# FROM PLOT TO REGIONAL SCALES: INTERACTIONS OF SLOPE AND CATCHMENT HYDROLOGICAL AND GEOMORPHIC PROCESSES IN THE SPANISH PYRENEES

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## Abstract

The hydrological and geomorphic effects of land use/land cover changes, particularly those associated with vegetation regrowth after farmland abandonment were investigated in the Central Spanish Pyrenees. The main focus was to assess the interactions among slope, catchment, basin, and fluvial channel processes over a range of spatial scales. In recent centuries most Mediterranean mountain areas have been subjected to significant human pressure through deforestation, cultivation of steep slopes, fires, and overgrazing. Depopulation commencing at the beginning of the 20th century, and particularly since the 1960s, has resulted in farmland abandonment and a reduction in livestock numbers, and this has led to an expansion of shrubs and forests. Studies in the Central Spanish Pyrenees, based on experimental plots and catchments, in large basins and fluvial channels, have confirmed that these land use changes have had hydrological and geomorphic consequences regardless of the spatial scale considered, and that processes occurring at any particular scale can be explained by such processes acting on other scales. Studies using experimental plots have demonstrated that during the period of greatest human pressure (mainly the 18th and 19th centuries), cultivation of steep slopes caused high runoff rates and extreme soil loss. Large parts of the small catchments behaved as runoff and sediment source areas, whereas the fluvial channels of large basins showed signs of high torrentiality (braided morphology, bare sedimentary bars, instability, prevalence of bedload transport). Depopulation has concentrated most human pressure on the valley bottoms and specific locations such as resorts, whereas the remainder of the area has been affected by an almost generalized abandonment. Subsequent plant recolonization has resulted in a reduction of overland flow and declining soil erosion. At a catchment scale this has caused a reduction in sediment sources, and channel incision in the secondary streams. At the regional scale, the most important consequences include a reduction in the frequency of floods, reduced sediment yields, increasing stabilization of the fluvial channels (colonization of sedimentary bars by riparian vegetation and a reduction in the braiding index), and stabilization of the alluvial fans. These results demonstrate the complexity and multiscalar nature of the interactions between land use and runoff generation, soil erosion, sediment transport, and fluvial channel dynamics, and highlight the need to adopt a multiscale approach in other mountain areas of the world.

**Keywords**: geomorphic scales, land cover changes, hillslope–channel interactions, experimental catchments, experimental plots, Central Spanish Pyrenees.

## Introduction

Mediterranean mountain areas are characterized by complex landscapes resulting from natural gradients in climate, relief, plant cover, and soil properties variability, and an intricate mosaic of human land uses (Thornes, 1999). There is abundant evidence indicating that intensive human activity since the Neolithic, particularly from the Bronze Age, has contributed substantially to plant cover and landscape changes. These activities have resulted in deforestation, soil erosion, sediment accumulation in alluvial plains and fans, and the development of deltas (Goudie, 1986; García-Ruiz and Valero-Garcés, 1998; García-Ruiz and López-Bermúdez, 2009; García-Ruiz, 2010), all of which have been exacerbated by the intense rainstorms characteristic of the Mediterranean climate.

Very significant land use changes occurred in most Mediterranean mountain areas during the last century (Taillefumier and Piégay, 2003). The changes in the Spanish Pyrenees have been intensively studied by Lasanta (1988, 1989) and García-

Ruiz and Lasanta (1990, 1993). Following centuries of intense human pressure on the environment, which included deforestation, cultivation of steep slopes and the frequent use of fire to manage grasslands, the population began to decrease from the middle of the 19th century, and, since the 1960s, there has been a marked decline in the impact on the landscape. This resulted in (i) a reduction in the number of livestock, (ii) a generalized abandonment of farmland on the hillslopes, (iii) reforestation of thousands of hectares, and, (iv) substitution of cereal crops by cutting meadows in the valley bottoms. Abandoned fields represent about 22% of the total study area (Upper Aragón and Gállego valleys), which is now occupied by forests (65%), shrubs (28%), and meadows (7%) (Lasanta, 2007). These changes have affected plant recovery and soil characteristics, and have consequently influenced interception, infiltration, runoff, soil erosion, sediment transport, and the dynamics and morphology of fluvial systems and alluvial fans (Ruiz-Flaño *et al.*, 1992; Ruiz-Flaño, 1993). The changes have been consistent with the concept of "hillslope-channel coupling" (Brunsden and Thornes, 1979; Caine and Swanson, 1989; Harvey, 1992, 2002, 2007; Michaelides and Wainwright, 2002; Kirkby *et al.*, 2002). Coupling and connectivity among the various components of a catchment (*i.e.,* hillslopes and fluvial channels) are critical factors for understanding the hydromorphological functioning of the landscape at different spatial and temporal scales (Liébault and Piégay, 2001, 2002; Piégay *et al.*, 2004; De Vente and Poesen, 2005; De Vente *et al.*, 2007; Chiverrell *et al.*, 2009).

The Department of Geo-environmental Processes and Global Change (http://www.ipe.csic.es/Geoenvironmental.html) at the Pyrenean Institute of Ecology (Zaragoza, Spain) has studied the geomorphic and hydrological evolution of the Central Spanish Pyrenees since 1987. Using a combination of field, experimental, and laboratory approaches, the Department has accumulated a wealth of information on sediment yield and transport, the temporal variability of sediment sources, historical evidence of soil erosion and extreme geomorphic events, and the relationships among land use/land cover changes, runoff generation, and soil erosion. This information has facilitated interpretation of recent changes in the hydrological and geomorphic functioning of the landscape at various temporal and spatial scales, and assessment of the interactions among slope, catchment, channel processes and human influence. However, investigations on the linkages between processes acting at various temporal and spatial scales are needed to assess the relative importance of climate and land use practices on soil erosion and runoff yield, and to foresee global change scenarios for land planning purposes (Beguería *et al*., 2008).

In this paper we review and discuss the main findings concerning changes in hydrological, soil erosion, and sediment transport processes in relation to land use and land cover variations at various spatial scales in the Central Spanish Pyrenees. Different studies were made on experimental plots (Ruiz-Flaño *et al*., 1992; García-Ruiz *et al*., 1995; Lasanta *et al*., 2006), hillslopes (Lorente *et al*., 2002, 2003), experimental catchments (Alvera and García-Ruiz, 2000; Lana-Renault and Regüés, 2007; Lana-Renault *et al*., 2007a, 2007b; Nadal-Romero *et al*., 2008a, 2008b; Serrano-Muela *et al*., 2008), regional scales (Beguería *et al*., 2003; López-Moreno *et al*., 2006, 2008) and stream channel dynamics (Beguería *et al*., 2006), each scale providing information on different geomorphic and hydrological processes. Evidence from plot studies through to those at regional scales enables interpretation of interactions at different scales, with the aim of developing a holistic perspective of the effects of land use changes on water resources and soil erosion.

## The study area

The experimental areas are located in the upper Aragón and Gállego valleys, in the Central Spanish Pyrenees (Fig. 1). They correspond to an intensively folded alpine mountain range with a series of overthrusting mantles. The highest mountain (the Collarada peak) is almost 3,000 m a.s.l., and altitudes exceeding 2,500 m occur throughout the range. The rivers run from north to south across the following morpho-structural units: (i) the Paleozoic rocks of the Axial Pyrenees (mostly limestone and shale, and a large granite massif in the headwater of the Gállego Valley); (ii) the Inner Sierras (limestone and sandstone), where the highest mountains occur; (iii) the Flysch Sector (alternating thin beds of sandstone and marls); and, (iv) the Inner Depression (marl, sandstone, claystone), extensively covered by Quaternary terraces and pediments, and the Outer Sierras (limestone, sandstone and calystone). The most important geomorphic processes are snow avalanches in the highest areas; rilling, gullying, and shallow landsliding in the subalpine belt; shallow landslides evolving into debris flows, sheet wash erosion and gullying in active headwaters of ravines in the Flysch Sector; and the presence of active badland areas developed on marls in the Inner Depression (García-Ruiz *et al*., 1990).

Precipitation shows a general increase toward the north along the altitudinal gradient, and toward the west because of the Atlantic influence. Average annual precipitation exceeds 1,500 mm in the northernmost sector of the Central Spanish Pyrenees, and is around 800 mm in the Inner Depression. The mean annual temperature decreases from south to north (11°C in Jaca; 8°C in Canfranc). The entire area is occasionally subject to very intense rainstorms that can cause flash floods and result in serious damage (White *et al*., 1997).

Plant cover has been strongly influenced by human activity. The upper forest belt was burnt in the Middle and Modern Ages and transformed into subalpine grasslands (Montserrat, 1992). Cultivated areas were traditionally located below 1,600 m in the valley bottoms, on perched flats, and on steep, south-facing hillslopes, which were farmed even under shifting agriculture systems (Lasanta *et al*., 2006). The stoniness and low field capacity of the calcaric regosol and rendsic leptosol soils indicate that these slopes have been affected by water erosion. The forest has remained relatively well-preserved on the north-facing slopes, and on slopes with any aspect between 1,600 and 1,800 m where deep and well-developed haplic kastanozem and haplic phaeozem soils predominate.

During the 20th century most of the cultivated fields in the study area were abandoned, with the exception of the valley bottoms and the Inner Depression. This explains the recent expansion of forests and shrubs (Lasanta, 1988).

## Data and methods

Studies of hillslope erosion and runoff generation were carried out at the Aísa Valley Experimental Station, which, in 1991, was equipped with a weather station and nine erosion plots under various traditional and modern land uses (García-Ruiz *et al*., 1995) including (i) cereal (barley) with added chemical fertilizers; (ii) fallow land (alternating every two years with a cereal plot); (iii) shifting agriculture based on barley fertilized with ashes after clearing off the original shrubs; (iv) cereal plots abandoned for 10 years (now covered by dense herbaceous communities); (v) shifting agriculture abandoned for 9 years (with herbs now covering 70% of the soil surface); (vi) burnt plot 1 (previously dense shrub cover that re-established within 2 years of a fire occurred in 1991); (vii) burnt plot 2 (previously dense shrub cover affected by fires in 1993 and 2001); (viii) grazing meadow, representing the evolved stage of an abandoned field that is frequently grazed; and, (ix) dense shrub cover (mainly *Genista scorpius* and *Rosa gr.*

*canina*), representing the evolution of most of the hillslopes 30 years after farmland abandonment. The plots were 30 $m^2$ in size and located in an old south-facing slope with a gradient of 25%. Runoff was measured using tipping buckets connected to data loggers, and sediment transport was estimated from overland flow collected in plastic containers after each rainstorm.

Catchment scale information on discharge and sediment transport was collected from four different environments. (i) The Izas catchment (0.33 $km^2$; 2,060-2,280 m a.s.l.) is located in the upper Gállego Valley. The lithology consists mainly of schist, and plant cover is composed of subalpine grasslands. Snow is present in the catchment for at least 6 months each year. (ii) The Arnás catchment (2.84 $km^2$; 900-1,340 m a.s.l.) includes a complex mosaic of various shrub and forest patches following recent farmland abandonment. The bedrock is Eocene flysch. (iii) The San Salvador catchment (0.92 $km^2$; 880-1,325 m a.s.l.) is covered by dense forest (*Pinus sylvestris, Fagus sylvatica* and *Quercus gr. faginea*), and is representative of undisturbed environments in Mediterranean middle-altitude mountains. The bedrock is Eocene flysch. (iv) The Araguás catchment (0.45 $km^2$; 780-1,105 m a.s.l.) is characterized in the lower part by a dense network of badlands developed on marls, typical of highly degraded environments. The bedrock in the upper part of the catchment is Eocene flysch (artificially reforested in the 1960s), and Eocene marls in the lower part.

The Izas, Arnás, San Salvador, and Araguás catchments have been monitored since 1986, 1996, 1998, and 2004, respectively. Each catchment is equipped with a complete weather station, several tipping bucket rain gauges, and a gauging station at which discharge and suspended sediment concentrations are recorded continuously. Solutes were recorded during floods, when the water reached a threshold for the operation of the water sampler (ISCO 3700). In the Arnás, San Salvador, and Izas catchments, bedload transport was estimated using sediment traps. The bedload in the Arnás catchment was also calculated by a volumetric approach using a large profilometer to evaluate the coarse sediment at the gauging station, just upstream of the sediment trap (Lana-Renault and Regüés, 2007).

Remote sensing and geographical information systems were used to assess sediment sources at larger scales (basins of more than 1,000 $km^2$). Information was also available on reservoir silting rates and the sedimentological evolution of several reservoirs. The effects of changes in land cover and climate on water resources throughout the Central Spanish Pyrenees were also analyzed using historical climate and river discharge data series (Beguería *et al*., 2003).

## Results

### *The hillslope scale*

A variety of geomorphic and hydrological processes were studied in environments ranging from sub-Mediterranean to high mountain. Results from the Aísa Valley Experimental Station enabled medium-term (1992-2008) comparisons of the effects of land use changes on runoff and soil erosion. Although the results from the experimental plots have to be treated with caution, given the size and other characteristics of the plots, they are useful for comparative purposes and to highlight the main features of the areas affected by human activities. Data from the reference period (1992-2009) indicate an average annual precipitation of 1182 mm, similar to the value recorded at the Aísa weather station for a longer period (1135 mm for 1968-2002).

Figures 2 and 3 show the runoff coefficients and soil erosion rates (in Mg $km^{-2}$ $year^{-1}$, equivalent to tons $km^{-2}$ $year^{-1}$) for each plot. In the case of runoff coefficients the lowest values corresponded to dense shrub cover (4.7%) and burnt plot 1 (6.1%), followed by the meadow plot (7.2%), thus indicating the role of a dense shrub cover in reducing overland flow. The highest values were related to traditional agriculture involving soil removal by ploughing and strong variations in plant cover throughout the year (cereal plot, 12.9%; fallow land, 13.1%; and shifting agriculture, 18.7%). The plots affected by major changes in plant cover throughout the study period are shown in the central part of the figure: this is the case for the two plots cultivated in the past and later abandoned. These plots followed a process of plant colonization from bare soil to dense herbaceous cover and incipient shrub colonization, although the runoff coefficients remained similar to those associated with traditional agricultural uses (abandoned cereal plot, 9.8%; abandoned shifting agriculture plot, 11.7%). Burnt plot 2 underwent two plant recolonization processes after having been burnt in 1993 and again in 2001. This resulted in fluctuating but decreasing runoff coefficients (average 13.7%) as the plant cover became increasingly more dense and complex. Ruiz-Flaño *et al*. (1992) concluded that the repeated human-induced fires in the oldest abandoned fields were the main reason for their degradation.

Figure 3 shows the average soil loss rate in each plot. In general, soil loss distribution pattern was similar to that of the runoff coefficient. Land uses with a permanent dense plant cover showed moderate erosion rates (10, 11, and 15 Mg km$^{-2}$ year$^{-1}$ for plots under dense shrub cover, in the burnt plot 1, and for cutting meadow, respectively), whereas relatively high values were recorded for plots associated with traditional agricultural uses (70, 90 and 150 Mg km$^{-2}$ year$^{-1}$ for the cereal, fallow land and shifting agriculture plots, respectively). Although the figures obtained in the experimental plots do not represent natural values of soil loss (Boix-Fayos *et al.*, 2006) the relative differences among them are a valid indicator of the effects of different land uses. Thus, shifting agriculture yielded 15 times more sediment than did dense shrub cover, and 10 times more than cutting meadows. It is also notable that runoff coefficients were about 3 times higher in plots associated with agricultural uses than in those with dense plant cover, but for erosion rates the differences were 6-15 times higher. The abandoned plots yielded intermediate values that were closer to those of plots with a permanent and dense plant cover. This suggests that progressive plant colonization after farmland abandonment produces a rapid decrease in soil loss, whereas runoff decreases more slowly.

The results obtained from the Aísa Valley Experimental Station illustrate the evolution of hillslopes in areas most affected by human activity. For instance, it is evident that cultivation of steep slopes (a common practice in periods of major population pressure, particularly during the 18th and 19th centuries) caused land degradation mainly on south-facing slopes. Consequently, such slopes are now covered by thin, stony soils that support a much slower rate of plant colonization (Pueyo and Beguería, 2007). Recent $^{137}$Cs measurements (Navas *et al.*, 2005) have demonstrated soil redistribution processes in abandoned lands of the Central Pyrenees; $^{137}$Cs values were lower in the profiles of sites sampled on south-facing slopes that were steepest, had the lowest shrub density, and high erosion rates. In contrast, almost no erosion was recorded on north-facing slopes. The degree of stoniness was higher on the south-facing slopes (> 400 g kg$^{-1}$), suggesting that a substantial amount of the fine fraction had been eroded from the upper soil layers.

The plot scale results from the Aísa Valley Experimental Station suggest that farmland abandonment on steep slopes in the middle mountain areas of the Central Pyrenees and subsequent replacement of cereal crops by dense shrub communities have led to a reduction in sediment yield and runoff generation (García-Ruiz *et al.*, 1995). Nevertheless, some areas on the south-facing slopes were affected by sheet wash erosion and unconfined debris flows after farmland abandonment (Lorente *et al*., 2002; Beguería, 2006) due to the low density of the shrub cover. Most of the unconfined debris flows, which averaged less than 200 $m^3$ in volume, had a relatively short runout distance and did not connect with the fluvial network (Lorente *et al*., 2003). The SHETRAN model for simulating the sediment yield from unconfined debris flows confirmed that these flows contributed a relatively minor proportion of the total sediment yield (about 13%), at least in dry years (Bathurst *et al*., 2007).

The connectivity between hillslopes and channels seems to be pronounced in the alpine and subalpine belts because of the steep gradients involved. Snow avalanches and debris falls result in rapid sediment transfer, particularly in the Inner Ranges and the craggy areas of the Paleozoic Axial sector (García-Ruiz *et al*., 1990). In the Flysch Sector, deforestation of the upper forest level during the Middle and Modern Ages explains the triggering of frequent shallow landslides with short tongues that did not evolve into debris flows. Even in dry conditions shallow landsliding occurred immediately after deforestation on slopes over 30°, whereas slopes of less than 15° were stable even when water-saturated (García-Ruiz *et al*., in press). Höllermann (1985) concluded that deforestation of a large part of the subalpine belt has led to a decline of the lower solifluction limit to about 400 m, increasing both runoff generation (2-fold higher) and sediment yield (at least 10-fold higher) (Puigdefábregas and Alvera, 1986) because of an increase in the drainage density (development of dense networks of parallel rills) and the presence of eroded headwaters in ravines. An incipient recolonization by trees has been observed in the subalpine belt as livestock pressure has decreased, thus reducing the runoff coefficient to current levels (Tappeiner and Cernusca, 1993). The development of ski resorts has increased the concentration of both particulate and solute sediment, especially in summer when the soil is free of snow (Alvera *et al*., 1991).

### *The catchment scale*

At the small catchment scale the hydrological and geomorphological responses have also been dependent on the plant cover and land use. Figure 4 shows hydrographs of the same rainfall event that affected the Arnás, San Salvador, and Araguás catchments during the dry season. Whereas no reaction was observed in the forested catchment (San Salvador), a small flood occurred in the Arnás catchment (characterized by abandoned fields), and a large flood occurred in the badlands catchment (Araguás).

Over a longer time scale, the hydrological response also shows major differences among the three catchments. García-Ruiz *et al*. (2008) noted that discharge shows contrasting seasonal variability. (i) In the San Salvador catchment high discharges occurred only in spring, whereas, for the remainder of the year, almost no water circulated in the channel, even during some intense summer rainstorms. (ii) In the Arnás catchment several floods occurred in winter and spring, with a markedly higher number of floods in the latter season, but almost no reaction was observed in summer. However, intense rainstorms at the beginning of autumn produced high streamflow. (iii) The Araguás catchment reacted to every rainfall event, including summer rainstorms (Nadal-Romero *et al*., 2008a). During the 2005-06 hydrological year 4 floods were recorded in the San Salvador catchment, and 12 and 44 were noted in the Arnás and Araguás catchments, respectively, suggesting the importance of plant cover density and the presence of badlands in the behavior of these catchments. The most important factors explaining the hydrological response of the Araguás catchment were the rainfall depth and the maximum rainfall intensity. In the Arnás catchment the hydrological response was related to rainfall depth and the antecedent moisture condition, in particular to water-table dynamics, whereas the rainfall intensity mostly influenced the peak flow (Lana-Renault *et al*., 2007a). In the San Salvador catchment the main factors were the preceding rainfall and the base flow (García-Ruiz *et al*., 2008). Rainfall depth and intensity did not influence discharge in the San Salvador catchment, except where the water table was close to the surface (Serrano-Muela *et al*., 2008).

The frequency of floods in each catchment and the main factors controlling the hydrological response provide indirect information on the contributing areas and sediment sources. It is evident that in the Araguás catchment the badland area (25% of the total surface) contributed water and sediment. The overall shape of the hydrographs was always similar to that of the rainfall distribution and the suspended sediment concentration was always very high, exceeding 300 g $L^{-1}$ during several floods (Nadal-Romero *et al*., 2008b). Mapping the infiltration and saturation excess runoff areas in the Arnás catchment (Lana-Renault, in press) has shown that the former occupies small degraded areas close to the main channel. These correspond to intensively grazed and trampled areas that remain stable throughout the year and together with the taluses connected to the channels are the main sediment sources in the catchment. The saturation excess runoff areas showed a high level of spatial dynamics throughout the year, ranging from zero to about 10% of the catchment under wet conditions. During rainstorms in the dry period only the infiltration excess runoff areas contributed, which resulted in small floods of short duration and high suspended sediment concentration (Lana-Renault *et al*., 2007b), with the peak of suspended sediment occuring slightly behind the peak flow (an anticlockwise hysteretic loop) (Seeger *et al*., 2004; Lana-Renault and Regüés, 2009). During the wet period, when the "water reserves" of the catchment were filled, the runoff contributing areas enlarged but the sediment sources remained stable. Consequently, the floods were very intense but the suspended sediment was diluted. Only a small proportion of the sediment came from the hillslopes, because of the shrub density and the poor connectivity between debris flows and the fluvial network (Bathurst *et al*., 2007).

The Izas catchment is controlled by snow accumulation and melting during much of the year. Figure 5 shows that there was a period of increasing snow accumulation from the end of October to April. Increases in snow accumulation were directly related to major rainfall events. Periodic visits to the catchment enabled changes in the surface of the catchment covered by snow to be estimated: 99% (14 May), 90% (25 May), 60% (3 June), 50% (10 June), 40% (17 June), 10% (23 June), and 1% (8 July). The evolution of discharge showed (i) large fluctuations in autumn, corresponding to rainfall events accompanied by short snowmelt periods; (ii) a long period in winter characterized by low flows, with almost constant discharge in February and March; and, (iii) a very significant period of high flows between the end of April and the end of June, coinciding with snow depletion in the catchment (Alvera, 2000; Alvera and García-Ruiz, 2000). Figure 5 also shows that suspended sediment transport occurred only during the late snowmelt period, when a large part of the catchment was free of snow, and in autumn, coinciding with heavy rainfall. Díez *et al*. (1988) also highlighted the occurrence of important sediment transport events caused by intense summer rainstorms. Following their conclusions, the main sediment source was the channel itself and a dense gully network in the headwater. Periglacial terracettes did not contribute sediment to the channel, even if they were poorly protected by plant cover, nor did shallow landslides that were not connected to the fluvial network.

The specific sediment yield also showed very large differences among catchments, with a clear decrease in sediment output with increasing density of plant cover. Thus, the average rate of sediment output was about 120 Mg km$^{-2}$ year$^{-1}$ in the San Salvador catchment, 160 Mg km$^{-2}$ year$^{-1}$ in the Arnás catchment, and 15,300 Mg km$^{-2}$ year$^{-1}$ in the Araguás catchment (57,500 Mg km$^{-2}$ year$^{-1}$ if only the badland area was considered) (García-Ruiz *et al.*, 2008). These values are about one order of magnitude greater than those recorded in the experimental plots, confirming the great importance at the catchment scale of both erosion caused by concentrated runoff in rills and gullies and stream erosion, processes that are not present at the plot scale. In the San Salvador catchment most of the material was exported in the form of solutes (74%), with only 25% exported as suspended sediment. No true bedload was recorded, except for small fragments (< 5 mm) of calcite deposited in the channel bed (1% of the total), which are commonly mobilized during spring floods (Serrano-Muela *et al.*, 2008). The maximum suspended sediment concentration recorded was about 1.9 g L$^{-1}$, and the average solute concentration was 325 mg L$^{-1}$. In the Arnás catchment the recorded sediment load indicated the prevalence of solutes (61%), followed by suspended sediment (34%) and bedload (5%). The percentage of bedload transport was sufficiently high to modify the channel morphology through the development of small gravel bars. The maximum suspended sediment concentration was about 15 g L$^{-1}$ and the average solute concentration was 250 mg L$^{-1}$. Suspended sediment dominated the sediment load in the Araguás catchment (about 96% of the total), with only small proportions of solutes and bedload material (Nadal-Romero *et al.*, 2008b).

The sediment output for the Izas catchment was estimated to be about 200−320 Mg km$^{-2}$ year$^{-1}$ (Alvera and García-Ruiz, 2000). The transport of each type of sediment was variable among years, with solutes contributing 60−85% of the total, suspended sediment 5−20%, and bedload 1−30%. The extreme variability of bedload transport depended on the occurrence of heavy rainstorms, particularly in autumn, and on sediment availability. For instance, an extreme event in October 1987 (return period: 25 years) transported 17 Mg of bedload, which was similar to the total bedload transported during the following 9 years. A second rainstorm that occurred 1 week later carried only 0.48 Mg despite generating a similar peak discharge (Martínez-Castroviejo *et al.*, 1991). The effect of bedload exhaustion was apparent for several years, as Figure 6 illustrates. No evidence of bedload exhaustion was detected in the Arnás catchment, where the taluses connected to the channels can supply almost unlimited gravel and boulders.

*The regional scale*

Information at the regional scale consists of historical data on climate variables and river discharge, reservoir siltation, fluvial channel morphology, and the identification of sediment sources and connectivity in large basins.

The temporal evolution of river discharge was studied for the main basins of the Central Spanish Pyrenees between the Aragón Subordán and Noguera Ribagorzana rivers. All gauging stations involved in the analyses are located in areas largely unaffected by human activity (*i.e.,* upstream of major reservoirs and water abstraction points). A hydrology and climate database was developed using the information from 18 weather stations and 28 gauging stations. The longest series commenced in 1920, but most records began in 1945. Three regional indices of precipitation, temperature, and discharge were used to summarize the variations in these parameters for the whole region (Beguería *et al*., 2003). The precipitation index was lower than the discharge index between 1945 and 1970, and higher after 1970. This suggests that there has been a progressive decrease in runoff for a given level of precipitation. Runoff was predicted by stepwise multiple regression, with precipitation and temperature as the independent variables. Figure 7 shows that in the first half of the study period the observed discharge was greater than that predicted, but was consistently lower than predicted in the second half, indicating the interplay of other nonclimatic factors inducing changes in discharge. The negative trend in discharge in the Pyrenean rivers coincided with major changes in land management, including abandonment of all farmland below 1,600 m a.s.l. on south-facing slopes, followed by a progressive increase in coverage by dense shrubs and forests. As demonstrated in the experimental plots and catchments, this change represented a significant reduction in discharge.

López-Moreno *et al*. (2006) analyzed the trends in high flows during the period 1959–1995. These authors reported a clear decrease in the contribution of high flows to annual runoff, whereas the importance of low flows increased, particularly during winter and spring. A decrease in the frequency and magnitude of flood events was also found. A similar trend was not noted for precipitation. This may also be related to the extensive regrowth of vegetation during the 20th century, particularly in the second half thereof.

Reservoirs reflect streamflow evolution and, particularly, sediment transport by rivers, as they behave as large sediment traps. López-Moreno *et al*. (2004) reported changes in the management of the Yesa reservoir, one of the largest in the Pyrenees. In the last decades of the 20th century, filling the reservoir was relatively difficult because of a reduction in the average streamflow of the Aragón River. Sedimentation in the Barasona and Yesa reservoirs clearly declined after 1970 (Valero *et al*., 1998). The declining streamflow observed throughout the Pyrenees and the reduction in the area of sediment sources could explain the lowering in the quantity of sediment reaching the reservoirs.

The shrinkage of sediment source areas was clearly evident using GIS and statistical analyses at the small catchment scale, particularly in the Arnás experimental catchment, but also at the regional scale. Beguería (2005) identified areas with evidence of active erosion in the upper Aragón River basin, and concluded that the most important sediment sources were located in the marl outcrops with very active badlands. Areas of active erosion were distributed haphazardly elsewhere in the study area, although in many cases they were disconnected from the fluvial network because of the expansion of plant cover. In another investigation performed close to the study area (the Ésera and Isábena river basins), Alatorre and Beguería (2009) tested a new method for identifying areas of severe erosion and areas susceptible to be affected by erosion, using remote sensing classification techniques across a badland landscape on Eocene marls. Most of the erosion risk areas coincided with low vegetation cover surrounding the badlands areas. The slope aspect was a determining factor in the dynamics, intensity, and effectiveness of weathering processes in badland areas developed in mountain subhumid regions (Nadal-Romero *et al*., 2007; Alatorre and Beguería, 2009).

One of the most obvious consequences of declining streamflow and sediment transport has been the adjustment of fluvial channels to the new hydrological conditions (Beguería *et al*., 2006). Most fluvial channels showed coarse sediment predominance, braided morphology, the presence of unstable bars and channels, and almost complete absence of vegetation, coinciding with the period of greatest human pressure on the hillslopes. At present, many fluvial channels show clear signs of declining activity, with plant cover (shrubs and trees) occupying not only the alluvial plain but also the bars, and the channels become progressively narrower. Most of the coarse sediment in the channels appears to be a legacy of past decades rather than a result of recent soil erosion and sediment transport. In some cases coarse sediment from the secondary streams has arrived in the main channels because of channel incision following the decline in sediment supply from the hillslopes (García-Ruiz *et al*., 2008). Alluvial fans also show a reduction in sediment transport, which is causing a shrinkage of the active depositional lobes of the fans and channel incision into previously deposited sediments (Gómez-Villar and García-Ruiz, 2000). The basins that feed these alluvial fans have been affected by generalized farmland abandonment, reforestation and complex structural works, including the construction of a number of check dams to reduce the sediment flux and the torrential character of the streams.

## Discussion and conclusions

Studies carried out by the Department of Geo-environmental Processes at the Pyrenean Institute of Ecology have confirmed the interconnections that exist between the hydrological and geomorphic processes that occur at different scales. This has been termed “coupling” by Brunsden and Thornes (1979), and led Harvey (2001, 2002, 2007) to study the relationships between hillslopes and channels in upland fluvial systems. However, coupling has received little attention, probably because of the importance given to small-scale processes and the complexity of hillslope and fluvial dynamics. Michaelides and Wainwright (2002, p. 1442) offered the following working definition: “hillslope–channel coupling can be defined as the connectivity of the hydrologic and/or geomorphic processes between hillslopes and river channels”.

Results from the Pyrenees showed that experimental plots provide information on the effects of various land uses and land cover on runoff generation and soil erosion, revealing the consequences of cultivation on steep slopes and of farmland abandonment. The results have allowed us to conclude that traditional agriculture contributed substantially to soil degradation and erosion, resulting in major soil loss and surface stoniness. Farmland abandonment has resulted in relatively rapid decreases in runoff production and soil loss because of plant recolonization. The replacement of cereal crops by meadows or dense shrub cover has caused hydrological changes at the plot scale, reducing the runoff and sediment contributing areas. These changes are more significant than those expected from climate change because of their speed and intensity, particularly in mountain areas during recent decades. This is extremely important because of the dependence of Mediterranean water resources on mountain areas (López-Moreno *et al.*, 2008).

Studies on the hydrological functioning of experimental catchments has confirmed the critical importance of plant cover, by analysis of decreases in the number of floods per year and the prevalence of sediment transport by solutes in the forested San Salvador catchment. The Arnás catchment, cultivated until 50 years ago and subsequently abandoned, has clearly demonstrated the effects of plant recolonization; sediment sources are restricted to small degraded areas close to the channel and most of the hillslopes are clearly disconnected from the channels (these are the discoupled landscape units of Brunsden; 1993). The channel itself shows signs of incision, supplying gravel-sized and fine-grained particles in an almost unlimited manner because of the decline in sediment arriving from the slopes. Although there are other areas affected by active erosion scattered throughout the catchment (scars of large mass movements, unconfined debris flows), these are disconnected from the fluvial channel and cannot be considered as significant contributing areas. The presence of eroded areas close to the channel explains the occurrence of higher suspended sediment concentrations in the Arnás catchment compared to the San Salvador catchment. These areas show a rapid hydrological response, and together with the development of areas that saturate under wet conditions, explain the higher number of floods per year in the Arnás catchment than in the San Salvador catchment. The relative importance of bedload in the total sediment load is a consequence of channel incision more than the effect of hillslope erosion. Thus, the Arnás catchment is an excellent example of the consequences of significant and rapid land use change: at present the Arnás catchment is behaving as a complex mosaic with large spatial and temporal variability in terms of the areas contributing sediment and runoff. Sediment outputs from the Araguás catchment were two orders of magnitude higher than in the Arnás and San Salvador catchments, confirming the important role of densely dissected marl outcrops as sediment sources and runoff generation areas (Beguería, 2005; Nadal-Romero, 2008).

Most of the features observed at the plot and catchment scales were also detected at the regional scale. Thus:

(i) an increasing imbalance has been observed between the evolution of regional precipitation and river discharges since the beginning of the 1970s, with a reduction in streamflow in the main Pyrenean rivers that is independent of the evolution of climate (Beguería *et al*., 2003; López-Moreno *et al*., 2006, 2008);

(ii) a decline has occurred in sediment transport by the large rivers in recent decades, resulting in a reduction of the sedimentation rate in reservoirs;

(iii) a trend toward stabilization of the fluvial channels, colonization of bars with riparian vegetation, and reduction in the braiding indices (Beguería *et al*., 2006) has followed the same trend observed in other basins affected by plant colonization (Piégay *et al.*, 2004; Harvey, 2007). Alluvial fans also show incised channels and shrinkage of the active depositional lobes.

It is likely that dense shrub and forest cover is unable to significantly reduce peak flows during extreme rainstorm events, as the interception capacity of vegetation is quickly saturated (Andréassian, 2004). However, during more frequent but less intense rainstorms a reduction in peak flows could be expected because of interception (Llorens *et al.*, 1997; Llorens and Domingo, 2007) and an increase in infiltration capacity as a consequence of preceding drier soil conditions (Caissie *et al.*, 2002). This may explain the significant decrease observed in the magnitude of relatively frequent floods in the Central Spanish Pyrenees (López-Moreno *et al.,* 2006). At present at least one-third of the old cultivated and grazed areas remain without dense shrub or forest cover (Vicente-Serrano *et al.*, 2004). This suggests that the observed trend in both average discharges and high flows will continue in the immediate future.

This study also demonstrates the importance of considering various spatial and temporal scales. It is well known that geomorphic and hydrological processes are scale-dependent (Seyfried and Wilcox, 1995; Skien *et al.*, 2003; De Vente and Poesen, 2005; Lesschen *et al.*, 2009), with each scale underpinning certain processes (Cammeraat, 2002; Cerdan *et al.*, 2004; Yair and Raz-Yassif, 2004). Studies focused only on experimental plots or rainfall simulations emphasize processes such as infiltration, splash or runoff generation, but do not consider connectivity with the fluvial channel and the consequences on sediment outputs from catchments and on temporal sediment stores. Similarly, studies at the regional scale can enable sediment balances to be assessed and identify sediment sources for large basins, but cannot contribute to understanding of what is happening “within the slopes”. A holistic perspective of the hydromorphological functioning of the region requires a multiscale approach integrating slopes, small catchments, large basins, and fluvial channels. Such an experimental design will enable better understanding of the short- and long-term consequences of changes in land use/land cover and climate.

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## FIGURE CAPTIONS

Figure 1. Location of the study area in the upper Aragón and Gállego valleys, central Spanish Pyrenees. Morpho-structural units: (A) Paleozoic rocks of the Axial Pyrenees; (B) the Inner Sierras; (C) the Flysch Sector; (D) the Inner Depression; (E) the pre-Pyrenean molasses. (1) the Aísa Valley Experimental Station; (2) the Arnás catchment; (3) the San Salvador catchment; (4) the Araguás catchment; (5) the Izas catchment.

Figure 2. Runoff coefficients under various land use conditions at the Aísa Valley Experimental Station. Error bars show standard deviation.

Figure 3. Soil erosion rates under various land use conditions at the Aísa Valley Experimental Station. Error bars show standard deviation.

Figure 4. The hydrological response of three catchments to the same rainstorm event during the dry season.

Figure 5. Daily rainfall, runoff, average daily air temperature, snowpack depth and suspended sediment concentration (SSC) for the period 1 October 2003 to 12 July 2004. Snowpack depth was measured at the lowest point of the catchment.

Figure 6. Annual bedload outputs from the Izas catchment.

Figure 7. Predicted and observed runoff indices for rivers in the Central Spanish Pyrenees.

Figure1

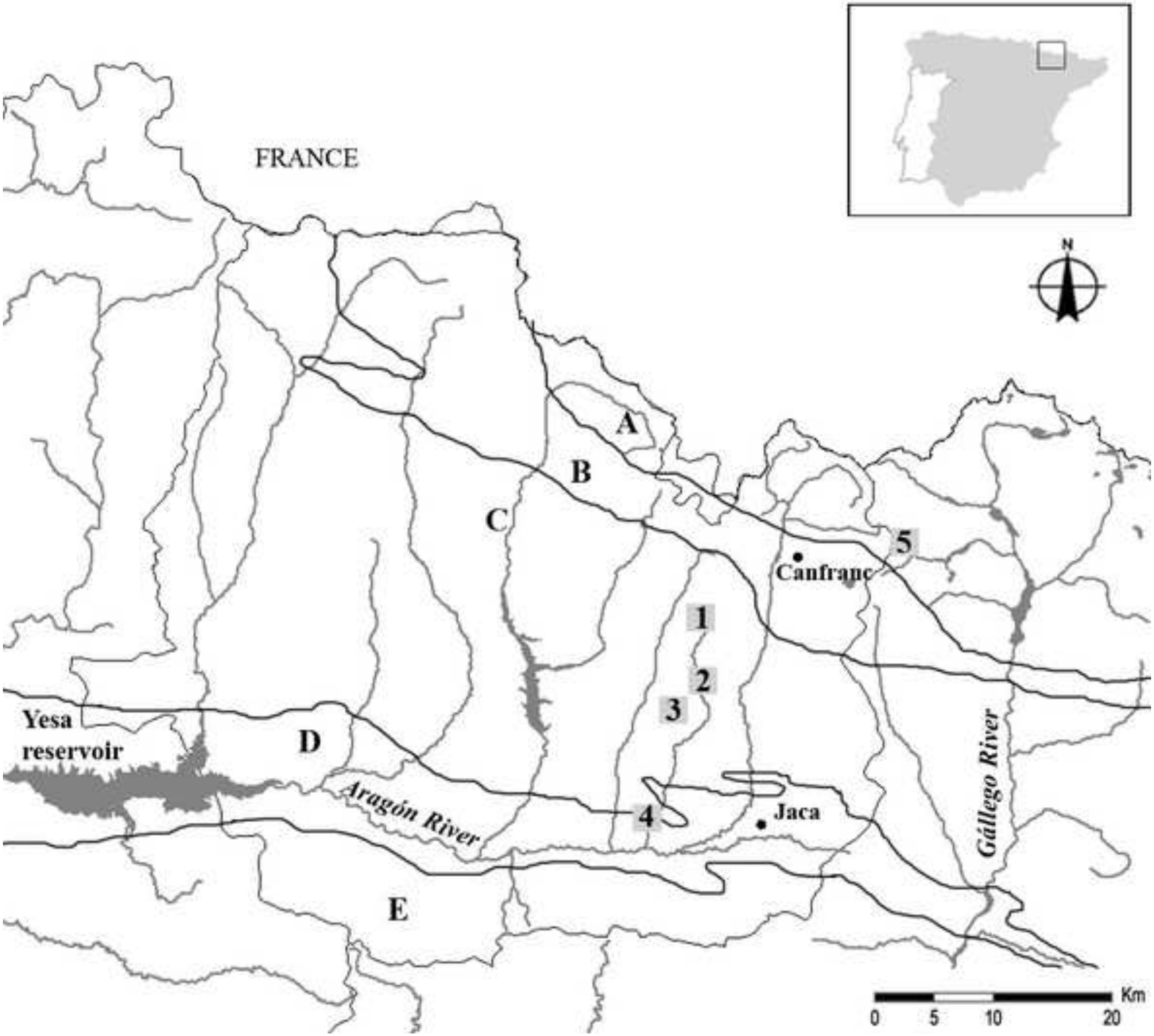
FRANCE
A
B
C
D
E
1
2
3
4
5
Canfranc
Jaca
Yesa reservoir
Aragón River
Gállego River
N
0
5
10
20
Km

Figure2

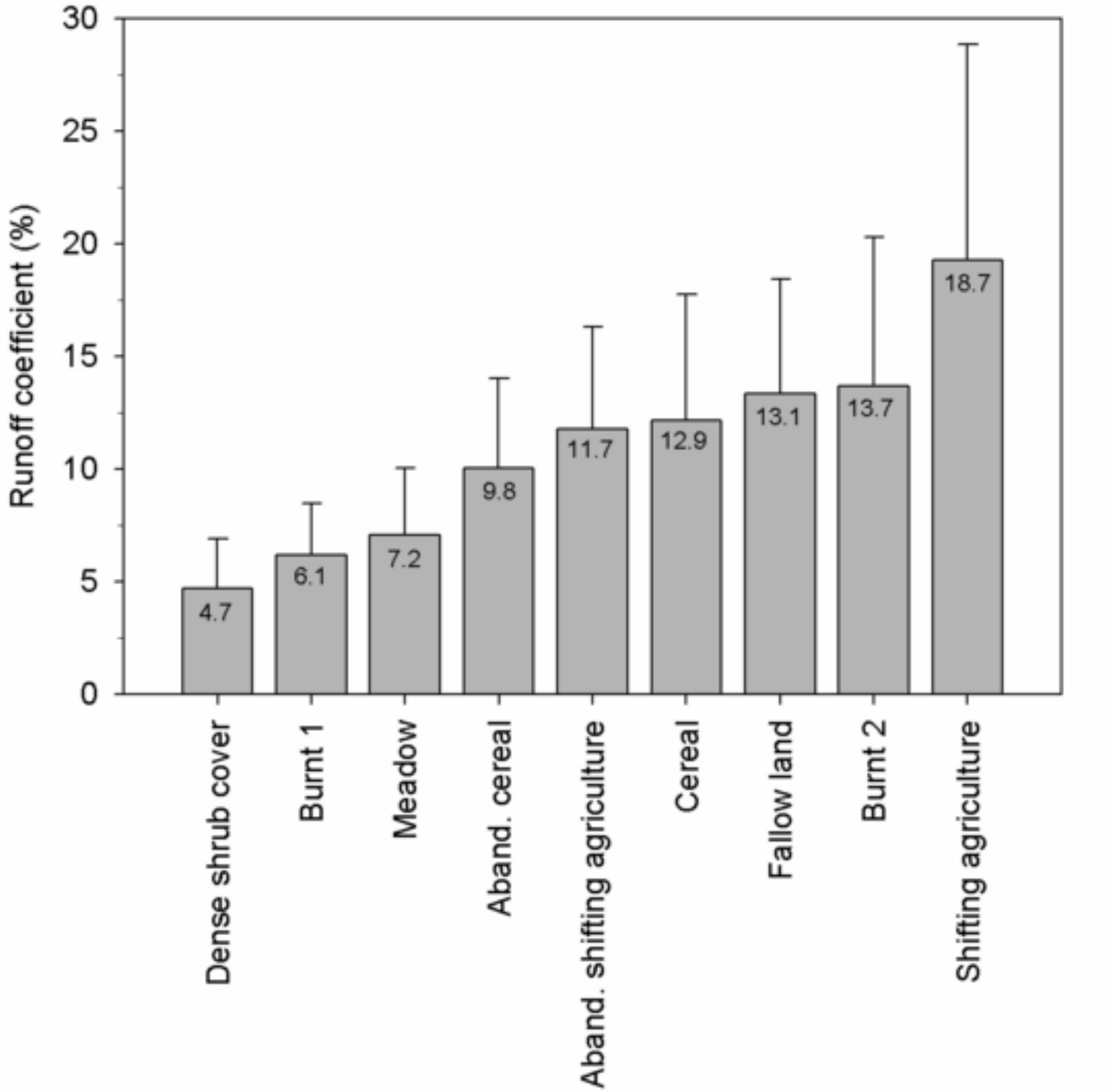
Runoff coefficient (%)
30
25
20
15
10
5
0
4.7
6.1
7.2
9.8
11.7
12.9
13.1
13.7
18.7
Dense shrub cover
Burnt 1
Meadow
Aband. cereal
Aband. shifting agriculture
Cereal
Fallow land
Burnt 2
Shifting agriculture

Figure3

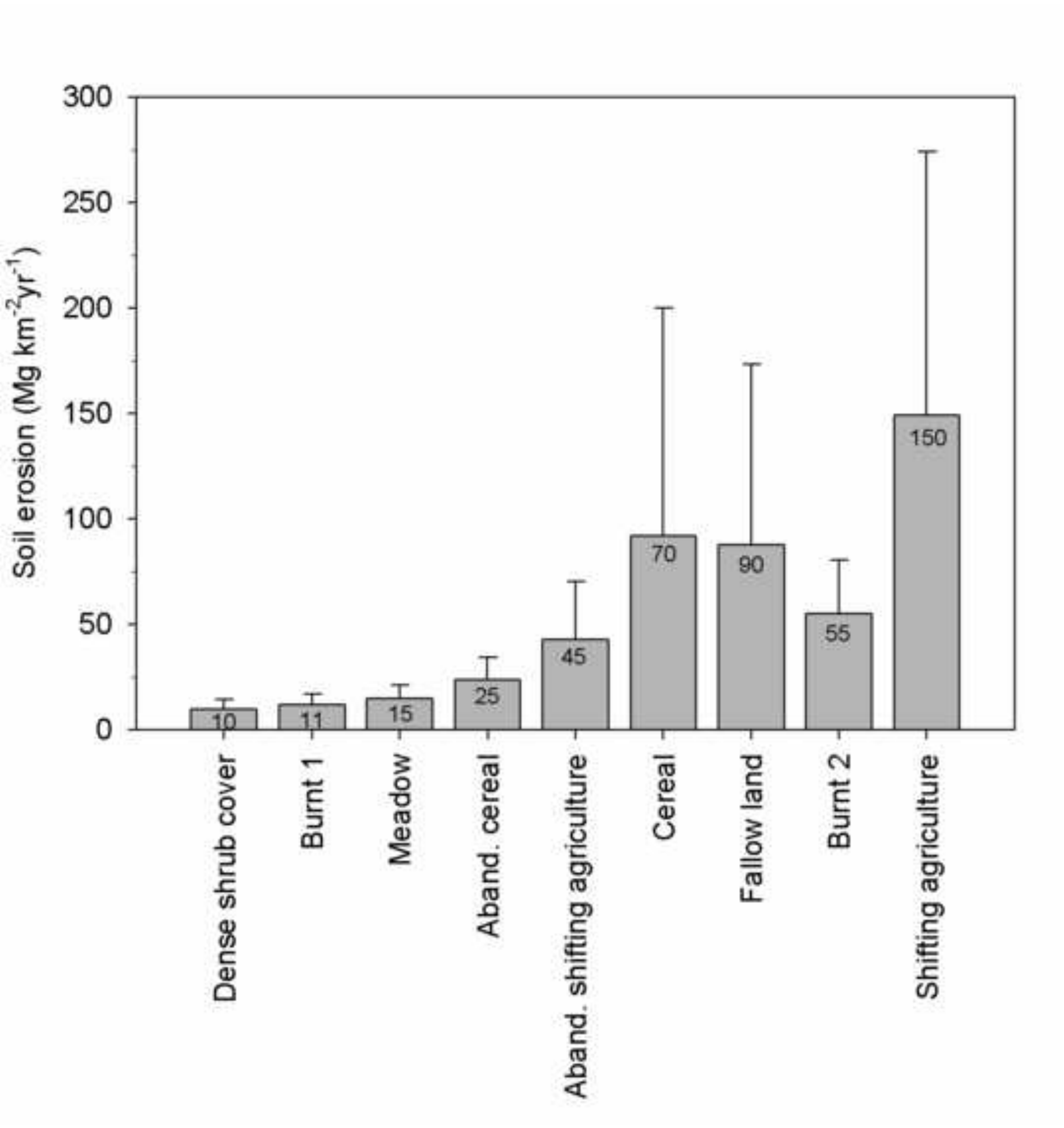
Soil erosion (Mg km$^{-2}$yr$^{-1}$)
300
250
200
150
100
50
0
10
11
15
25
45
70
90
55
150
Dense shrub cover
Burnt 1
Meadow
Aband. cereal
Aband. shifting agriculture
Cereal
Fallow land
Burnt 2
Shifting agriculture

**Figure4**

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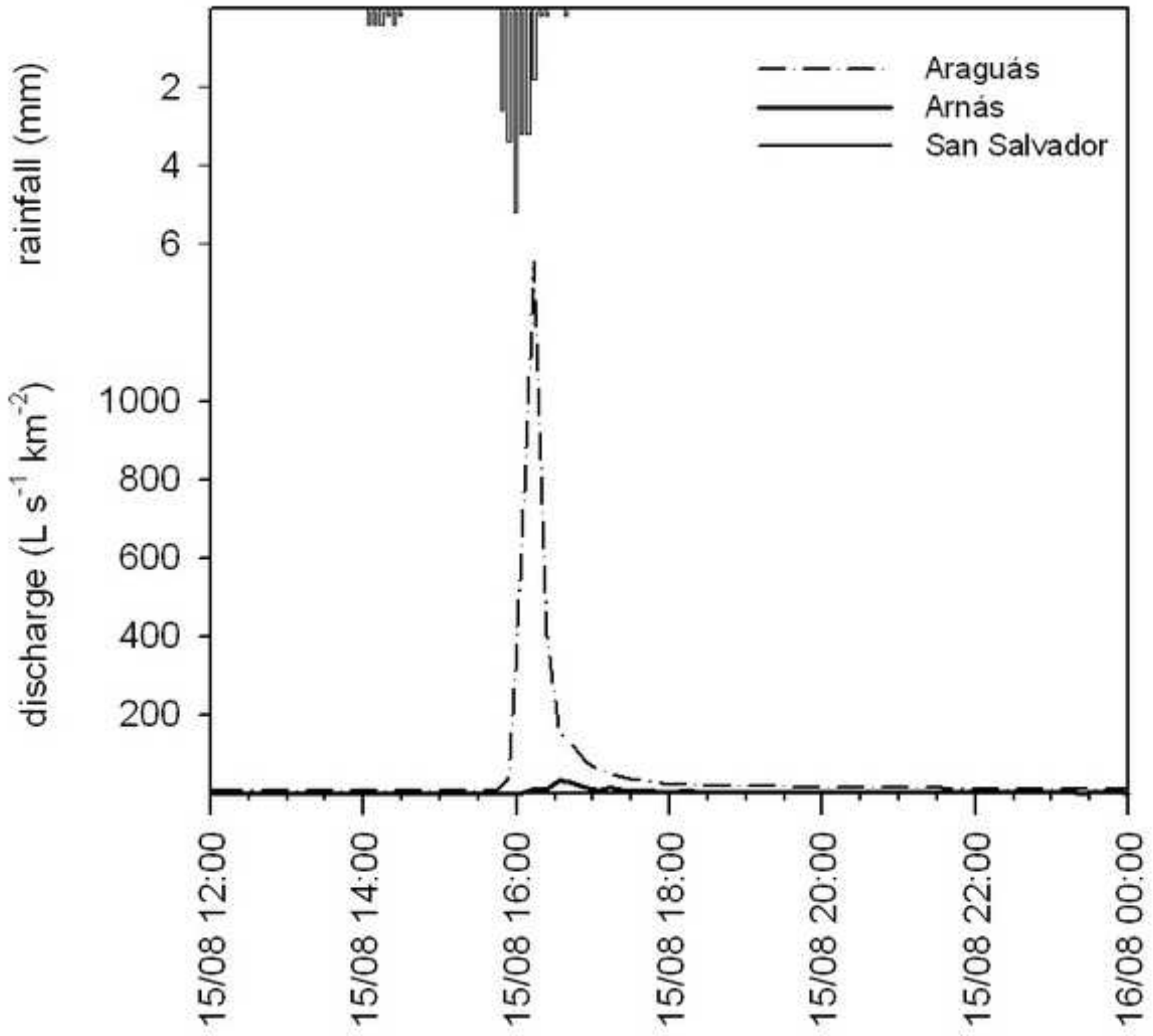

**Figure5**
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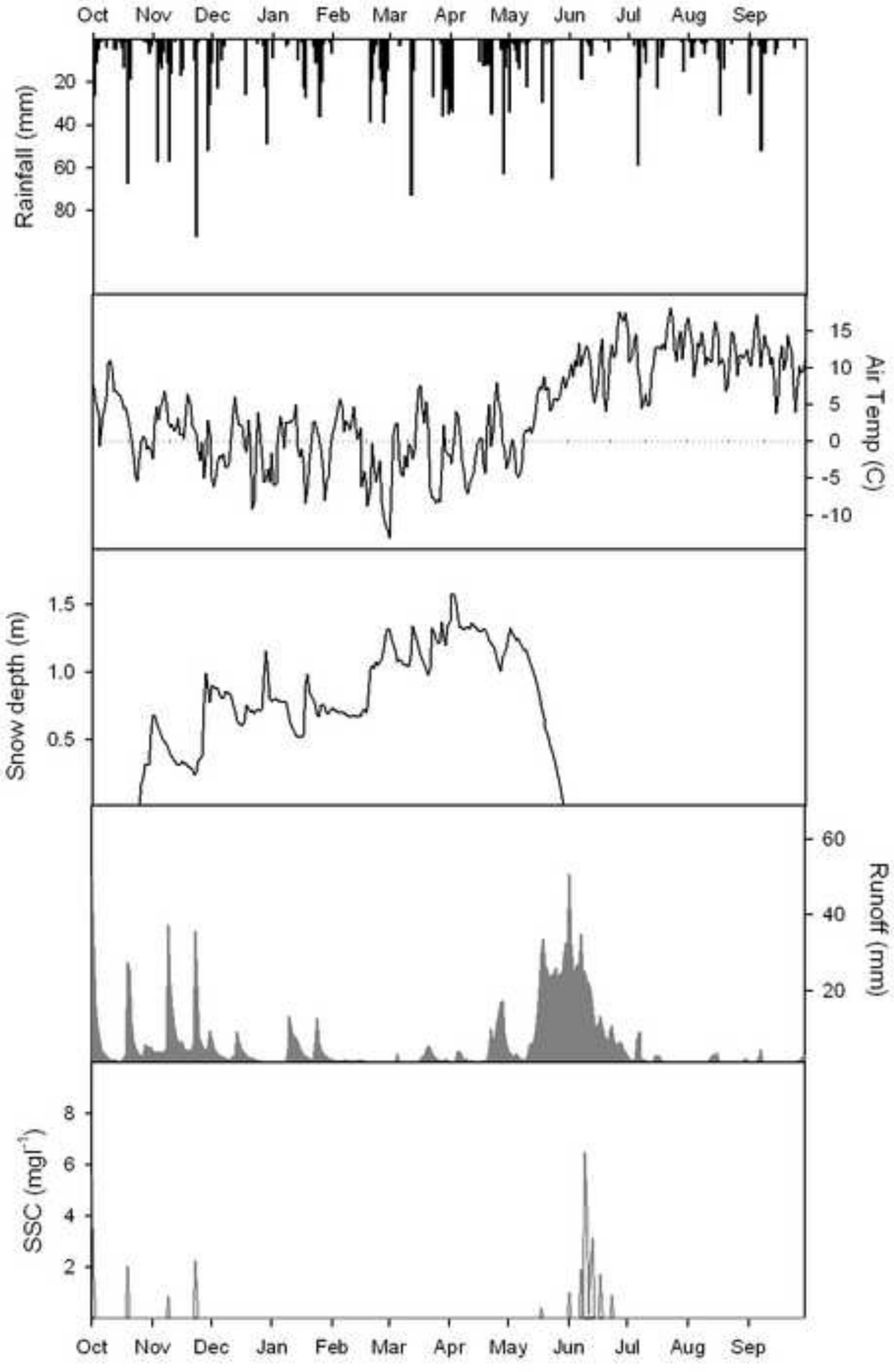

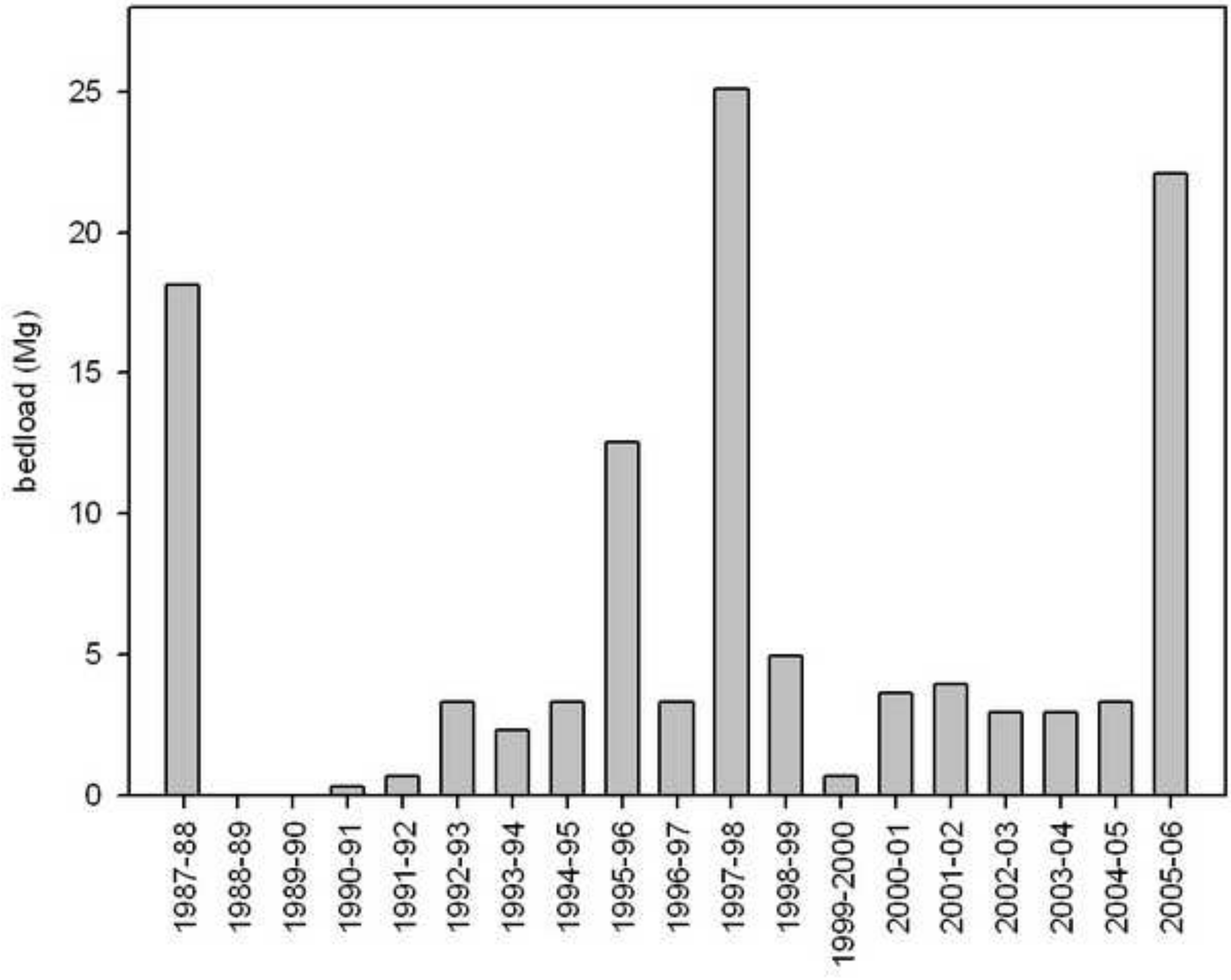
bedload (Mg)
0
5
10
15
20
25
1987-88
1988-89
1989-90
1990-91
1991-92
1992-93
1993-94
1994-95
1995-96
1996-97
1997-98
1998-99
1999-2000
2000-01
2001-02
2002-03
2003-04
2004-05
2005-06

Figure7

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