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The influence of soil moisture on threshold runoff generation processes in an alpine headwater catchment

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Abstract

This study investigates the role of soil moisture on the threshold runoff response in a small headwater catchment in the Italian Alps that is characterised by steep hillslopes and a distinct riparian zone. This study focuses on: (i) the threshold soil moisture-runoff relationship and the influence of catchment topography on this relation; (ii) the temporal dynamics of soil moisture, streamflow and groundwater that characterize the catchment's response to rainfall during dry and wet periods; and (iii) the combined effect of antecedent wetness conditions and rainfall amount on hillslope and riparian runoff. Our results highlight the strong control exerted by soil moisture on runoff in this catchment: a sharp threshold exists in the relationship between soil water content and runoff coefficient, streamflow, and hillslope-averaged depth to water table. Low runoff ratios were related to the response of the riparian zone, which was always close to saturation. High runoff ratios occurred during wet antecedent conditions, when the soil moisture threshold was exceeded. In these cases, subsurface flow was activated on hillslopes, which became major contributors to runoff. Antecedent wetness conditions also controlled the catchment's response time: during dry periods, streamflow reacted and peaked prior to hillslope soil moisture whereas during wet conditions the opposite occurred. This difference resulted in a hysteretic behaviour in the soil moisture-streamflow relationship. Finally, the influence of antecedent moisture conditions on runoff was also evident in the relation between cumulative rainfall and total stormflow. Small storms during dry conditions produced low runoff amounts, mainly from overland flow from the near saturated riparian zone. Conversely, for rainfall events during wet conditions, hillslopes contributed to streamflow and higher runoff values were observed.

1 Introduction

Thresholds and other non-linear behaviours are common in hydrologic and geomorphic systems. They can occur at different levels of complexity (Zehe and Sivapalan, 2009), at various spatial scales and may limit the predictability of processes and the repeatability of hydrological observations (Zehe et al., 2007). Therefore, investigating and understanding the controls exerted by thresholds is essential to understand stream responses at the catchment scale (Tetzlaff et al., 2008). One hydrological variable frequently found to be non-linearly related to runoff is soil moisture. Early work by Western and Grayson (1998) in the Tarrawarra catchment, in South-eastern Australia, clearly showed that surface runoff was a threshold process controlled by catchment wetness conditions, with runoff coefficients abruptly increasing when a certain moisture threshold was exceeded. Similar results for the relationship between near surface soil water content and runoff were recently found by other authors (Tromp-van Meerveld and McDonnell, 2005; James and Roulet, 2007, 2009; Latron and Gallart, 2008; Zehe et al., 2010) with varying values of the moisture threshold, likely due to differences in soil type, soil depth and climatic conditions. Other investigations on hillslopes and experimental catchments have revealed the occurrence of threshold relations between soil moisture and water table variations (Peters et al., 2003; Latron and Gallart, 2008), highlighting the critical role of wetness conditions on surface and subsurface runoff generation. Sidle et al. (1995) showed that hollows or zero-order basins, which produced little or no runoff during dry conditions, contributed significantly to total catchment runoff once an antecedent moisture threshold was reached. These findings were consistent with later observations by Torres (2002), who speculated on the presence of a threshold value in the relationship between soil moisture and pressure head, above which rapid pressure head reactions occurred in the unsaturated zone, leading to a quick soil-water redistribution and fast discharge responses. Furthermore, in two recent papers Detty and McGuire (2010a,b) identified a clear threshold relationship between the sum of antecedent wetness conditions and gross precipitation and storm runoff: below the threshold total runoff was minimal whereas above it total runoff was linearly correlated with the combination of antecedent soil moisture and rainfall.

The control exerted by wetness conditions on runoff generation has been shown to be especially important in steep, humid catchments with shallow soils, where

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topographic properties exert a significant role on the dominant hydrological processes (Sidle et al., 2000; McGlynn, 2005). Relatively flat areas close to the stream have the potential to store water, to quickly saturate even during small rainfall events and to rapidly deliver water to the stream network, resulting in a fast runoff response. Conversely, soil water stored in the far-stream/hillslope zones may be released only during wetter conditions, when flowpaths between the hillslope and riparian zone become connected. Experimental evidence in mountainous and agricultural catchments has revealed that riparian zones tend to respond differently and almost independent from upslope zones with runoff typically being generated first in riparian areas, and with riparian-hillslope hydrological connectivity increasing under wet conditions (McGlynn et al., 2004; Wenninger et al., 2004; Ocampo et al., 2006). These different response times reveal distinctly different groundwater dynamics in riparian and upslope zones (Kendall et al., 1999; Seibert et al., 2003; Rassam et al., 2006), leading at times to hysteretic behaviours in the groundwater-runoff relationship (Kendall et al., 1999; McGlynn et al., 2004; Norbiato and Borga, 2008; Penna et al., 2010). The influence of rapid soil saturation in riparian zones on catchment runoff response has been highlighted in various studies. Investigating the runoff generation processes in a small headwater catchment in Japan, Sidle et al. (2000) identified saturated overland flow from the narrow riparian corridor as the major contributor to runoff during dry conditions whereas, as antecedent wetness increased, subsurface flow from adjacent hillslopes became the main source for streamflow with a corresponding decrease in the riparian contribution to streamflow. Burns et al. (2001) assessed the role of riparian groundwater at the Panola Mountain Research Watershed (Georgia, USA) using an end-member mixing analysis and concluded that riparian groundwater runoff was the largest component of runoff during rising streamflow and throughout stream recession. Similarly, McGlynn and McDonnell (2003) and McGlynn (2005) assessed the fundamental landscape controls on runoff generation and showed piezometric and tensiometric evidence for quicker responses to precipitation inputs of riparian zones than hillslope areas. Particularly, they found that riparian water dominated total storm runoff during small and

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moderate events or in early periods of large events. For larger events, hillslopes became the main contributor once runoff from the hillslope zone started, although riparian water was still more important during the hydrograph rising limb.

Along this vein of studies, this work focuses on three main questions for an experimental headwater catchment in the Italian Dolomites: (i) Is there a soil moisture threshold that controls both surface and subsurface response and how does the catchment topography affect this control? (ii) What are the main factors determining the catchment response time during dry and wet periods? (iii) What is the combined influence of antecedent wetness condition and rainfall event size on runoff?

2 Study area

The study area is located in the Rio Vauz Basin (1.9 km^2), an alpine headwater catchment located in the Italian Dolomites (central-eastern Alps, Fig. 1). Elevations range from 1835 to 3152 m a.s.l. with an average slope of 27.4°. The site features alpine climatic conditions, with a mean annual precipitation of 1220 mm (49% of which is snow), and average monthly temperatures varying from-5.7 °C in January to 14.1 °C in July. Snowmelt is the most important source of runoff in late spring but summer and early autumn storm responses significantly contribute to the flow regime. The catchment can be divided into three morphological units: (i) an upper part (3152–2200 m a.s.l.) entirely formed by Dolomitic rock cliffs, (ii) a middle part (2200–2000 m a.s.l.) composed by steep slopes and (iii) a valley bottom (2000–1835 m a.s.l.) covered by Quaternary till. As such, the Rio Vauz Basin can be deemed as morphologically and hydrologically representative of headwater catchments in the Dolomitic region.

Hydro-meteorological measurements were taken in a sub-catchment of the Rio Vauz Basin, named Bridge Creek Catchment (BCC, 0.14 km^2), with elevations ranging from 1932 to 2515 m a.s.l. (Fig. 1). The site is densely vegetated by alpine grasslands whereas trees (Norway spruce and European larch) are very rare and only form small shrubs. In the lower part of BCC, two hillslopes of similar size but different topographic

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shape were selected: "Piramide" (0.46 ha, divergent-convex) and "Emme" (0.47 ha, relatively planar). Elevations range between 1930 m and 1975 m a.s.l. for Piramide and between 1935 m and 1985 m a.s.l. for Emme. Detailed physical and chemical analyses were conducted on soil samples taken every 10 cm from a 70 cm-profile dug at the toe of Piramide. The soil was classified as Cambisoil with mull, characterized by a thick layer of organic matter strongly developed by earthworm activity. Average porosity ranged from 70.5% in the first 10 cm of soil to 45.0% in the deeper layers, with a mean value of 57.6% along the whole profile. Clay content decreases with depth from 73.3% to 44.4%, silt content increases with depth from 15.6% to 28.3%, whereas sand was the less common component, ranging between 9.2% and 1.4%. Further information about the Rio Vauz Basin, its topographic characteristics and climatic conditions, and the two experimental hillslopes can be found in Penna et al. (2009) and references therein.

3 Materials and methods

3.1 Precipitation, streamflow and groundwater monitoring

Precipitation, discharge, soil moisture and groundwater data were collected at BCC during two monitoring periods, from 1 June to 10 October 2005 and from 1 June to 15 October 2006.

Precipitation was recorded by a 0.2 mm tipping bucket rain gauge (Onset Computer Corporation, USA) located on the west of Piramide hillslope at 1923 m a.s.l. (Fig. 1). Discharge at BCC outlet (1932 m a.s.l.) was obtained at a V-notch sharp-crested weir equipped with a pressure transducer (Keller AG für Druckmesstechnik, Switzerland) recording at a 5-min time step. Groundwater levels were measured at nine piezometers equipped with capacitance water level sensors (Trutrack, New Zealand), recording at a 5-min time interval. Four piezometers were installed at Piramide and five at Emme with maximum depths ranging between 0.63 m and 1.18 m from the soil surface (Fig. 1).

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Precipitation, streamflow and groundwater records were aggregated to a 15-min interval for the data processing.

3.2 Soil moisture monitoring

Volumetric soil moisture was measured at different depths at various locations within the study area. Soil water content at 0–6 cm depth was manually measured on a 26-point grid on each hillslope (Fig. 1) during two field campaigns carried out between 28 June–21 July 2005 (24 surveys) and 21 June–16 July 2006 (23 surveys) using an impedance sensor (Theta Probe, Delta-T Devices Ltd., UK). Soil moisture at 0–12 and 0–20 cm was measured during the field campaigns at the same sampling points using a portable Time Domain Reflectometry probe (TDR 300, Spectrum Technologies Inc., USA), equipped with two pairs of interchangeable rods 12 and 20 cm long. Soil moisture at 0–30 cm depth was monitored hourly with Time Domain Reflectometers (CS625, Campbell Scientific, UK) at four sites located in the lower hillslope zone at Emme (Fig. 1). The average of the four values was in good agreement with the temporal patterns of average soil moisture derived from the measurements taken at the different depths at the 26 points on each experimental hillslope. Moreover, a marked temporal stability of the soil moisture spatial patterns was found for the two sites (Penna et al., 2007). These observations allowed us to consider the average of the four measurements at 0–30 cm as representative of the wetness conditions of the hillslope zone in the lower part of BCC. The Theta Probe and TDR 300 measurements were calibrated for the local soil conditions against 55, 45 and 40 soil cores collected at the three investigated depths, using a split tube soil sampler. It was not possible to collect undisturbed soil cores at 0–30 cm due to compaction of the samples. Thus, the standard calibration equation for clay soils was used. Further information on the soil moisture measurements can be found in Penna et al. (2009).

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3.3 Selection of rainfall-runoff events

To analyze the catchment's response to precipitation and the influence of soil moisture on runoff processes, 40 rainfall-runoff events during the two monitoring periods were identified. Storms were defined as events with more than 6 mm of precipitation. Events were considered distinct if they were separated by at least 6 h of no precipitation. Runoff from each event was summed from the storm onset before the first response to rainfall to the break in slope on the recession, which was visually determined. Baseflow was subtracted from total flow to obtain the value of event stormflow. Event runoff coefficients were defined as total stormflow (in mm) divided by total rainfall. The events were generally characterized by relatively short and intense convective storms but a long autumn rainfall event (1–4 October 2005) was recorded as well. Total event precipitation ranged between 6.8 and 134.2 mm. The main characteristics of the selected rainfall-runoff events are given in Table 1. The water content reflectometers were re-installed in the study area on 28 June 2005, therefore soil moisture data at 0–30 cm were not available for the first four events in 2005.

3.4 Determination of the size of the riparian area

In high elevation, small headwater catchments, the marked topographical features allow for a relatively easy determination of the fundamental landscape units. At BCC, we assessed the extent of the riparian zone by combining field surveys and DEM analysis, partially following the procedure suggested by McGlynn and Seibert (2003). In the field, we walked the whole stream length and mapped the relatively flat zones characterized by very wet soils that were close to saturation. For the DEM analysis, we used a 1 m resolution Digital Elevation Model derived from a LIDAR dataset. We chose a slope threshold value greater than the mean longitudinal slope of the stream channel and less than the ridge slope. By visually assessing the slope distribution over the whole catchment based on orthophotos and hillshade representations, we indentified a value of 15° as the threshold to distinguish between grid cells belonging to the riparian zone

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(cell value below the threshold slope) and grid cells belonging to the hillslope zone (cell value above the threshold slope). The two approaches gave similar results, yielding a riparian zone that was approximately 1.2 ha or 8.5% of the total catchment area (Fig. 1). This value for the size of the riparian area was used to compute the maximum potential runoff from the riparian area as discussed in Sect. 4.4.

4 Results and discussion

4.1 Time series of streamflow, soil moisture and water table

Figure 2 shows the time series of streamflow, soil moisture and water table for the two study periods. The total cumulative precipitation from 1 June to 10 October was 647 mm and 500 mm for 2005 and 2006 respectively, whereas the 18-year average cumulative precipitation for the same period in this region was 588 mm. Total runoff was 561 mm in 2005 and 428 mm in 2006 and the average runoff for the same period at BCC (computed over four years) was 473 mm. This reveals that 2005 was a relatively wet period and, conversely, 2006 was a period slightly drier than average. Generally, rainfall maximum intensity was also higher in 2005 than in 2006 and events were associated with moderately short storms. The catchment's hydrological response was similar for the two years, yielding a comparable number of rainfall-runoff events (19 and 21, in 2005 and 2006 respectively). A low flow period between mid-July and the beginning of August (usually, the driest and warmest period of the year) was observed in both time series. Generally, streamflow and soil water content were highly reactive, showing marked fluctuations over the entire period and rapid, sharp responses, even to small rainfall events. Conversely, groundwater response was characterized by smoother variations, especially during recessions (Fig. 2). A large storm event occurred at the beginning of October 2005, triggering a large hydrometric and piezometric response.

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4.2 Event runoff coefficients

Runoff coefficients were highly variable over the two study periods, with values ranging from 0.02 to 0.69 and a coefficient of variation larger than 1 (Table 1). This distribution likely reflects the variability of the storms analyzed, mostly in terms of total precipitation, storm duration, rainfall intensity, and antecedent wetness conditions. The mean value (0.15) was noticeably lower than that found by Norbiato et al. (2009) for two larger catchments in the same Dolomitic region (Cordevole at La Vizza, 7.3 km^2, mean: 0.33; Cordevole at Saviner, 109 km^2, mean: 0.28). Besides a difference in the calculation method, this was likely due to the longer study periods considered by these authors and the significant contribution of snowmelt, which was not included in our dataset.

4.3 Relation between soil moisture and runoff

The relationship between antecedent soil moisture at 0–30 cm (defined as the mean of the four spatial measurements taken before the storm onset) and the runoff coefficients for the 40 rainfall-runoff events observed during the study period was strongly non-linear and allowed the identification of a soil moisture threshold value (approximately 45%) above which runoff significantly increased (Fig. 3). This behaviour was very similar to that found in other catchments with different topographical, climatic and land use characteristics: smooth undulating hills and temperate climate in Tarrawarra, Australia, (Western and Grayson, 1998), low-elevation mountain grassland with Mediterranean semi-humid climate, Colorso, Central Italy (Brocca et al., 2005), significant topographic relief and a humid climate in Mont Saint-Hilaire, Canada (James and Roulet, 2007), and gentle agro-forested terrain with a sub-humid climate at Fiumarella of Corleto, Southern Italy (Onorati et al., 2007).

A clear threshold behaviour was also observed in the soil moisture at 0–30 cm and streamflow relationship (Fig. 4a) and the soil moisture at 0–30 cm and groundwater relationship (Fig. 4b). Discharge and water table level were low during dry conditions and a sharp increase occurred when the 45% moisture threshold was exceeded. These

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results agree with previous findings in other experimental watersheds and hillslopes (Meyles et al., 2003; Peters et al., 2003; Latron and Gallart, 2008) and underline the influence of soil moisture on non-linear runoff generation. Interestingly, the moisture value above which the hillslope average water level considerably rose was the same as for discharge, revealing the strong influence exerted by wetness conditions on both surface and subsurface response. Similar results were found at Piramide and Emme sites for the relationships between hillslope-averaged soil moisture at 0–6 cm, 0–12 cm and 0–20 cm depth and hillslope-averaged depth to water table (Fig. 5).

4.4 Soil moisture and the contribution of the riparian zone to storm runoff

The high elevation range and the clear distinction between the two fundamental landscape units at BCC were assumed to play an important role on streamflow generation. Disaggregating the watershed into discrete landscape units and determining the percentage of riparian and hillslope area can be used as a tool to assess the relative contribution of riparian water (event and pre-event water originating from riparian zones) and hillslope water (event and pre-event water originating from upland and hillslope zones) to total catchment runoff (McGlynn, 2005). In order to assess and quantify the contribution of the riparian zone to total stormflow at BCC, the "maximum potential riparian runoff" was computed by multiplying the rainfall depth by the extent of the riparian area (see Sect. 3.4), thus assuming complete soil saturation and therefore a total conversion of rainfall into streamflow for the riparian zone (Sidle et al., 2000). The "maximum potential percentage of riparian contribution to storm runoff" was then calculated as the ratio between the maximum potential riparian runoff and stormflow. Although some scatter existed in the relationship between the maximum percentage riparian contribution to stormflow and antecedent moisture conditions, the potential riparian contribution clearly decreased with increasing antecedent wetness (Fig. 6). For dry conditions, stormflow could totally or almost totally be caused by the response of the narrow riparian zone, with no or a very small contribution of water from the hillslope area. With increasing catchment wetness, hillslope must have become the dominant

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source of runoff, significantly releasing water so that the relative riparian contribution to storm runoff decreased markedly. Variability in the maximum percentage of riparian contribution also decreased when soil moisture increased.

Thus, the low runoff ratios presented in Fig. 3, derived from small storms with dry antecedent soil moisture conditions, were likely due to overland flow from the riparian zone that was characterized by high soil moisture conditions and was therefore prone to saturation and rapid response. Conversely, during wetter conditions and larger events, higher runoff ratios occurred. For these events, the most important contribution to streamflow must have come from hillslopes, which became hydrologically active and started to release water once the soil moisture threshold was exceeded. We currently do not have isotopic or hydrochemical data to confirm these hypotheses but they agree with previous tracer-based results in other experimental catchments (Sidle et al., 2000; Burns et al., 2001; McGlynn and McDonnell, 2003), which describe the dominant role of riparian zone for runoff generation during small events/early in the event and low antecedent wetness conditions and, on the other hand, the major contribution from hillslopes for larger events/later in the event during wetter conditions. These findings, based on runoff volumes, confirm the strong control exerted by topography on runoff generation in mountain watersheds and the essential role of hillslopes and riparian zones as fundamental landscape units in controlling the catchment hydrological response.

4.5 Response time

The temporal dynamics characterizing the catchment's response to precipitation were investigated to better understand the dominant processes controlling the hydrological behaviour of BCC. Response times were computed following the methodology of Blume et al. (2009). Time lags between storm onset and the start and peak of soil moisture, streamflow and water table response were calculated for all rainfall-runoff events. In order to reduce the effects of storm duration (the longer the rainfall event, the longer the response time, especially to peak response), all time lag values were normalized

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by dividing by the time between rainfall start and water table peak (typically the longest time lag). In order to determine the influence of antecedent soil moisture on the timing of the response, all events were classified into wet and dry antecedent conditions (according to the 45% soil moisture threshold) and the mean and median normalized time lags were computed for both conditions (Table 2). Overall, the observed high values of the standard deviation of the time lag indicated a marked variability of response lag time for the various events. However, distinct behaviours emerged as well. On average, soil moisture and streamflow tended to start to rise at approximately the same time after the precipitation input while soil moisture peaked earlier than stream discharge during wet conditions. Conversely, streamflow started to increase and peaked prior to (hillslope) soil moisture during dry conditions (Table 2). Hillslope-averaged water table response always exhibited a delayed start and peak, confirming previous observations found in another subcatchment of the Rio Vauz Basin (Penna et al., 2010) and elsewhere (Kendall et al., 1999; McGlynn et al., 2004). Rapid soil saturation of the riparian zone (McGlynn and McDonnell, 2003) could lead to a quick streamflow response whereas deeper percolation and filling of the soil moisture deficits likely resulted in a delay of the water table response.

Two rainfall-runoff events with similar cumulative precipitation but different antecedent soil moisture conditions are compared in Figure 7. During dry conditions (AMC $<$ 45%, panel a), soil moisture peaked after streamflow whereas during wet conditions (AMC $>$ 45%, panel b) the reverse occurred. Moreover, during dry conditions the soil moisture recession was slow, with water being retained in the soil. On the contrary, during wet conditions, reduced storage deficits and higher hydraulic conductivity facilitated the rapid displacement of water through the soil. This resulted in a faster recession and in shorter response times for events with wet conditions. These observations agree with previous findings about the different contributions of the riparian and hillslope zone to runoff: during dry periods, streamflow mainly increased due to channel interception and riparian runoff, resulting in peak stream discharge prior to peak hillslope soil moisture. When wetness conditions increased, hillslope runoff commenced

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and became the main source of catchment runoff and hillslope soil moisture peaked prior to streamflow.

The difference in timing of streamflow and soil moisture response resulted in clear hysteretic relationships between soil moisture and streamflow at BCC. Particularly, during rainfall-runoff events with dry antecedent conditions, streamflow responded and peaked earlier than hillslope soil moisture, leading to hysteretic loops with a clockwise direction (Fig. 8, panel a). For events with wet antecedent conditions, the reverse response time resulted in a hysteretic behaviour with an anticlockwise direction (Fig. 8, panel b). In the recent literature, hysteresis in catchment response has been found in the relationship between streamflow and water table response (McGlynn et al., 2004; Beven, 2006; Ewen and Birkinshaw, 2007; Norbiato and Borga, 2008; Penna et al., 2010). A few studies have also identified two opposite directions of hysteretic loops according to the location (near-stream riparian zone or hillslope zone) and the difference in timing of the water table response (Kendall et al., 1999; Detty and McGuire, 2008). Moreover, very recently McGuire and McDonnell (2010) showed hillslope-streamflow hysteresis patterns that changed direction over time, as a result of increasing wetness conditions.

4.6 Relationship between total precipitation and total storm runoff

The relationship between cumulative rainfall and total stormflow for the selected events is shown in Fig. 9. As expected, total storm runoff increased with total precipitation but very small values of stormflow occurred for low precipitation events. The effect of antecedent moisture conditions on storm runoff production was assessed by dividing the 40 rainfall-runoff events into four classes based on two threshold values: 45% of soil moisture, as previously identified, and 23 mm of cumulative rainfall because stormflow appeared to significantly increase when rainfall exceeded 23 mm. A clear combined effect of precipitation depth and antecedent soil wetness on total storm runoff was observed at BCC: small storms produced very low runoff amounts during dry conditions and greater runoff amounts during wet conditions (see inset of Fig. 9).

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A noticeable increase of stormflow occurred when both precipitation amount and antecedent wetness conditions increased. The best fit line through the data points had a slope of 0.09 ($R^2 = 0.66$) for storms smaller than 23 mm with dry antecedent moisture conditions (< 45%) and a slope of 0.26 ($R^2 = 0.57$) for storms smaller than 23 mm with wet antecedent moisture conditions. The runoff coefficient for small events with dry antecedent conditions (9%) compared surprisingly well with the size of the riparian zone (8.5%). These results, therefore, also suggest that the overland flow from the near saturated riparian zone was the major source of runoff during small events with dry antecedent moisture conditions but that the hillslopes must contribute to runoff during small events with wet antecedent conditions. A clear threshold in the relationship between storm total runoff and storm total precipitation was not apparent for events with wet antecedent conditions. The slope of the linear relationship between storm total precipitation and total runoff was 0.43 ($R^2 = 0.85$) for all events with wet antecedent conditions, except the large October 2005 storm, suggesting that total runoff increased linearly with precipitation, almost half of the precipitation was converted to streamflow, and that hillslopes must thus contribute to streamflow when antecedent soil moisture is high. The slope of the relationship increased to 0.70 ($R^2 = 0.94$) when the large October 2005 event was included.

5 Towards a conceptual model of hydrological behaviour at BCC

In alpine basins with complex terrain, hydrological processes result from the interaction of several factors, including topographic, geologic, pedologic and climatic properties. The analyses carried out in this study helped us to better understand the dominant processes and runoff generation mechanisms controlling the hydrological response to summer rainfall events at BCC. We observed similar behaviours at BCC as those described in Sidle et al.'s (2000) conceptual hydrogeomorphic model for steep headwater catchments based on the results obtained at Hitachi Ohta Experimental Watershed, Japan:

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i. During dry conditions (soil moisture at 0–30 cm in the 35%–45% range), streamflow and hillslope water table were low. Small storms resulted in low runoff coefficients (Fig. 3) and stormflow generation was related to the response of the near-stream riparian zone (Fig. 6) that was prone to saturation and reactive to precipitation. The increase in streamflow with precipitation was 9% of the precipitation, which suggested that streamflow could be explained by the contribution of the entire riparian zone. Streamflow and soil moisture were very sensitive to rainfall inputs whereas water table was less reactive. Streamflow response was faster than soil moisture measured on the hillslope, resulting in a clockwise hysteretic relationship between the two variables.

ii. As wetness increased, saturation in the riparian zone likely expanded laterally to the lower parts of hillslopes that are characterized by gentler slopes and shallow soils. Experimental evidence is not available to support this view but such a behaviour could be assumed based on a comparison of the topographic and geomorphologic properties of BCC with those of the Hitachi Ohta Watershed (e.g., incised morphology, shallow soils, steep slopes).

iii. With further increasing wetness, a moisture threshold was exceeded, resulting in a marked increase of streamflow (Fig. 4a) and likely the triggering of transient lateral subsurface flow on the hillslopes (Fig. 4b) as suggested by the abrupt increase in runoff coefficients above the 45% soil moisture threshold (Fig. 3) and the much larger increase in runoff depth with increasing precipitation (Fig. 9). A connection was likely established between the riparian area and hillslopes, which became hydrologically active zones. The relative contribution of the riparian zone to runoff significantly decreased with the increasing hillslope contribution (Fig. 6). Response times changed compared to dry conditions: hillslope soil moisture responded and peaked before streamflow, resulting in an anticlockwise hysteretic loop. Saturation overland flow over the hillslopes was not observed in the field during runoff events and is assumed to be a negligible contribution to total catchment

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runoff. Therefore it is concluded that hillslope contributions to streamflow were most likely in the form of subsurface flow.

The information gathered in this study represents a first step towards the development of a conceptual model able to describe the hydrological behaviour of this catchment. Further investigations using isotope data and/or geochemical data (which are currently not available) will be carried out to confirm this conceptual model.

The results from the experimental data presented in this study can be useful for future conceptualizations and development and application of hydrological models for alpine headwater catchments in the Dolomitic region. For instance at BCC, where a moisture threshold controls the storage-runoff relationship, the concept of competitive state variables (Duffy, 1996) might be applied and verified. In this context, the competitive inverse dependence between unsaturated and saturated moisture storage might be found to become more important for rainfall events with increasing wetness conditions and could lead to a better comprehension of the rainfall-runoff dynamics in this catchment. The highly non-linear phenomena which characterize the BCC response represent a challenge for most hydrological models based on linearity assumptions. Moreover, the switching direction of the hysteretic loops according to antecedent moisture conditions, which reflect complex hydrological processes generated under different watershed conditions, seems to disagree with the hypothesis of catchments as simple dynamic systems (Kirchner, 2009).

6 Conclusions

This paper focused on the hydrological response of a small headwater catchment in the Italian Alps with a humid climate, shallow soils and a clear distinction between riparian and hillslope areas. Particularly, the critical role exerted by near-surface soil moisture on runoff generation and its influence on threshold runoff processes was assessed by examining 40 rainfall-runoff events that occurred during two summer periods. In summary, the following results were obtained:

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- A clear response of soil water content and streamflow to almost any precipitation input was observed whereas the hillslope-averaged water table was less reactive, especially during dry conditions.
- A clear threshold relationship between soil moisture prior to the event and runoff was found. Above 45% volumetric soil moisture content runoff coefficients, streamflow and water table level abruptly increased revealing the strong influence exerted by initial wetness conditions on both surface and subsurface runoff. The low runoff ratios could be explained by saturation overland flow in the riparian zone whereas the higher runoff ratios observed during wet periods were attributed to the increased contribution of hillslopes, which became hydrologically active once the soil moisture threshold was exceeded.
- The potential riparian contribution to storm runoff was highest during dry conditions, whereas with increasing wetness, hillslopes must have contributed to streamflow and the contribution of the narrow riparian corridor became less important.
- Analysis of response times showed a quick reaction of streamflow and soil moisture while water table rise lagged behind. During dry conditions, hillslope soil moisture reacted and peaked after streamflow whereas during wet conditions the opposite occurred. This distinct timing led to a hysteretic behaviour in the soil moisture-streamflow relationship with a switch in the hysteretic loop direction based on the wetness conditions prior to the event.
- Total storm runoff values showed the combined effect of antecedent conditions and precipitation. During dry conditions, small storms generated low runoff amounts that could be explained by contributions from the riparian zone whereas during wet conditions small storms produced more runoff, suggesting a significant hillslope contribution.

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Table 1. Properties of selected rainfall-runoff events. The runoff coefficient had a mean of 0.15, a coefficient of variation of 1.05, and a skewness of 1.71.

date	total rainfall (mm)	duration (h)	total stormflow (mm)	peak discharge (l/s)	runoff ratio (–)
12 June 2005	10.4	3.0	0.4	8.1	0.03
14 June 2005	9.0	16.5	1.9	9.4	0.18
24 June 2005	23.2	1.7	0.7	14.7	0.03
25 June 2005	6.8	0.5	0.2	8.7	0.02
29 June 2005	20.4	8.2	1.2	13.4	0.05
30 June 2005	38.4	19.7	17.2	48.8	0.38
5 July 2005	32.0	12.5	10.9	39.3	0.29
7 July 2005	27.4	32.7	16.2	37.4	0.50
18 July 2005	11.0	1.2	0.2	14.1	0.02
23 July 2005	12.4	5.7	0.4	13.5	0.03
13 August 2005	11.8	6.0	0.4	11.2	0.03
14 August 2005	13.8	3.0	0.6	14.5	0.04
18 August 2005	14.6	2.7	0.9	16.6	0.06
20 August 2005	58.8	67.5	22.6	26.2	0.32
3 Sept. 2005	28.0	7.5	1.7	21.9	0.05
9 Sept. 2005	15.2	4.7	2.3	21.2	0.13
17 Sept. 2005	35.8	67.5	12.9	24.5	0.31
29 Sept. 2005	12.0	8.7	1.6	15.8	0.11
1 Oct. 2005	134.2	126.2	108.1	78.9	0.69
29 June 2006	22.4	11.3	2.0	21.3	0.07
2 July 2006	8.0	2.0	0.2	9.7	0.02
5 July 2006	17.4	5.3	1.1	19.3	0.05
6 July 2006	14.2	12.5	3.6	21.3	0.22
9 July 2006	14.8	8.5	2.8	23.3	0.16
27 July 2006	13.2	2.8	0.4	13.8	0.03
31 July 2006	11.6	1.3	0.6	15.9	0.05

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Table 1. Continued.

date	total rainfall (mm)	duration (h)	total stormflow (mm)	peak discharge (l/s)	runoff ratio (–)
1 August 2006	17.0	8.3	1.8	16.3	0.09
2 August 2006	52.0	40.3	25.4	60.9	0.42
9 August 2006	15.2	6.3	0.6	14.6	0.03
10 August 2006	10.8	4.8	1.4	15.9	0.11
11 August 2006	24.8	30.8	9.2	25.2	0.32
14 August 2006	8.8	7.0	2.0	21.4	0.20
16 August 2006	17.4	17.5	4.3	23.7	0.21
17 August 2006	12.4	10.0	1.3	21.5	0.09
25 August 2006	9.8	4.3	0.3	14.8	0.03
26 August 2006	26.6	5.3	5.7	39.0	0.18
7 Sept. 2006	21.8	7.5	0.9	18.7	0.04
15 Sept. 2006	56.6	15.3	9.8	53.4	0.15
16 Sept. 2006	11.8	8.8	1.6	20.8	0.12
14 Oct. 2006	10.4	3.0	0.3	11.6	0.02

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Table 2. Mean, median and standard deviation of time lags normalized by the peak water table time lag. SF: streamflow; SM: average soil moisture at 0–30 cm; WT: hillslope-averaged water table. Events where a water table response did not occur were excluded.

	time lag (h) between storm onset and:					
	SF start	SM start	WT start	SF peak	SM peak	WT peak
Mean						
all events	0.12	0.12	0.28	0.65	0.62	1.00
events in dry conditions	0.24	0.25	0.34	0.73	0.91	1.00
events in wet conditions	0.06	0.05	0.24	0.60	0.46	1.00
Median						
all events	0.07	0.08	0.29	0.67	0.59	1.00
events in dry conditions	0.21	0.21	0.30	0.76	0.70	1.00
events in wet conditions	0.04	0.03	0.28	0.61	0.44	1.00
Standard deviation						
all events	0.14	0.15	0.21	0.29	0.38	0.00
events in dry conditions	0.19	0.19	0.24	0.35	0.43	0.00
events in wet conditions	0.05	0.04	0.19	0.25	0.25	0.00

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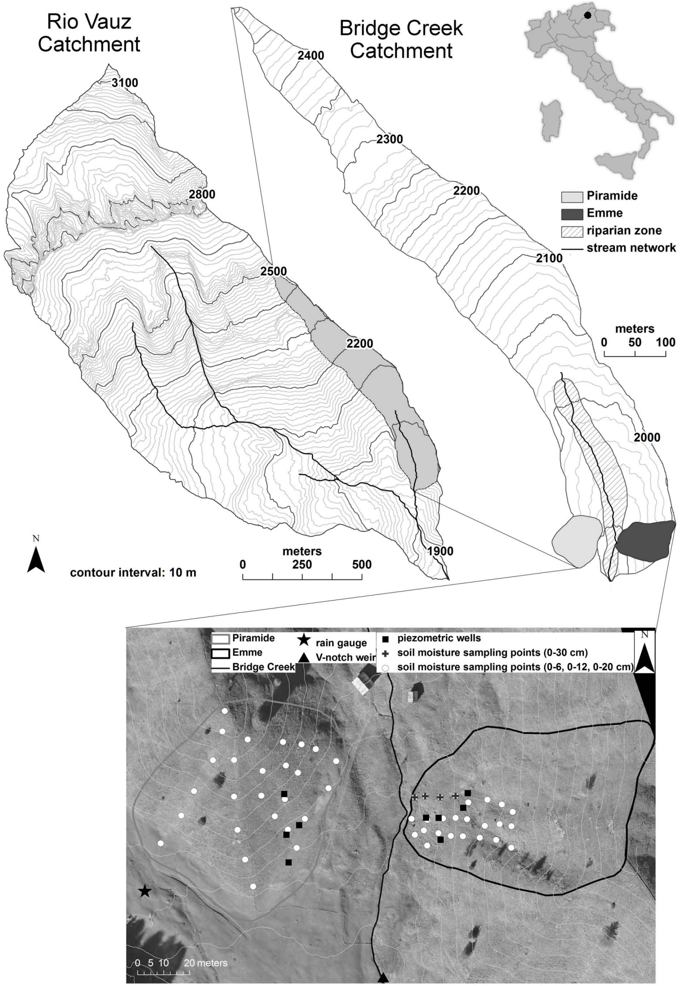

Fig. 1. Location of the study area and field instrumentation.

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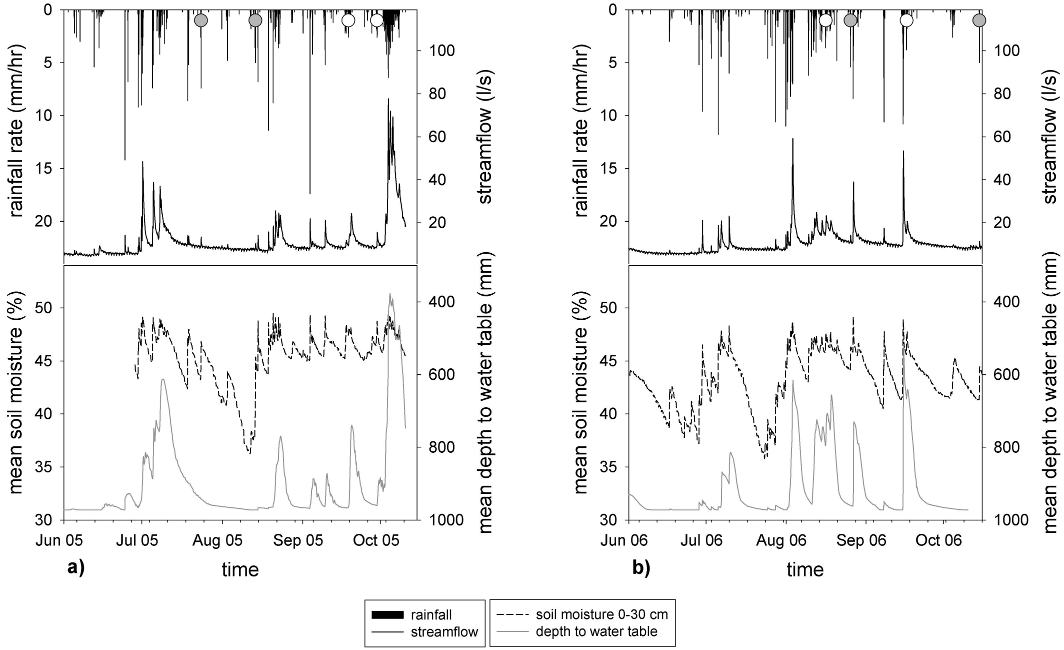

Fig. 2. Hourly time series of streamflow, mean soil moisture and hillslope-averaged depth to water table for the 2005 **(a)** and 2006 **(b)** periods. Gray and white dots represent the events with dry and wet antecedent conditions respectively shown in Fig. 8.

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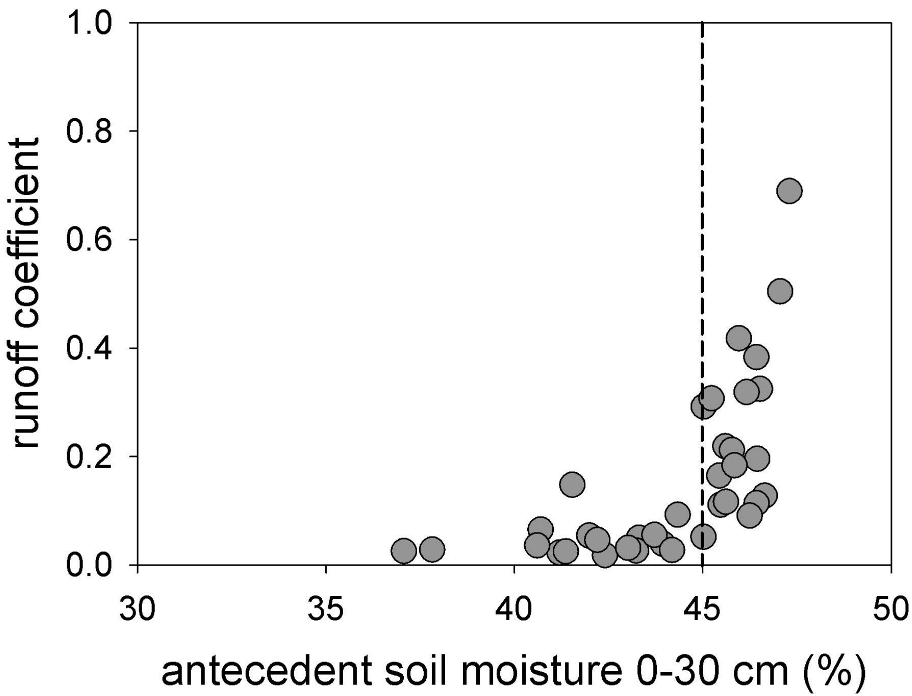

Fig. 3. Threshold behaviour in the relationship between soil moisture at 0–30 cm prior to the event and the runoff coefficient.

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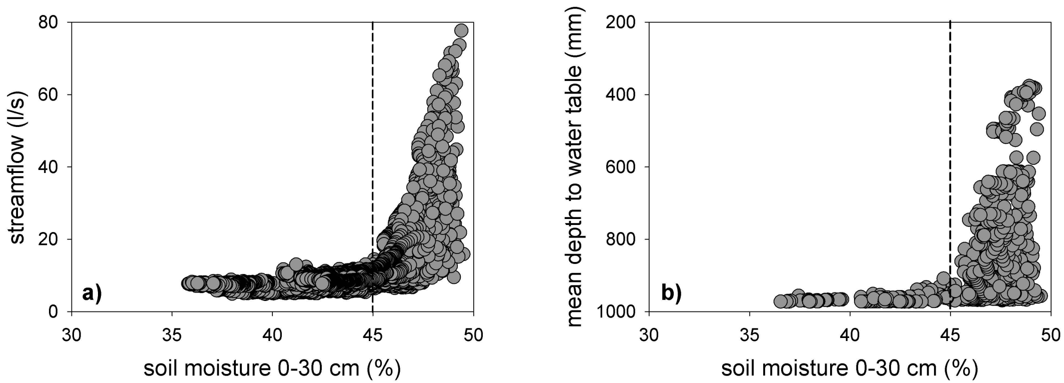

Fig. 4. Threshold behaviour in the relationship between soil moisture and streamflow **(a)** and between soil moisture and hillslope-averaged depth to water table **(b)**.

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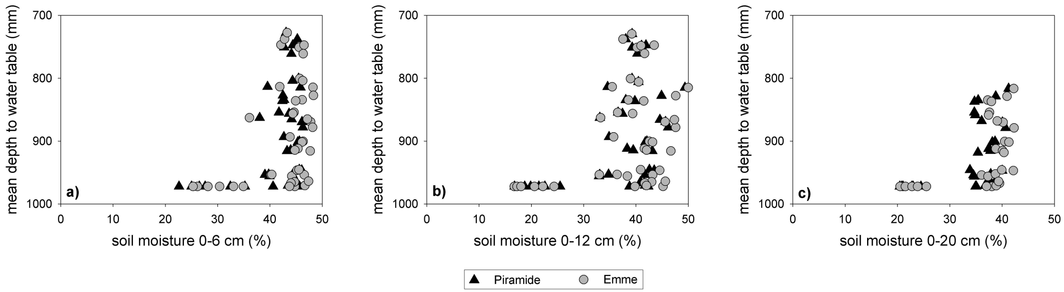

Fig. 5. Threshold behaviour in the relationship between hillslope-averaged soil moisture at 0–6 cm **(a)**, 0–12 cm **(b)**, 0–20 cm **(c)** and hillslope-averaged depth to water table.

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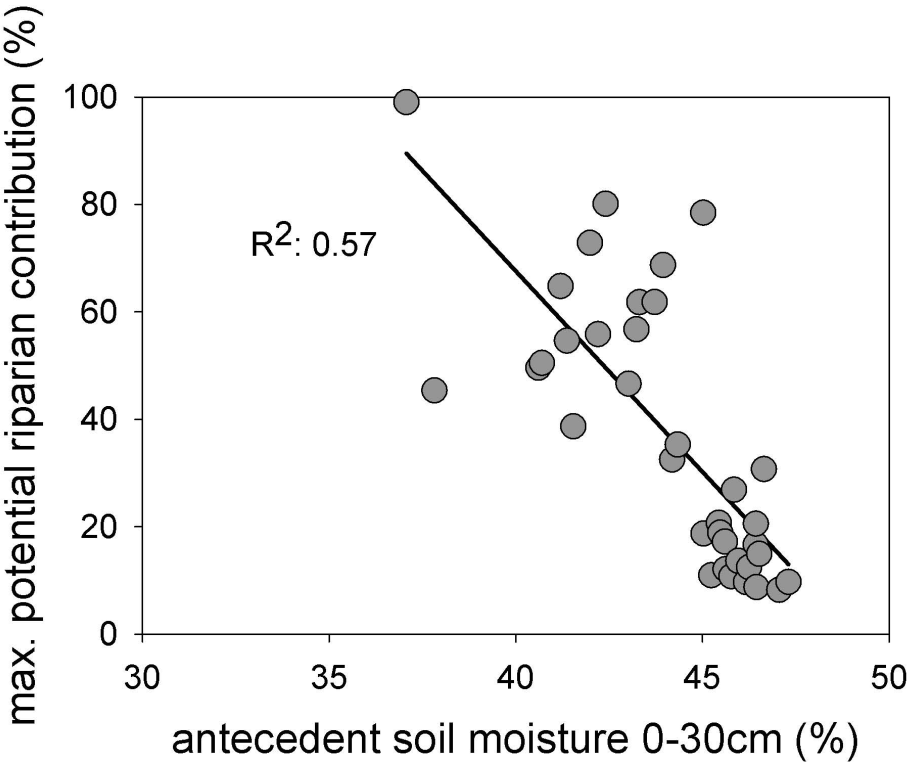

Fig. 6. Maximum potential contribution of the riparian zone to storm runoff as a function of antecedent wetness conditions. The calculation of the maximum potential riparian contribution assumes a runoff coefficient of 100% from the riparian zone.

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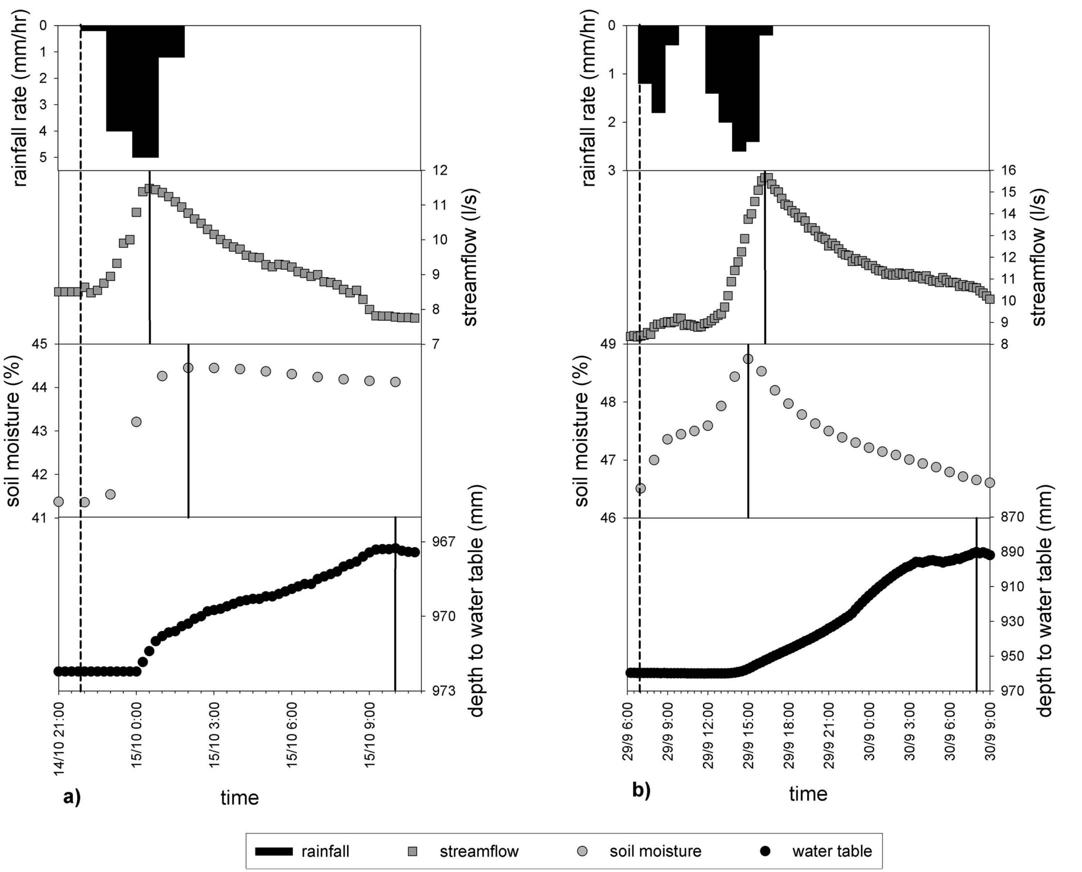

Fig. 7. Timing of streamflow, soil moisture and water table for **(a)** a dry event (14 October 2006, 10.4 mm) and **(b)** a wet event (29 September 2005, 12.0 mm) Note the difference in scale of the axes. The vertical dashed line represents the time of the start of the rainfall event. The vertical solid lines represent the time of the peak of the response.

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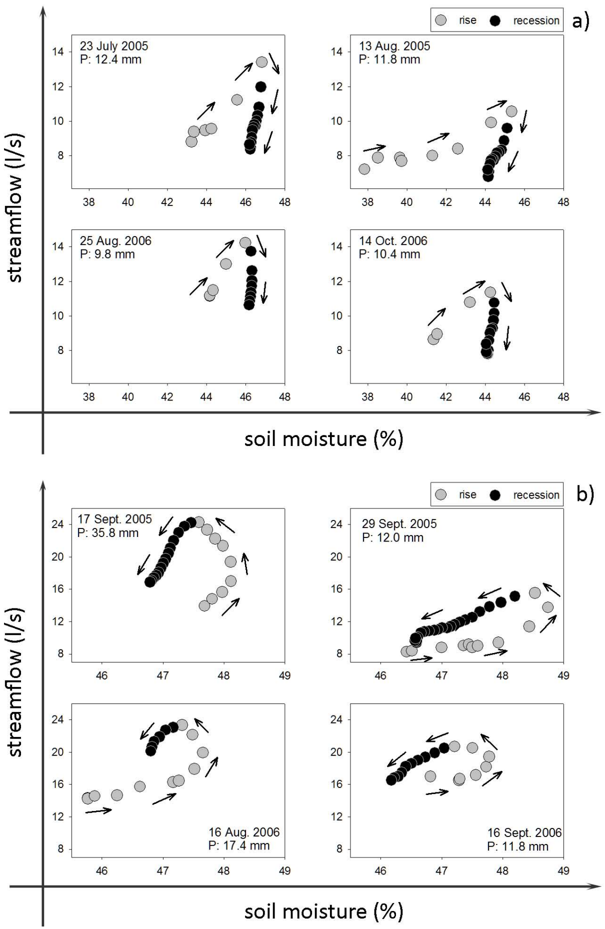

Fig. 8. Hysteretic behaviour in the relationship between average soil moisture at 0–30 cm and streamflow for various events with dry **(a)** and wet **(b)** antecedent conditions.

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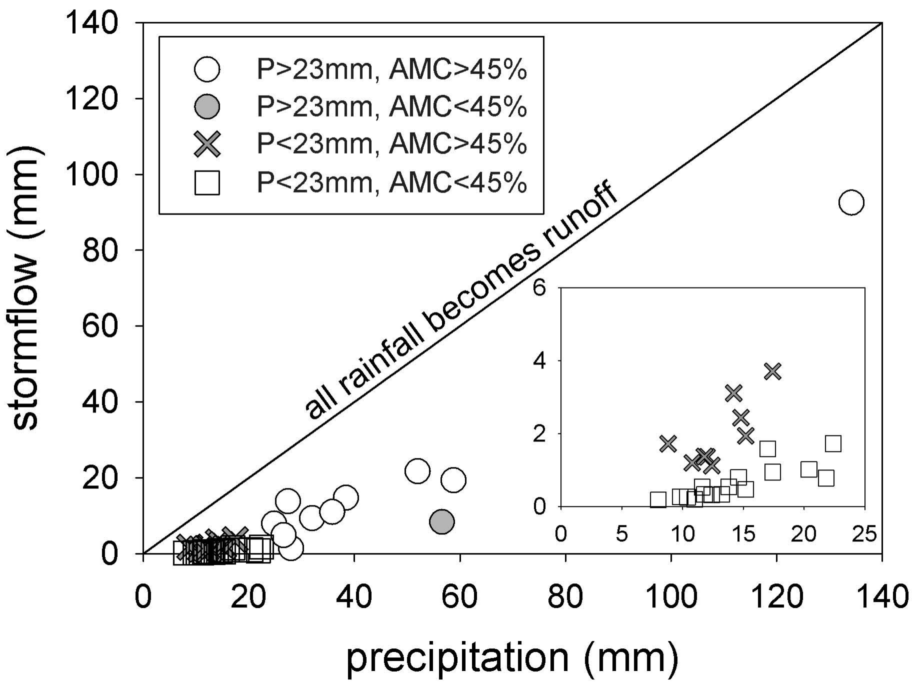

Fig. 9. Total stormflow as a function of total precipitation for all events. *P*: Precipitation; AMC: Antecedent Moisture Content measured at 0–30 cm. In the inset: zoom for the relation at low precipitation values.

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