi.org/10.1016/0022-1694(79)90164-1.

van Meerveld, H.J.I., Kirchner, J.W., Vis, M.J.P., Assendelft, R.S., Seibert, J., 2019. Expansion and contraction of the flowing stream network alter hillslope flowpath lengths and the shape of the travel time distribution. Hydrol. Earth Syst. Sci. 23, 4825–4834. https://doi.org/10.5194/hess-23-4825-2019.

Vasiliades, L., Loukas, A., 2009. Hydrological response to meteorological drought using the Palmer drought indices in Thessaly. Greece. Desalination 237 (1–3), 3–21. https://doi.org/10.1016/j.desal.2007.12.019.

von Freyberg, J., Studer, B., Rinderer, M., Kirchner, J.W., 2018. Studying catchment storm response using event- and pre-event-water volumes as fractions of precipitation rather than discharge. Hydrol. Earth Syst. Sci. 22, 5847–5865. https://doi.org/10.5194/hess-22-5847-2018.

Wei, L., Qiu, Z., Zhou, G., Kinouchi, T., Liu, Y., 2020. Stormflow threshold behaviour in a subtropical mountainous headwater catchment during forest recovery period. Hydrol. Process. 34 (8), 1728–1740. https://doi.org/10.1002/hyp.13658.

Zemzami, M., Benaabidate, L., Layan, B., Dridri, A., 2013. Design flood estimation in ungauged catchments and statistical characterization using principal components analysis: application of Gradex method in Upper Moulouya. Hydrol. Process. 27 (2), 186–195. https://doi.org/10.1002/hyp.9212.

Zhang, G., Cui, P., Gualtieri, C., Zhang, J., Bazai, N.A., Zhang, Z., Wang, J., Tang, J., Chen, R., Lei, M., 2021. Stormflow generation in a humid forest watershed controlled by antecedent wetness and rainfall amounts. J. Hydrol. 603, 127107 https://doi.org/10.1016/j.jhydrol.2021.127107.

Zuecco, G., Rinderer, M., Penna, D., Borga, M., van Meerveld, H.J., 2019. Quantification of subsurface hydrologic connectivity in four headwater catchments using graph theory. Sci. Total Environ. 646, 1265–1280. https://doi.org/10.1016/j.scitotenv.2018.07.269.