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Differences in stream flow in relation to changes in land cover: A comparative study in two sub-Mediterranean mountain catchments

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SUMMARY

The stream flow response of two neighboring catchments in the central Spanish Pyrenees was compared for 26 rainstorms covering both catchments: one catchment (2.84 km^2) was extensively used for agriculture in the past, and the other (0.92 km^2) is covered by dense natural forest. Their similarity in terms of lithology and topography enabled us to separate the effects of soil and land cover on their hydrological responses. Relative to the forested catchment, peak flows in the past agricultural catchment were always greater (566 *vs.* 119 $l\,s^{-1}\,km^{-2}$), the response time was 2- to 3-fold faster (131 *vs.* 356 min), and the recession limbs were 1–2 orders of magnitude shorter (7 *vs.* 72 h). Storm flow was usually greater in the former agricultural catchment, especially for low–intermediate sized flood events; only for larger events the storm flow in the forested catchment was sometimes greater. Storm flow differences were closely related to catchment wetness conditions and showed a marked seasonal pattern, with higher values in the past agricultural catchment under dry conditions, and usually higher values in the forested catchment under wet conditions. In the past agricultural catchment, runoff was generated during the entire water year, through both surface (i.e. infiltration excess and saturation excess overland flow) and subsurface flow. We suggest that the forested catchment can be characterized by a dual (or switching) behavior controlled by soil moisture conditions, which regulates the hydrological connectivity and favors the release of large amounts of subsurface flow. Differences in soil depth and permeability, together with differences in vegetation cover, may explain the contrasting dominant runoff generation processes operating in each catchment, and consequently the differences between their hydrograph characteristics.

1. Introduction

The effect of land cover change on water yield is an ongoing issue of concern to hydrologists, and land and water managers. Studies based on (i) the classical paired-catchments approach (e.g. Hewlett and Helvey, 1970; Troendle and King, 1985; Hornbeck et al., 1993); (ii) single catchment experiments in which the land cover changes during the study period (e.g. Dubicki, 1994; Lavabre et al., 1993; Grayson et al., 2010); and (iii) the comparison of the hydrological responses of neighboring catchments with different land covers (e.g. Burch et al., 1987; Cosandey, 1993) have provided substantial information on the hydrological impacts of land use/land cover changes.

Reviews of such studies worldwide (Hibbert, 1967; Bosch and Hewlett, 1982; Hornbeck et al., 1993; Robinson et al., 2003; Andréassian, 2004; Cosandey et al., 2005) have demonstrated a short-term increase in annual water yields following deforestation, and often a reduction in annual flows following reforestation. Studies at the flood event scale are less numerous and most data indicate that the impacts of forests on floods are much more variable (Robinson et al., 2003; Andréassian, 2004; Bruijnzeel, 2004; Bruijnzeel et al., 2004), making the results controversial (Cosandey et al., 2005; van Dijk et al., 2009). Deforestation generally increases storm and peak flows (Hewlett and Helvey, 1970; Burton, 1997), but this pattern can be less evident or even reversed under some hydrometeorological conditions (Troendle and King, 1985; Hornbeck et al., 1997 cited in Andréassian, 2004). The opposite effect, expected as a consequence of reforestation, is in some cases evident (López-Moreno et al., 2006), but in other cases limited (McGuinness and Harrold, 1971; Robinson et al., 2003). Cosandey et al. (2005) noted that this is not surprising given the variability of factors (type of soil, climate conditions, vegetation characteristics, characteristics of floods, type of land use/forest treatment) involved in the generation of runoff, and the enormous diversity in

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the functioning of catchments (i.e. hydrological processes associated with runoff generation).

It is therefore essential to take a closer look at the hydrological behavior of catchments with different land covers to enable the effects of vegetation on flood generation to be identified, and to understand the variability involved. For this purpose, in this study a detailed analysis of the stream flow response of two neighboring catchments differing in land cover was carried out: a past agricultural catchment and an undisturbed forested catchment. The catchments were selected for their similar climatic conditions, lithology and topography, which enabled to separate the effects of soil and land cover on their hydrological responses. García-Ruiz et al. (2008) had previously identified some hydrological differences between these catchments, particularly in the relationship of rainfall to runoff, and the frequency and seasonality of floods. However, a more detailed analysis at the event scale (flood events in each catchment caused by the same rainstorm) is necessary to assess the magnitude and nature of these differences.

The two catchments are located in the Pyrenees mountain range, in the Mediterranean region. The effect of land cover change on hydrological response is particularly relevant in this area (García-Ruiz and Lana-Renault, 2011) because: (i) water resources are scarce and uneven in this region which relies on runoff generated in mountain areas and where extensive farmland abandonment has occurred in recent decades; (ii) the resulting expansion of forest and shrubs has been associated with a reduction of stream flow (e.g., Beguería et al., 2003; Delgado et al., 2010), although the relationship between changes in vegetation cover and stream flow is poorly understood (Cosandey et al., 2005), primarily because of the complexity of runoff generation processes under Mediterranean conditions (Latron et al., 2009); (iii) the increasing expansion of vegetation (Vicente-Serrano et al., 2005; Rounsevell et al., 2006) together with a general increase in water demand may result in water shortages in the near future (López-Moreno et al., 2008). In this context, it is of paramount importance to predict the impact of land cover changes on water yield, which is not possible without an understanding of the relationship between land cover change and changes in catchment hydrology.

The aim of this study is to identify significant stream flow differences between two catchments with different land cover, and to assess the extent to which these differences are related to soil and vegetation characteristics. A general overview of the effect of catchment attributes on hydrograph characteristics is first presented. Then, based on a set of 26 flood events caused by the same rainfall event in each catchment, differences in their various hydrographs parameters (storm flow depth, peak flow discharge, response time and recession time) are investigated. Analysis of these parameters under varying rainfall and wetness conditions provided insights into the nature of the differences and the hydrological functioning of each catchment. Based on these analyses and the overview previously presented, the role of vegetation and soils on catchment behavior is discussed.

2. Catchment attributes and their effect on the hydrological response

The hydrological response of a catchment is a function of a combination of factors related to meteorological drivers, the hydrological status of the catchment (i.e. initial conditions), and catchment attributes including topography, and soil and land cover properties. This is described in equation 1:

$$Q = f(P, A, T, S, V) \tag{1}$$

where Q is the hydrograph characteristics, P is the rainfall characteristics, A is the preceding moisture conditions, T is topography, and S and V are properties related to soil and vegetation, respectively. Given the same rainfall and preceding moisture conditions (P and A constant), the differences in Q between two catchments are a function of catchment attributes. If it is assumed that topography (T) is similar between the catchments, then the differences in Q can be explained by differences in soil (S) and land cover (V) properties. This approach underpinned this study.

Table 1 summarizes the main catchment attributes, their significance in catchment hydrology, and possible effects on hydrograph characteristics including: (i) storm flow discharge; (ii) peak flow; (iii) response time (defined as the lag time between the centroid of the rainfall event and the peak flow); and (iv) recession limb.

Topography is a major controlling influence on stream flow response because it determines the movement of water over and within slopes. Aspect mainly regulates the input of precipitation and energy. In a small catchment in the Vosges mountains (France), Ambroise and Najjar (1983) detected higher evapotranspiration rates on the ridges of south facing slopes relative to slopes oriented westward, which were subject to less radiation and wind. The slope mainly controls the downward flow velocity, and in some studies more rapid stream flow responses have been associated with the steepness of the hillslopes (Arnaud-Fassetta et al., 1993; Chen et al., 2010). In contrast, if the topsoil is permeable, steep slopes may also reduce the likelihood of soil saturation and therefore favor subsurface flow (Freeze, 1972; McDonnell, 1990), which may in turn produce lower peak flows, a slower response, and longer recession limbs (Calver et al., 1972, cited in Dunne, 1978; Chen et al., 2010). Flow path length affects the time of transfer over and within slopes (Kirkby, 1988), and thus slower responses would be expected from longer path lengths. However, the effect may become less important in smaller catchments. Surface curvature controls converging/diverging flows. The observation that convergent surfaces are usually characterized by higher soil water content (Anderson and Burt, 1978) led to the development of topographic indices that predict areas prone to soil saturation (Kirkby, 1975; ÓLoughlin, 1986). Increasing soil saturation facilitates runoff generation, and therefore greater storm flows (Anderson and Burt, 1978; Beven et al., 1988). A larger contribution of saturation excess overland flow related to convergent surfaces has often been associated with greater peak flows, more rapid responses, and shorter recession limbs (Calver et al., 1972, cited in Dunne, 1978; Chen et al., 2010).

Differences in soil characteristics have commonly been reported to be the main factor explaining differences in stream flow responses among catchments (Burch et al., 1987; Cosandey, 1993; Richard and Mathys, 1999). Soil thickness determines the water storage capacity of the soil reservoir. Shallow soils have lower water storage capacity, so tend to generate greater stream flow discharges at the catchment outlet (Burch et al., 1987; Cosandey, 1993). They can encourage soil saturation and subsequent saturation excess overland flow (Hewlett and Nutter, 1970), which is commonly associated with more rapid responses, greater peak flows, and shorter recession limbs (Burch et al., 1987; Combes et al., 1994). Soil properties including texture, structure, organic matter content and macroporosity affect the water transmissivity of soils. Highly permeable soils (i.e. well-structured soils with coarse texture and high organic matter content), which typically occur in forested areas (Harr, 1977; Bonell et al., 1983), favor flow within the matrix or through macropores. In such environments a large contribution of subsurface flow is usually reported (Whipkey, 1965; Bonell et al., 1984), and low peak flows, slow responses and long recessions are observed (Freeze, 1972; Burt and Butcher, 1985; Chen et al., 2010). However, the presence of numerous macropores in a soil may result in a large contribution of preferential flow (Beven and Germann, 1982; Burch et al., 1987), which can subsequently lead to more rapid stream flow responses (Bonell and Williams, 1986; Kirkby, 1988).

Table 1
Catchment properties, their main hydrological influence, and examples of their effect on hydrological processes and hydrograph characteristics (italics).

Catchment properties	Hydrological influence	Examples of effects on hydrological processes and hydrograph characteristics
Topography[a]		
Aspect	Solar radiation-potential evapotranspiration	South-facing slopes[b]: Higher evapotranspiration (Ambroise and Najjar, 1983) → *Less storm flow discharge*
Slope gradient	Flow velocity	Steep slopes: Higher downslope flow velocity → *Shorter response time* (Arnaud-Fassetta et al., 1993; Chen et al., 2010); but larger contribution of subsurface storm-flow (Freeze, 1972; McDonnell, 1990) → *Lower peak flow, slower response, longer recessions* (Calver et al., 1972, cited in Dunne, 1978; Chen et al., 2010)
Flow path length	Time of concentration	Long flowpaths: Slower transfer over/within the slope (Kirkby, 1988) → *Longer response time*
Surface curvature	Converging/Diverging flows	Convergent surfaces: Convergence lateral water movement and more soil water content (Anderson and Burt, 1978) → *More storm flow discharge* (Anderson and Burt, 1978; Beven et al., 1988); If larger contribution of saturation overlandflow (Anderson and Burt, 1978) → *Higher peak flow, quicker response, shorter recession limb* (Calver et al., 1972, cited in Dunne, 1978; Chen et al., 2010)
Soil		
Regolith thickness	Storage capacity	Thin soils: Less storage capacity → *More stormflow discharge* (Burch et al., 1987; Cosandey, 1993); Larger contribution of saturation overlandflow (Hewlett and Nutter, 1970) → *Higher peak flow, quicker response, shorter recession limb* (Burch et al., 1987; Combes et al., 1994)
Physical characteristics of the soil (structure, texture, macroporosity)	Transmissivity within the soil	Coarser texture, well-structured soils: higher transmissivity: Larger contribution of subsurface flow (Whipkey, 1965; Bonell et al., 1984; Burch et al., 1987) → *Lower peak flow, slower response, longer recession* (Freeze, 1972; Burt and Butcher, 1985; Burch et al., 1987; Chen et al., 2010) but if preferential flow → *quicker response* (Bonell and Williams, 1986; Kirkby, 1988)
Vegetation		
Characteristics of the stand (density, structure, aerodynamic and surface resistances, roots density and depth)	Interception and evapotranspiration	Dense tree cover: more interception and evapotranspiration (Law, 1956; Calder and Newson, 1979; Zhang et al., 2001) → *Less stormflow yield* (Hornbeck, 1973).

[a] Based on Moore et al., 1991.
[b] For northern hemisphere.

The hydrological impact of vegetation has received considerable attention, primarily because of its changing nature, which is usually associated with human activity. Vegetation regulates the transfer of water between the land surface and the atmosphere, through rainfall interception and evapotranspiration processes. The non-linearity between rainfall and runoff observed in vegetated catchments (Hewlett et al., 1984) demonstrates the buffer role played by plant cover, although this effect appears to be negligible under very intense rainstorms in the tropical area (Howard et al., 2010). The mechanisms by which vegetation controls these processes are complex, and mainly depend on the physiological characteristics of the vegetation (density, structure, aerodynamic and surface resistances, root density and depth) and the (hydro)climatic conditions (Wallace and Oliver, 1990). Trees intercept and lose (through evaporation) enormous quantities of rainfall (Law, 1956; Calder and Newson, 1979) because of their structure and low aerodynamic resistance (Wallace and Oliver, 1990). Transpiration is thought to be low in forests because of their high surface resistance (Wallace and Oliver, 1990), but the large evaporative potential of trees usually guarantees substantial water transfer to the atmosphere (Zhang et al., 2001). The loss of water by interception and transpiration is commonly given as the explanation for the low soil water content observed under forest cover (Gallart et al., 2002), and the associated low storm flow discharges (Hornbeck, 1973).

3. The catchments

The two catchments considered in the study are located in the upper Aragón River valley, in the central Spanish Pyrenees (Fig. 1). As with most of the middle Mediterranean mountains, this area has been markedly affected by land use changes. Agricultural practices have been very intensive over many centuries (García-Ruiz and Lasanta, 1990; García-Ruiz et al., 2000), but depopulation during the 20th century resulted in progressive abandonment of most of the cultivated fields and a reduction in livestock numbers, which has resulted in a significant expansion of shrubs and forests (Vicente-Serrano et al., 2005).

Table 2 summarizes the main characteristics of the two catchments, both of which are located between 850 and 1350 m a.s.l. Bedrock is Eocene flysch composed of thin, alternating layers of sandstones and marls, where no significant hydrogeological units (aquifers) occurred (Ebro Hydrographic Confederation, www.oph.chebro.es); thus, assumption of zero seepage from bedrock is valid in the studied catchments.

The Arnás catchment was heavily cultivated with cereal crops in non-terraced fields until the 1950s, after which it was abandoned and left to recolonize by native vegetation. The San Salvador catchment is covered by dense natural forest, and is effectively an undisturbed environment. The two catchments are adjacent to each other and have similar climatic conditions. The mean annual temperature is 10 °C, and the mean annual precipitation from 1999 to 2008 was 926 mm in the Arnás catchment and 935 mm in the San Salvador catchment. Snowfall occurs only occasionally. Rainfall is usually concentrated in autumn and spring, whereas winter is a period with less precipitation and lower temperatures; summers are hot and relatively dry, although intense convective storms of short duration are relatively frequent. Mean annual reference evapotranspiration in the study area calculated by the method of Hargreaves and Samani (1985) was 1088 ± 31 mm.

3.1. Topography and geomorphology

The east–west orientation of the ravine in the past agricultural catchment (the Arnás catchment) results in an asymmetry between the north and south facing slopes (*cuesta* relief). The gentler north facing slope is marked by an undulating topography with old scars

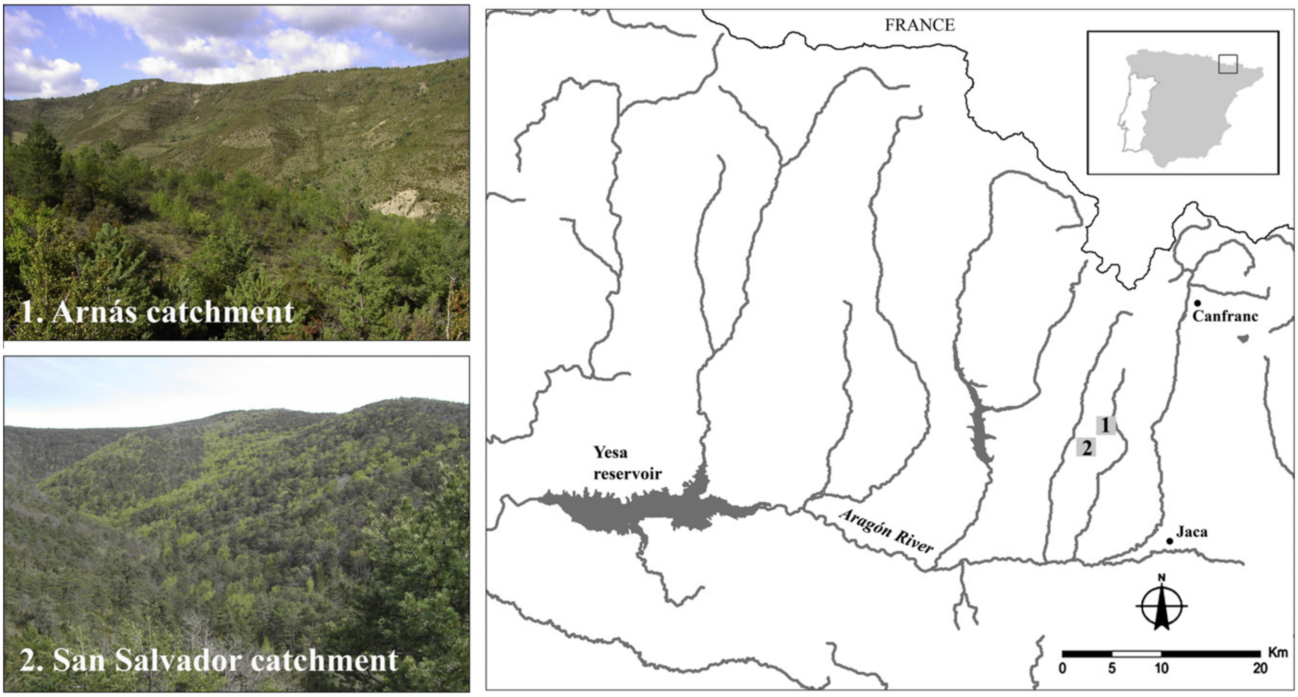

Fig. 1. Locations of the past agricultural (1) and forested (2) catchments.

Table 2
General characteristics of the experimental catchments.

	Former agricultural catchment (Arnás)	Forested catchment (San Salvador)
Area (km^2)	2.84	0.92
Min–Max altitudes (m a.s.l.)	910–1340	875–1300
Bedrock	Flysch	Flysch
Mean slope (mm^{-1})	0.38	0.52
Mean topographic index ln (a/tan b) (–)	6.3	5.6
Drainage density (km km^{-2})	0.12	0.11
Bare ground (%)	2	<1
Herbaceous (%)	7	<1
Shrubs (%)	71	1
Forest (%)	20	98
Rainfall 1999–2008 (mm)	926 ± 182	935 ± 171

and stable deep mass movement deposits. The south facing slope is characterized in the upper parts by recent and relatively active debris flows, which are disconnected from the drainage network. In the forested San Salvador catchment a deep, stony colluvium covers most of the slopes, explaining the lack of geomorphological contrasts.

Fig. 2 compares the topographical attributes of aspect, slope and the topographic index for the two catchments. The topographic index is defined as $\ln(\alpha/\tan\beta)$ (Kirkby, 1975), where α is the upslope area contributing to a given point in the catchment, and β is the local surface slope angle. The proportion of the surface area with south orientation (i.e. between 135° and 225°) is similar (Fig. 2a) in the past agricultural catchment (15%) and the forested catchment (25%), indicating comparable rates of potential evaporative demand. The mean slope in the past agricultural catchment (0.38 m m^{-1}) is lower than in the forested catchment (0.52 m m^{-1}), but the frequency of flatter (i.e. <0.10 m m^{-1}) and steeper (i.e. >0.70 m m^{-1}) areas is similar in both catchments, as each of these categories represents only about 5% of either catchment (Fig. 2b). Fig. 2c shows that the distribution of the topographic index in each catchment is comparable, with 50% of the area having values below 6. The highest values (i.e. > 8) were moderately more frequent in the former agricultural catchment (14%) than in the forested catchment (3%). The mean drainage density (flow path divided by catchment area) is almost the same in the two catchments (0.11 and 0.12 for the former agricultural and forested catchments, respectively), suggesting similar times of flow concentration. Analysis of these topographical attributes suggests that T in equation 1 can be considered to be approximately the same for each catchment.

3.2. Soils

Soils in the past agricultural catchment are dominated by silt although the percentage of clay is significantly higher (up to 30%) in the valley bottom (Navas et al., 2005). The south facing slope is characterized by compact and shallow soils, inherited from past human activities. These soils are mostly rendsic leptosols and calcaric regosols (FAO, 1988), generally less than 0.25 m thick, with a bulk density ranging between 1.2 and 1.3 g cm^{-3}, and showing signs of major degradation (Navas et al., 2005). On the north facing slope, brown and deeper haplic kastanozems and haplic phaeozems (up to 0.75 m thick) soils are present, with a high content of organic matter (Navas et al., 2005) and a bulk density ranging between 0.8 and 1.1 g cm^{-3}. In the mass movement deposits close to the valley bottom, soil thickness can locally reach 2 m.

The forested catchment is mainly composed of well-developed kastanozems and cambisols. Soils texture is also dominated by silt and soil density ranges between 0.9 and 1.1 g cm^{-3} (Serrano-Muela, 2005) Preliminary surveys indicated that the soil depth to rock was 0.9–1.2 m, and slightly shallower in the upper parts (<0.5 m) (Serrano-Muela, 2005). The homogeneity in terms of slope shape

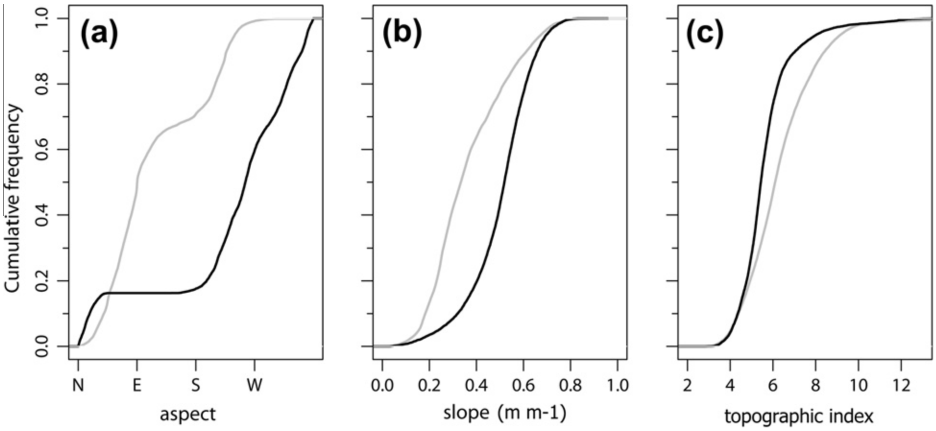

Fig. 2. Comparison of topographical variables in the past agricultural (gray line) and forested (black line) catchments.

and gradient suggests that this range of soil depths is relatively consistent throughout the forested catchment.

Soil saturated hydraulic conductivity was estimated using Rosetta v.1.2 (Shaap, 2000) and soil texture and bulk density data taken from Navas et al. (2005) and Serrano-Muela (2005). In the past agricultural catchment, saturated conductivity was estimated around 10 mm h^{-1} in the south facing slope, and 30 mm h^{-1} in the north facing slope, where it could reach values up to 55 mm h^{-1} in localized areas, especially under forest. In the forested catchment, saturated conductivity estimations ranged between 40 and 90 mm h^{-1}.

3.3. Vegetation

Since it was abandoned the past agricultural catchment has been recolonized by shrubs (*Genista scorpius*, *Echinospartum horridum*, *Juniperus communis*, *Rosa* gr. *canina* and *Buxus sempervirens*) and some stands of developing forest (*Pinus sylvestris* and *Quercus faginea*). At present shrubs occupy most of the catchment (71%), although a large proportion comprises low density cover. Forest occupies about 20%, and herbaceous vegetation covers some parts of the valley floor (approximately 7% of the catchment), indicating more recent farmland abandonment. Bare ground comprises about 2% of the catchment. The forested catchment is almost totally covered by dense natural forest (98%) of Scots pine (*P. sylvestris*), in combination with beech trees (*Fagus sylvatica*) in the shady concavities and oaks (*Q. faginea*) in areas with a sunny aspect. Interception data obtained inform experimental plots in the forested catchment indicated that, on an annual basis, pine and oak forest intercept 22% and 23% of the rainfall, respectively, whereas interception under beech trees varies between 17% in winter and 28% in the active period (Serrano-Muela et al., 2008).

3.4. Hydrological background

Previous studies (García-Ruiz et al., 2005, 2008; Lana-Renault et al., 2007) showed that the hydrological response of the past agricultural catchment was mainly related to rainfall characteristics (volume and rainfall intensity) and catchment wetness conditions. Here, as in most Mediterranean mountain catchments (Latron et al., 2009), the combination of temperature (which has a direct effect on evapotranspiration) and rainfall over the water year regulates the dynamics of the water-table, which usually shows a saturation period in winter and the first half of spring, and a depletion period in late spring and summer (Lana-Renault et al., 2007). The analysis at the event scale of the water-table and stream-flow responses, together with the suspended sediment transport revealed the complexity of the hydrological processes operating in this catchment (Lana-Renault et al., 2007; Lana-Renault and Regüés, 2009): during summer dry conditions, infiltration excess runoff into the stream channel and upon non-vegetated areas close to it is the only active runoff process, occurring in response to short and intense rainstorms; during wet conditions both saturated excess runoff and subsurface flow are most likely to be the dominant runoff processes; finally, during the wetting-up and drying-down transition periods, the hydrological response is variable, with infiltration excess runoff and saturation excess runoff processes occurring at the same time in different parts of the catchment, depending on the depth of the water table before the event and rainfall depth and intensity.

The hydrological response in the forested catchment is unrelated to the volume or intensity of the rainfall; instead, it is strongly influenced by the base flow at the start of the event which is an indicator of catchment moisture conditions (García-Ruiz et al., 2008; Serrano-Muela et al., 2008). These authors showed that discharge in the forested catchment was only significant when the water table was close to the soil surface at the beginning of the rainfall event, which in turn was closely related to antecedent rainfall. As a consequence, the hydrological response in this catchment shows a marked seasonality, with late winter and spring being the only high flow periods, and autumn and summer with almost no flow (García-Ruiz et al., 2008; Serrano-Muela et al., 2008; Lana-Renault et al., 2010). The strong influence of the water table dynamics on the stream flow discharge and the general absence of saturated areas indicate the dominance of subsurface flow processes (García-Ruiz et al., 2008).

4. Data collection and methods

Each of the two catchments is equipped with a complete weather station and three tipping buckets that collect rainfall, installed along the main stream. At the outlet of each catchment stream flow is measured at a gauging station (a concrete weir in the past agricultural catchment and a 90° V-notch weir in the forested one). At each gauging station the water level in the stream is recorded directly using an ultrasound sensor (Lundahl DCU-7110) and a water pressure sensor (Keller DCX-22 AA). Discharge is determined using established stage rating curves. In the past agricultural catchment information on sediment transport (solutes, suspended sediment and bed load) is also collected. In each catchment the depth to the water table is continuously measured with pressure sensors

(Keller DCX-22 AA) installed in several piezometers located at various distances from the main channel. All sensors are connected to data loggers that record average data every 5–20 min, depending on which variable is being measured. In the forested catchment throughfall and stemflow under forest cover (*P. sylvestris*, *F. sylvatica* and *Q. faginea*) was measured at three plots, each containing 25 pluviometers (Serrano-Muela et al., in press).

This study used rainfall and discharge data obtained over the 7 water years (October to September) from 1999 to 2005. Based on the same sample used by Lana-Renault et al. (2007), a set of 26 rainfall–runoff events that co-occurred in each catchment as a consequence of the same rainstorm was selected. Floods that were either too small, presented successive peak flows (making it impossible to apply the hydrograph separation method), or that were related to snow fall events were not considered. Flood events were identified as increases in discharge exceeding 1.5-times the baseflow discharge prior to the beginning of the rainfall event. Storm flow was distinguished from base flow using the classical graphic method of Hewlett and Hibbert (1967). As the slope proposed by these authors was too steep to apply in the present study, we used the modified slope value of 1.83 $\mathrm{l\,s^{-1}\,day^{-1}\,km^{-2}}$ suggested by Latron et al. (2008). For each rainfall–runoff event the following variables were derived from the hyetograph and hydrograph: rainfall depth (mm); maximum rainfall intensity in 5 min ($\mathrm{mm\,h^{-1}}$); storm flow depth; peak flow specific discharge ($\mathrm{l\,s^{-1}\,km^{-2}}$); base flow specific discharge at the start of the event ($\mathrm{l\,s^{-1}\,km^{-2}}$); response time (min), which is defined as the time lag between the centroid of the rainfall and the peak flow discharge; and an indicator of the duration of the recession limb (min), which corresponds to the time interval between peak flow and the time when discharge is equal to one-third of the peak flow discharge.

To analyze differences between the storm hydrographs of the two catchments under varying hydrological conditions, the relative difference q, calculated from Eq. (2) was used for each hydrograph parameter Q (i.e. storm flow depth, peak flow discharge, response time, recession time index).

$$q = \frac{Q_{\text{former agricultural}} - Q_{\text{forested}}}{(Q_{\text{former agricultural}} + Q_{\text{forested}})/2} \qquad (2)$$

Thus, positive values indicate higher Q in the past agricultural catchment, and negative values indicate higher Q in the forested catchment.

5. Results and discussion

Mean monthly runoff in the two catchments is compared in Fig. 3. The average rainfall shown in the figure, with two peaks in autumn and spring, is representative of the trend observed over a longer period (Lana-Renault, 2011). March was the most responsive month in both catchments (>55 mm), followed by December (>40 mm). Very little runoff (<4 mm) occurred in June, July and August, as a result of the low rainfall and high evapotranspiration demand, which is typical of Mediterranean summer conditions (Latron et al., 2009). In September and October runoff was moderate (<15 mm) despite the heavy rainfall (>120 mm). As reported in previous studies (Gallart et al., 2002; Lana-Renault et al., 2007; Latron et al., 2008), rain recorded at the beginning of the water year usually produced a limited hydrological response because it is largely used to recharge catchment soil moisture. Runoff from June to November was greater in the former agricultural catchment, but from December to May it was usually greater in the forested catchment, particularly in March.

5.1. Analysis at the event scale

Over the course of the 26 rainfall–runoff events, rainfall depth ranged from 11.4 to 83.0 mm (median 35.8 mm), which is within the range of frequent (<1 year return period) rainstorms in the study area. Storm-flow varied from 2 to 27 mm in the past agricultural catchment (a similar range than that reported by Lana-Renault et al., 2007) and from 0.6 to 35 mm in the forested catchment. These events represent approximately 70% of the annual storm flow in these catchments.

5.2. Comparisons between hydrograph characteristics

For the 26 rainfall–runoff events a paired samples *t*-test was performed to assess whether differences in the hydrograph parameters between the two catchments were significant. The test showed that peak flow specific discharge, the response time and the recession time index were statistically different at the level of $p < 0.01$, whereas storm flow depth was not. Fig. 4 shows the four hydrograph parameters for the two catchments. The average storm flow depth was slightly greater in the past agricultural catchment (9.9 mm) compared with the forested catchment (8.9 mm) (Fig. 4a), although this was not a general rule. Fig. 5a shows that for smaller events storm flow depth was usually greater in the past agricultural catchment, whereas for larger flood events (>10 mm), storm flow depth tended to be greater in the forested catchment. The absence of a fixed ratio between storm flow depth in forested and non-forested catchments has been observed elsewhere, and has often been related to specific meteorological factors including snow, the occurrence of extreme rainstorms (Troendle and King, 1985; Robinson et al., 2003), and to variations in catchment moisture conditions (Burch et al., 1987; Cosandey, 1993).

The peak flow specific discharge (Figs. 4b and 5b) was always greater (often one order of magnitude) in the past agricultural catchment than in the forested catchment, with average values of 566 and 119 $\mathrm{l\,s^{-1}\,km^{-2}}$, respectively. In the former the range of peak flow discharges was very high (55–1500 $\mathrm{l\,s^{-1}\,km^{-2}}$) compared with the forested catchment (15 and 470 $\mathrm{l\,s^{-1}\,km^{-2}}$). An increase in the peak flow discharge after deforestation has often been reported, but the effect can vary depending on rainfall characteristics (Combes et al., 1994; Robinson et al., 2003), seasonal variability of the snowmelt period (Hornbeck, 1973; Troendle and King, 1985), or soil moisture conditions (Burch et al., 1987).

The forested catchment usually responded 2- to 3-fold more slowly (356 min) than the former agricultural catchment (131 min) (Figs. 4c and 5c). The response time of the latter catchment varied from 15 to 330 min, whereas the response time of the forested catchment was generally >200 min. Recession limbs (Figs. 4d and 5d) in the forested catchment were much longer (1–2 orders of magnitude) than in the former agricultural catchment, with average recession time index values of 4325 min and 418 min (approximately 72 h and 7 h), respectively. Timing parameters have not been extensively studied, and the observed effects of land cover changes on response times or flood duration are mixed. However, Burch et al. (1987) and Dubicki (1994) do report a more rapid stream flow responses in deforested catchments relative to forested catchments.

5.3. Factors influencing the hydrological differences between the catchments

As seen in Figs. 4 and 5, significant differences can be observed between the hydrograph characteristics of the two catchments. To understand the magnitude of these differences we regressed the relative difference q (Eq. (2)) for each hydrograph parameter with rainfall depth, maximum rainfall intensity, and base flow specific

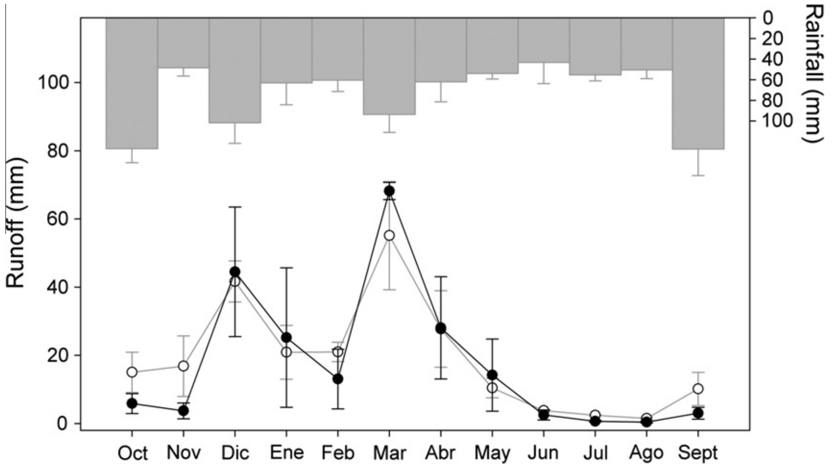

Fig. 3. Monthly mean values of rainfall and runoff for the study period in the past agricultural (gray line) and forested (black line) catchments. Error bars show natural variation over years.

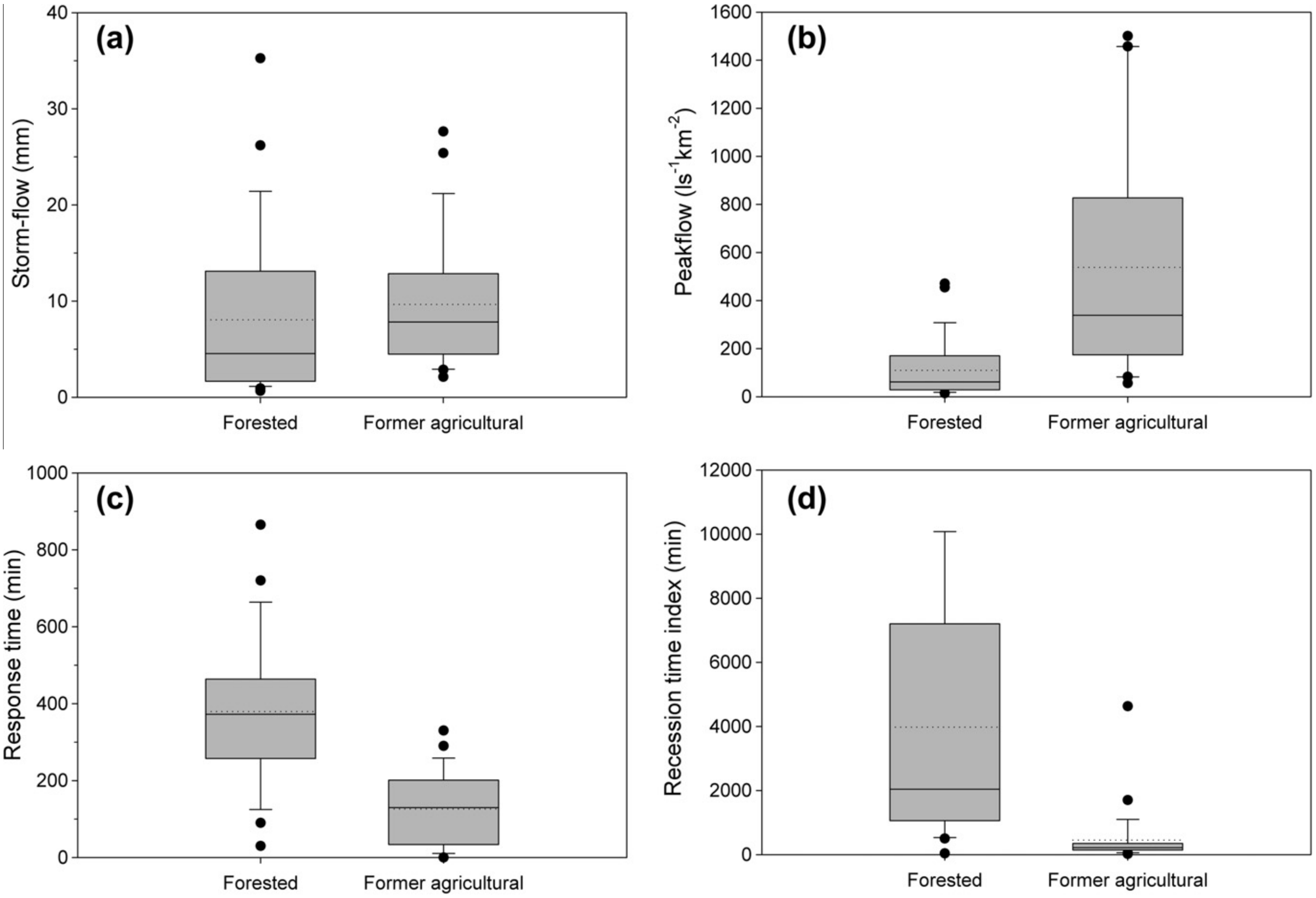

Fig. 4. Storm flow (a), peak flow (b), response time (c) and recession time index (d) for the forested and the past agricultural catchments (median value, 1st and 3rd quartiles, 1st and 9th deciles, outliers; average is the dotted line).

discharge at the start of the event, the latter being an indicator of the preceding wetness conditions of the catchment.

Differences in storm flow depth between the two catchments were not correlated with rainfall depth or rainfall intensity. A weak but significant negative correlation was found with the base flow discharge at the start of the event ($R = -0.55$, $p < 0.05$). Fig. 6 shows the relationship between the difference in storm flow depth and the base flow discharge, and suggests the presence of a base flow threshold (approximately 10 l s^{-1} km^{-2}), below which storm flows in the past agricultural catchment were typically greater, whereas above this threshold the storm flows tended to be greater in the forested catchment.

The differences in peak flow discharge were not statistically correlated with rainfall depth or base flow discharge. However, a slight positive relationship ($R = 0.29$, $p > 0.05$) was observed with the maximum rainfall intensity (Fig. 7), suggesting that peak flows

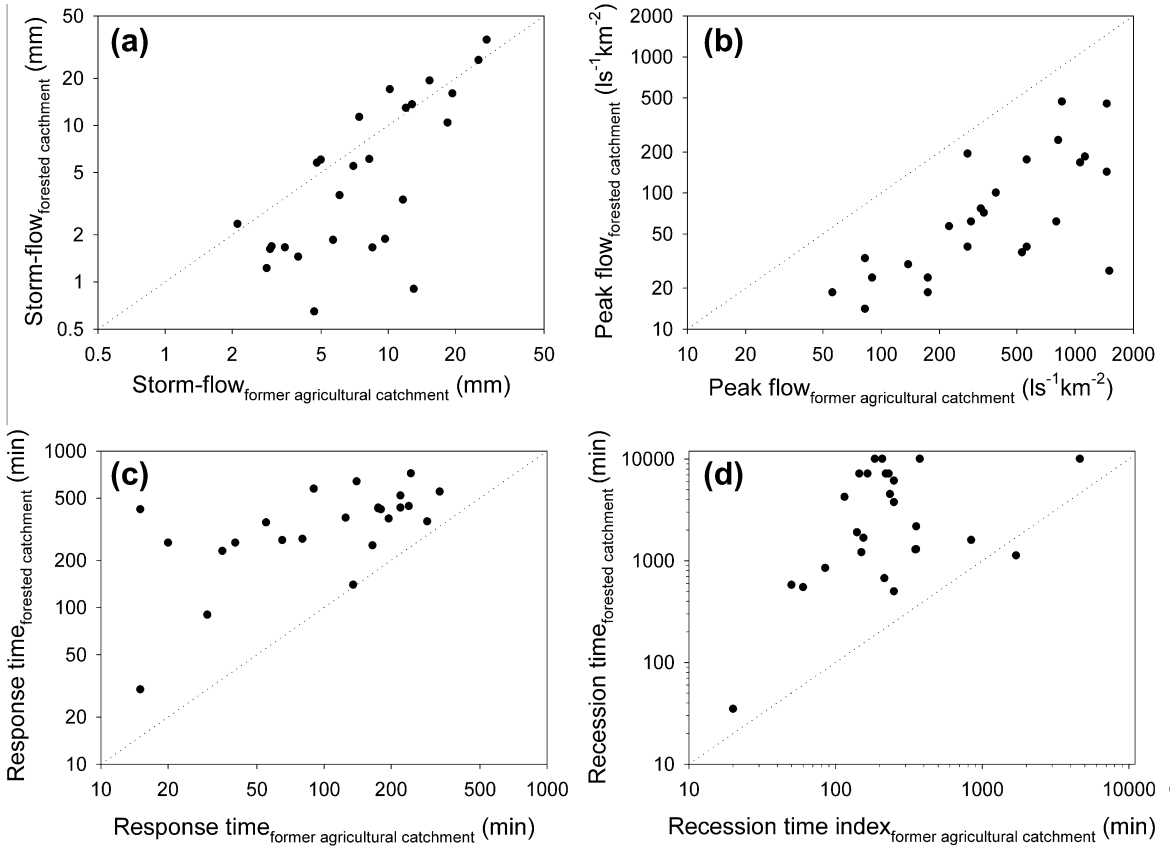

Fig. 5. Relationship between storm flow (a), peak flow (b), response time (c) and recession time index (c) in the forested and the past agricultural catchments.

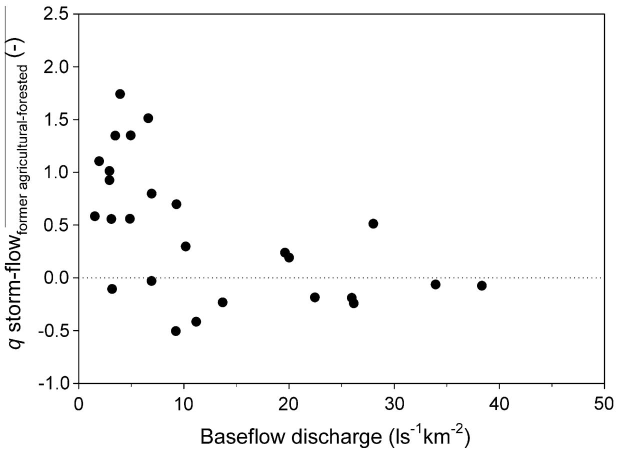

Fig. 6. Relationship between the relative difference (q) in the storm flow depth and the base flow discharge at the start of the event (mean value of the two catchments).

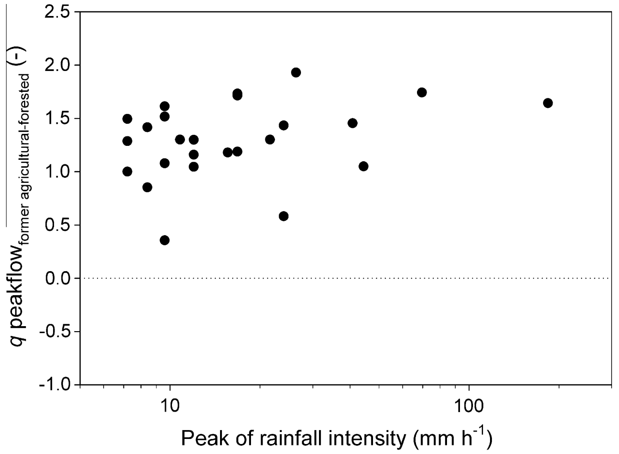

Fig. 7. Relationship between the relative difference (q) in the peak flow and the peak of rainfall intensity (mean value of the two catchments).

were sometimes higher in the past agricultural catchment with more intense rainfall. This can be explained by the contrasting response of the two catchments to high rainfall intensities. Previous studies in the past agricultural catchment (García-Ruiz et al., 2005; Lana-Renault et al., 2007) showed a significant correlation between peak flow discharge and rainfall intensity, suggesting the occurrence of surface runoff generation (e.g. infiltration excess overland flow in areas of low permeability). In contrast, no effect of rainfall depth or intensity on the hydrological response of the forested catchment was observed by Serrano-Muela et al. (2008), which is consistent with the reported results for densely vegetated catchments in temperate latitudes (Hewlett et al., 1984). These results differ however from those found in tropical regions where intense rainstorms have a significant influence on storm flow (Howard et al., 2010).

In our analysis no significant relationships were found between differences in the response time of the catchments and either rainfall characteristics or preceding wetness conditions. Differences in the duration of the recession limb showed a weak negative correlation with the base flow discharge at the start of the event ($R = -0.39$, $p < 0.05$). Again, a threshold base flow discharge of

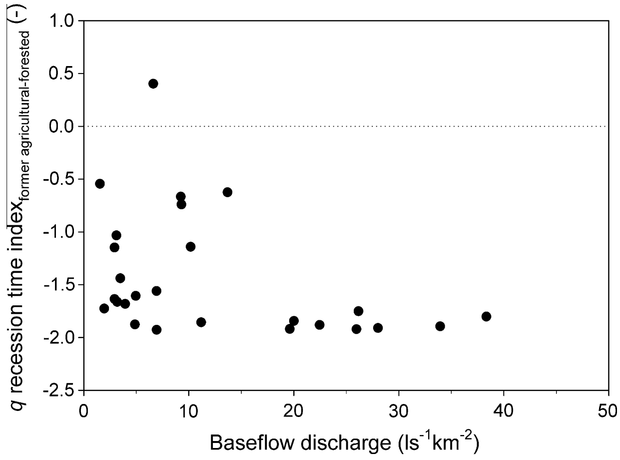

Fig. 8. Relationship between the relative difference (q) in the recession time index and the base flow at the start of the event (mean value of the two catchments).

approximately 10 l s^{-1} km^{-2} was observed (Fig. 8), above which the recession limb in the forested catchment was notably longer (by 3–6 days) than in the former agricultural catchment. Below this value the recession limb was still longer in the forested catchment, but the differences were usually smaller. The longer recession limb in the forested catchment suggests that a large contribution of a slow flow component (i.e. subsurface flow within the soil matrix) dominates runoff in this catchment, especially under higher moisture conditions, which is consistent with the generally accepted view that storm flow from forested land is dominated by subsurface processes (Bonell, 1993).

The differences in the hydrological responses of the two catchments as a function of catchment wetness conditions are illustrated in Fig. 9, which shows three pairs of hydrographs ranging from dry to wetter conditions. Under dry conditions (event 1) the storm flow depth was approximately 5-fold greater in the past agricultural catchment (9.7 mm) than in the forested catchment (1.9 mm). The difference in storm flow depth decreased as the catchments became wetter (event 2; 18.5 mm and 10.4 mm in the past agricultural and forested catchments, respectively), and under the wettest conditions (event 3) the storm flow depth was slightly greater in the forested catchment (25.4 and 26.2 mm, respectively). In these three events, peak flows were always higher in the past agricultural catchment although differences tended to decrease with increasingly wet conditions (peak flows were 12.3, 6.3 and 3.2-fold higher in the past agricultural catchment for events 1–3, respectively). The response time was always shorter in the past agricultural catchment, but a trend in relation to preceding moisture conditions could not be observed. The forested hydrograph in event 3 showed a quicker response compared to events 1 and 2, but response time was 90 min (1.5-fold more slowly than in the former agricultural catchment), which does not necessarily suggests overland flow (Dunne, 1978). The recession limb in the forested catchment was always longer than in the past agricultural catchment, and the recession time index increased substantially with increasingly wet conditions, from 14 h for event 1 to 1 day for event 2, and to more than 5 days for event 3. This trend was not observed in the past agricultural catchment, which had recession time indices of 1, 3.5 and 2.5 h for events 1–3, respectively. This series of hydrographs suggests that in the forested catchment, the greater storm flow depths observed under wetter conditions can be explained by the contribution of a larger slow flow component.

Fig. 10 shows a marked pattern in the seasonal evolution of the differences in storm flow depth for the set of the 26 floods over the water year from October to September. With one exception, storm flows depths from June to October were always greater in the former agricultural catchment. The greatest differences usually occurred during this period, and were sometimes associated with intense rainfall events (>25 mm h^{-1}). For instance, a rain storm that occurred on 23 September 2006 (rainfall, 44 mm; 5 min rainfall intensity, 26 mm h^{-1}) produced a flood event with a storm flow depth of 13 mm in the former agricultural catchment, but only 0.9 mm in the forested catchment. In some occasions, similar type of rainfall event occasionally produced a limited stream flow response in the former agricultural catchment, and failed to generate a response in the forested catchment. Previous studies in the former agricultural catchment (Lana-Renault et al., 2007) and in other similar areas (Latron and Gallart, 2008) have demonstrated that in summer and the beginning of autumn the catchment water reserves (soil water storage and groundwater) tend to dry off, and thus the stream flow response is small because most of the incoming rainfall is used to recharge soil moisture and groundwater. However, infiltration excess runoff can occur in response to intense rainstorms over degraded areas (bare and poorly vegetated areas)

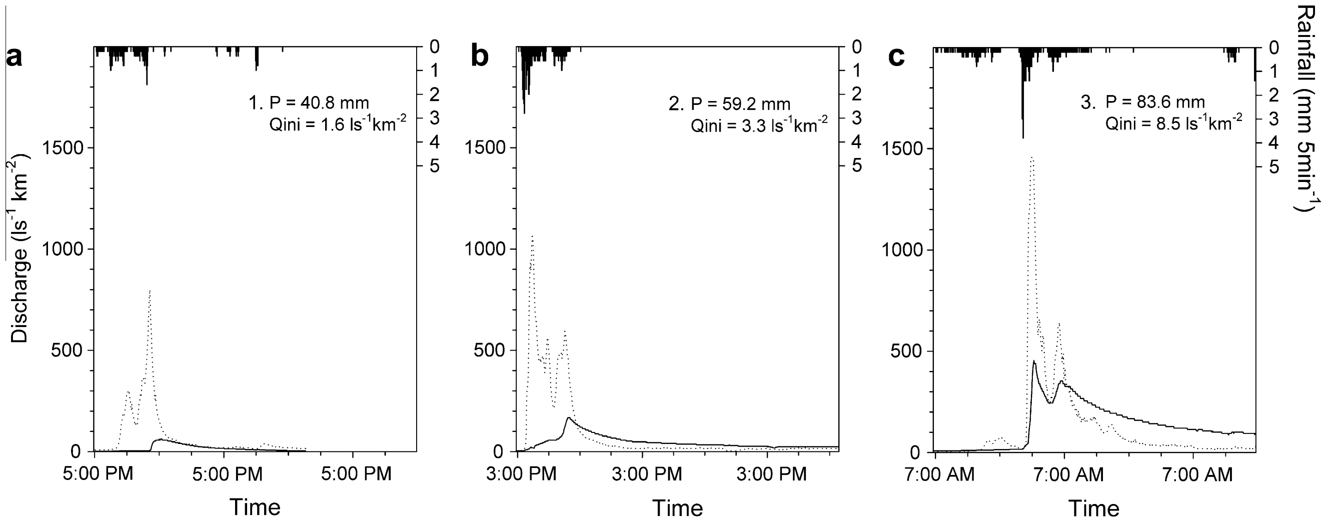

Fig. 9. Hydrographs of the past agricultural (dotted line) and forested (solid line) catchments for different preceding conditions. Qini: baseflow discharge at the start of the event.

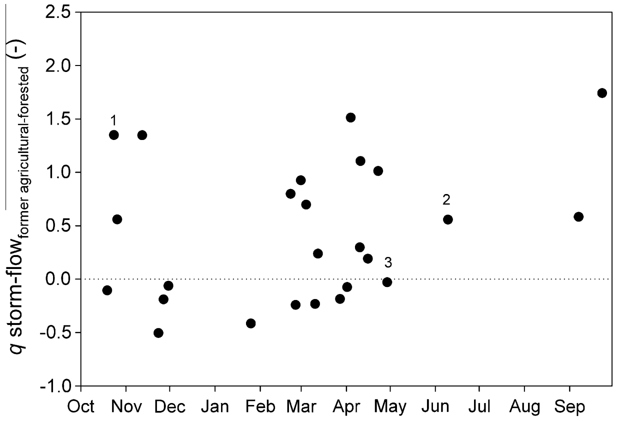

Fig. 10. Seasonal evolution of the relative difference (q) in storm flow between the two catchments. The numbers 1–3 refer to the hydrographs shown in Fig. 9.

most of which coincide with the main sediment sources (García-Ruiz et al., 2005; Lana-Renault et al., 2007; Lana-Renault and Regüés, 2009). In the forested catchment the effect of drying of the water reserves is accentuated by rainfall interception and the consumption of water by trees (Llorens et al., 1997; Haria and Price, 2000), which could explain an even more limited stream flow response. Furthermore, infiltration excess runoff can be considered negligible, as the bare or poorly vegetated areas comprise less than 1% of the catchment.

From November to March the storm flow depths were usually greater in the forested catchment. However, the magnitude of the differences was not as large as during dry conditions. As reported in similar areas (e.g., Latron and Gallart, 2008), Lana-Renault et al. (2007) showed that during this period catchment groundwater reserves in the past agricultural catchment were usually refilled, and both saturated excess runoff and subsurface flow were the dominant runoff processes. However, field mapping (Lana-Renault, 2011) demonstrated that the extent of saturated areas was restricted to the valley bottom, suggesting that the contribution of saturation excess runoff was limited after a certain moisture level was reached. In the forested catchment saturated areas were never observed. On the contrary, the slow response and longer recession limbs for most of the hydrographs, together with the strong relationship between water table fluctuations and stream flow response (García-Ruiz et al., 2008; Serrano-Muela et al., 2008), indicate a significant contribution of subsurface flow in the forested catchment, which probably increases under wetter conditions. Studies in other forested areas (Cosandey, 1993; Sidle et al., 1995; Stieglitz et al., 2003; Medici et al., 2008) suggest the existence of a moisture threshold above which the hydrological connectivity within the catchment (e.g. between ridge and valley) increases rapidly, such that all or a very large part of the system contributes to runoff. This is similar to what Grayson et al. (1997) and Gallart et al. (2002) referred to as switching behavior of the underground water transfer, and could explain the threshold observed in Fig. 6. The greater water storage capacity of the forested soils compared with those of the past agricultural catchment can explain the greater discharge as subsurface flow under these conditions. At some point, this contribution is large enough (i.e. larger than the contribution from the past agricultural catchment, with less subsurface flow and limited saturation excess runoff) to explain the greater storm flow depths in the forested catchment under very wet conditions.

During the wetting period (October) and the beginning of the drying period (March–April), the pattern was not so clear. This can be partly explained by yearly variation of these transition phases (Latron et al., 2009). Also, the storm flow depth was sometimes greater in the former agricultural catchment under wet conditions (i.e., with base flow >10 l s^{-1} km^{-2}, Fig. 6). In these cases the moisture conditions in the forested catchment probably did not reach the point above which the subsurface system was connected and contributed to stream flow. Surface saturation occurred in some parts of the former agricultural catchment (Lana-Renault et al., 2007), which in combination with a contribution from infiltration excess runoff (favored by intense rainfall conditions) may have generated a greater hydrological response than in the forested catchment.

5.4. Effects of vegetation on the hydrological response

The characteristics of the two catchments (Section 3) suggests that differences in topography were negligible compared with differences in soils and vegetation. This enabled assessment of the combined effect of vegetation and soils on the hydrological response of the catchments. As shown in Table 1, soils largely determine the water storage capacity of the catchments and downslope water transfer, whereas vegetation directly controls interception and evapotranspiration processes.

Differences between the storm flow responses of the two catchments were closely related to the status of the catchment groundwater reserves. In the forested catchment the average depth of the soil was twice that in the past agricultural catchment, indicating a greater water storage capacity but also a greater soil water deficit. The greater soil water deficit is exacerbated by the presence of trees, which reduce the amount of rainfall reaching the soil (between 22% and 28% of the rainfall, Serrano-Muela et al., 2008) and withdraw soil water for transpiration. A large proportion of the past agricultural catchment is occupied by poorly developed open shrub cover, suggesting that interception is probably minor. Given that trees only represent 20% of the catchment, the amount of rainfall intercepted and lost through evaporation is less than in the forested catchment. As a result, the rainfall that does not contribute to runoff or recharge of water reserves is probably greater in the forested catchment. This, together with the fact that the soil reservoir in the forested catchment is larger, implies a delay in the replenishment of water reserves in the forested catchment, which explains the lower hydrological response at the beginning of the water year (September–October). The peak flow discharge, response time and recession limb were significantly different between the two catchments, reflecting the contrasting dominant runoff generation processes in each catchment: subsurface flow in the forested catchment, favored by thicker soils with higher transmissivity (as suggested by soil saturated hydraulic conductivity values); and surface overland flow in the former agricultural catchment, favored by shallower and less permeable soils.

It thus appears that soil properties have a major influence on the hydrological behavior of the catchments, as they control catchment groundwater reserves and the dominant runoff generation processes. The role of vegetation is more complex: its main effect is that because of interception process, more rainfall may be necessary to generate runoff or to recharge the soil water reserves; on the other hand, transpiration by vegetation lowers the soil moisture content. In addition, vegetation also has an indirect effect because it modifies soil properties (Kelly et al., 1998). For instance, re-growth of forest in an area is associated with soil development in that area, while removal of vegetation would lead to soil loss. Finally, in the past agricultural catchment, previous human activities reduced soil depth and soil infiltration capacity, especially in the south facing slopes and in areas close to the main channel (Navas et al., 2005). The presence of such degraded areas favors a larger contribution of direct runoff in the past agricultural catchment, with higher peak flows, shorter response times and recessions, and also high erosion rates (Seeger et al., 2004; Lana-Renault and Regüés, 2009). Thin and poorly structured soils delay plant colonization in those areas, which could explain that the agricultural catchment is far from having the same hydrological behavior as the forested catchment, even after more than 50 years of abandonment.

6. Conclusions

In this study we compared the stream flow responses of two neighboring catchments in the central Spanish Pyrenees with similar lithology and topography but different history of land use and land cover: one is a past agricultural catchment and the other is a forested catchment. Monthly runoff was always greater in the past agricultural catchment at the beginning of the water year (September to November), whereas at the end of the wet season (March, April) it was usually greater in the forested catchment. For flood events of low-to-intermediate size the storm flow depth was greater in the past agricultural catchment than in the forested catchment, but smaller for large-sized events. In the past agricultural catchment peak flows were always greater (usually one order of magnitude) compared with the forested catchment, the response was 2- to 3-fold faster, and the recession limbs were shorter (usually 1–2 orders of magnitude). Moisture conditions and, to a less degree, rainfall intensity were the main factors causing the hydrological differences between the catchments at the event scale. Differences in storm flow were characterized by marked seasonality during the year: under dry conditions storm flows tended to be greater in the past agricultural catchment, whereas under wet conditions they tended to be greater in the forested catchment.

The non-linearity in the storm flow differences between the two catchments was dictated by their contrasting hydrological functioning during the year. In the past agricultural catchment a broader range of hydrological and rainfall conditions generated runoff through different runoff processes (i.e. excess infiltration, saturation excess runoff, subsurface flow). A greater contribution of surface overland flow in the past agricultural catchment (which contrasts with the dominant subsurface flow in the forested catchment) may explain the greater peak flows, and the shorter response times and recession limbs observed in its hydrographs. The forested catchment presented a dual (or switching) behavior controlled by soil moisture conditions, which regulated the release of large amounts of subsurface flow. One explanation for this switching behavior could be an increase in the hydrological connectivity within the slopes of the catchment as it becomes wetter. When this occurs the storm flow in the forested catchment is greater than in the past agricultural catchment. However, without more evidence this is a hypothesis that remains to be tested. In this context, efforts must be made to acquire the information needed (e.g. dynamics of the soil water content and the water table) to confirm the catchment hydrological functioning described herein, particularly for the forested catchment.

The hydrological differences between the two catchments were related to differences in both vegetation and soil properties (soil depth and permeability), but also to the presence of degraded areas, inherited from past human activities. It is noteworthy that in temperate areas, many modeling studies of the hydrological impacts of land use/land cover changes have focused on changes to vegetation (Beven, 2002), but have usually ignored changes in soil properties. Considering the soil-forest relationship and distinguishing the relative effects of these two factors on the stream flow response (e.g. using model simulations) are without doubt a key issue for future research (Andréassian, 2004), particularly for studying the long-term hydrological effects of the forest establishment in previously cultivated areas in Mediterranean mountains.

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