Temporal and spatial interactions of slope and catchment processes in the Central Spanish Pyrenees

JOSÉ M. GARCÍA-RUIZ, NOEMÍ LANA-RENAULT, SANTIAGO BEGUERÍA, BLAS VALERO-GARCÉS, TEODORO LASANTA, JOSÉ ARNÁEZ, JUAN I. LÓPEZ-MORENO, DAVID REGÜÉS & CARLOS MARTÍ-BONO

Instituto Pirenaico de Ecología, CSIC, Campus de Aula Dei, Apartado 202, ES-50080 Zaragoza, Spain
humberto@ipe.csic.es

Abstract Historical and present day changes in land use and plant cover explain the complex interactions assessed in the Central Spanish Pyrenees between geomorphic processes in hillslopes and channels. More intense erosion periods caused an enlargement of sediment source areas and an increase of sediment supply toward the rivers, characterized by braided channels. A sharp difference existed between the human-induced eroded areas and the rest of the territory, which shows moderate erosion rates. Farmland abandonment in the last few decades has reduced the sediment sources, thus decreasing both sediment delivery and streamflow, as a consequence of plant colonization of the old fields. Fluvial channels also show a decreasing torrential activity over the 20th century.

Key words Central Spanish Pyrenees; experimental basins and plots; geomorphic scales; hillslope–channel interactions; temporal scales

INTRODUCTION

Mountain areas, especially those located in Mediterranean environments, are characterized by a high interannual variability of rainfall and an extreme spatial heterogeneity of relief, plant cover and soil properties. There are several groups of factors to explain such a variability and diversity: (a) Mediterranean mountains are subject to the fluctuating activity of both the Azores Anticyclone and the Polar Front, causing severe contrasts in precipitation at different temporal scales (i.e. between dry and wet season or between dry and wet periods); (b) the relief is a result of the Alpine tectonics, resulting in a relatively young topography intensively dissected by the fluvial network. Deep valleys, steep gradients and a contrasting lithology explain the diversity of geomorphic landscapes, ultimately affected by moderate glacial activity at over 2000 m a.m.s.l.; (c) human disturbances have contributed to both soil erosion in most cases and soil conservation in others, and they have destroyed the original vegetation in many places and have created a mosaic landscape that, in addition, changes with time.

The Department of Soil Erosion and Land Use Changes (http://www.ipe.csic.es/erosion_hidrologia/home.htm) from the Pyrenean Institute of Ecology (Zaragoza, Spain) has studied the geomorphic evolution of the Central Spanish Pyrenees since 1987. Using combined field, experimental and laboratory approaches, it has accumulated a wealth of information on sediment yield and transport, temporal variability of sediment sources, historical evidence of soil erosion and extreme geomorphic events, and the relationships between land use/land cover changes and soil erosion. The purpose of this paper is to show the interactions between

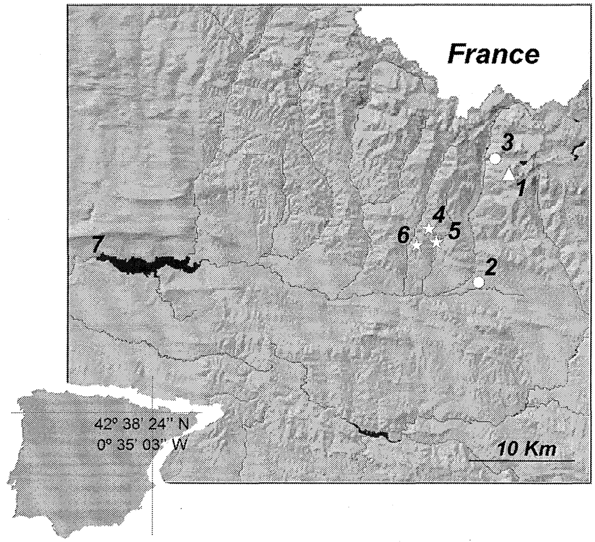

Fig. 1 The study area. (1) Collarada peak (2886 m); (2) Jaca; (3) Canfranc; (4) Aisa Valley Experimental Station; (5) Arnás catchment; (6) San Salvador catchment; (7) Yesa reservoir.

different temporal and spatial scales, in order to underline the processes that prevail at any scale considered.

THE STUDY AREA

The highest altitudes are located in the north of the study area (around 3000 m). Rivers run north–south across the Paleozoic area (mostly limestone and shale), the Inner Sierras (limestone and sandstone), the flysch sector and, finally, they cross the Inner Depression (marl, sandstone, claystone) and the Outer Sierras (limestone and sandstone) (Fig. 1).

Precipitation increases toward the north along the altitudinal gradient, and toward the west because of the Atlantic influence. The average annual precipitation in the northernmost sector of the Central Spanish Pyrenees reaches values above 1500 mm, and around 800 mm in the Inner Depression. The mean annual temperature decreases from north to south (8° in Canfranc and 11° in Jaca). The whole area is occasionally subject to very intense rainstorms, which can cause serious damage by flash floods.

Plant cover has been strongly impacted by human activities. As a result of the changes in land use during the 20th century, most cultivated fields have been abandoned, except in the Inner Depression and the valley bottoms (fluvial terraces), where cutting meadows and cereal crops prevail. Natural forests occur at any altitude in shady aspects and above 1400 m a.m.s.l in the sunny ones.

DATA AND METHODS

Studies on hillslope erosion have been undertaken at the Aisa Valley Experimental Station, where eight erosion plots under different traditional and modern land uses assess the effects of agricultural changes on runoff generation and soil erosion at a local scale (García-Ruiz *et al.*, 1995). The research includes the following land uses: cereal (barley), fallow land (alternating every 2 years with cereal), shifting agriculture (barley), abandoned cereal (now covered by dense herbaceous communities after 5 years of abandonment), abandoned shifting agriculture (with herbs now covering 60% of the soil after 4 years of abandonment), burnt plot (previously dense shrub cover), already re-established 2 years after a 1991 fire, meadow and dense shrub cover (representing the evolution of most of the hillslopes 30 years after farmland abandonment). The plots are 30 m^2 in size, located in a field with a 25% slope.

Basin-scale information on discharge and sediment transport has been collected from two different environments: The Arnás catchment (285 ha) was previously cultivated with cereals and abandoned 40 years ago. Now it is covered by shrubs with a variety of densities. The San Salvador catchment (136 ha) corresponds to a densely forest-covered, non-disturbed area. Both catchments are located at similar altitude, rock substratum and topography, and precipitation features are the same at any temporal scale.

In addition, remote sensing and Geographical Information Systems have been used to assess sediment sources at a larger scale (basins of more than 1000 km^2). Information is also available on reservoir siltation rates and sedimentological evolution of some of the Pyrenean reservoirs. The effects of changes in land cover and climate on water resources throughout the Central Spanish Pyrenees have also been analysed (Beguería *et al.*, 2003). Additional information on erosion during the last few millennia is available from proxy records as lacustrine sediment cores and analyses of slope screes and mass movements.

SOIL EROSION AND STREAMFLOW: FROM PLOTS TO LARGE BASINS

Runoff coefficients and soil erosion rates from plots are clearly higher in the cultivated plots, especially in the plot with shifting agriculture, followed by the fallow plot and the cereal plot. The lowest values are recorded from the plot with dense shrub cover, the meadow plot and the burnt (already re-colonized) plot (Fig. 2). In general, the erosion rates can be considered as moderate, ranging from 0.11 to 1.37 t ha^{-1} $year^{-1}$ in extreme cases. These results confirm the importance of old cultivated slopes as sediment sources in mountain areas, and the progressive decrease in soil erosion after farmland abandonment, especially when plant re-colonization reaches the stage of a mature shrub cover. The experimental data also demonstrate the importance of a dense shrub cover (probably similar to that of a forest) for soil conservation and the moderate response of overland flow during rainfall events. The actual landscape reflects very well the effects of shifting agriculture in steep slopes, frequent human-induced fires and grazing: areas with open scrubs on the sunny, convex slopes, affected by sheet wash erosion, soil stoniness, and relatively frequent occurrence of shallow landslides and debris flows, whereas concave areas are very stable.

At a small catchment scale, the hydrological and geomorphological response also depends on plant cover and land uses. Figure 3 shows, as an example, the hydrographs of the same rainfall and flood event for Arnás and San Salvador catchments. Arnás reacts almost immediately to every rainstorm event. This fast response is likely to be due to the presence of eroded areas close to the main channel, which are inherited from past farming activities and grazing. Nevertheless, the hydrological response tends to be, at an annual scale,

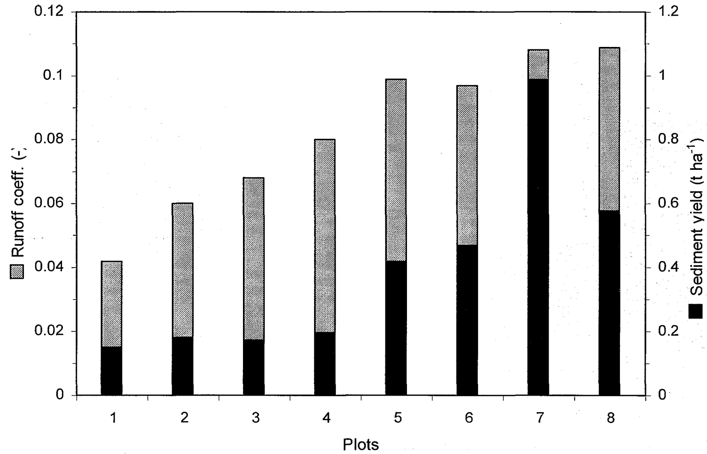

Fig. 2 Runoff and sediment yield from different land uses in the Aísa Valley Experimental Station. (1) shrub; (2) meadow; (3) burnt (old); (4) abandoned; (5) shifting agriculture; (6) cereal; (7) fallow; (8) burnt (recent).

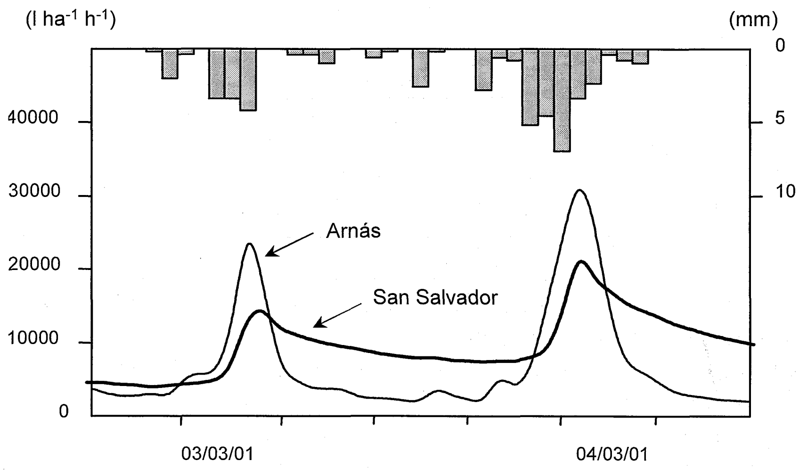

Fig. 3 Hydrographs from the same rainstorm event in the Arnás and San Salvador experimental catchments.

relatively complex: although the shape of the hydrograph suggests a prevailing Hortonian overland flow for the whole catchment, the correlation between rainfall and discharge is quite low (r^2 = 0.44), thus suggesting the importance of other factors, above all the antecedent soil humidity. Seeger *et al.* (2004) illustrate the occurrence of at least two situations during flood generation: (a) in the wet season the whole catchment is able to yield runoff, the hydrological response is fast and with a high peak flow; and (b) in the dry season, runoff is only supplied by the areas close to the channel, especially those affected by sheet wash erosion with open scrubs, and the peak flow is relatively low, even with intense and voluminous rainstorms. In San Salvador the hydrograph shows a very moderate response to rainfall events and a long recession curve after each event. In this case the role of

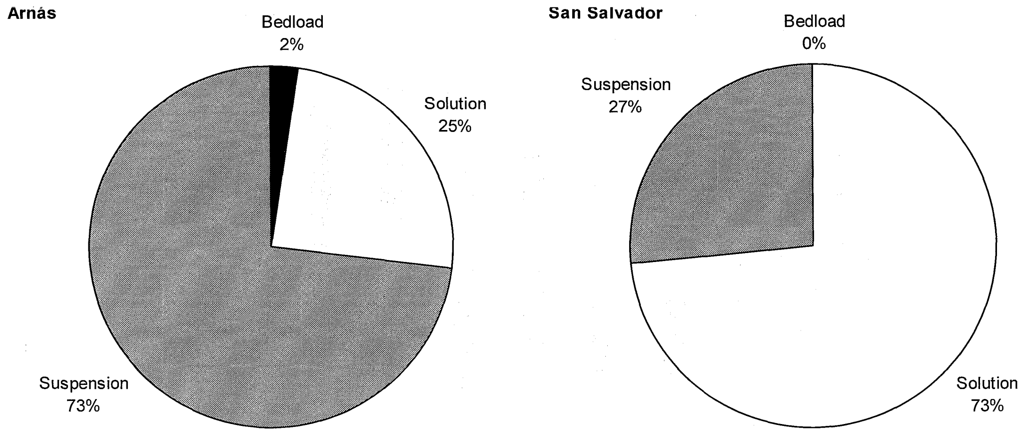

Fig. 4 Sediment balance in the Arnás and San Salvador experimental catchments.

interception and infiltration explains the moderate hydrological behaviour. Sediment transport also shows great differences between both catchments (Fig. 4). In Arnás 75% of the sediment outputs corresponds to suspended sediment, whereas 20% to solutes and 5% to bed load. In San Salvador 60% is carried as solutes and 40% as suspended sediment. Erosion rates are 2.04 and 1.87 t ha^{-1} $year^{-1}$, respectively, for the years 1999 and 2000.

At a large basin scale (regional scale: >1000 km^2) the use of remote sensing and models help to identify sediment sources. Beguería (2003) concludes that in the upper Aragón River basin, sediment sources are mainly related to: (a) the occurrence of marly outcrops, affected by gullying (extensive badlands) and located very close to the main channel, behaving as contributing areas during any rainstorm event; and (b) the past human activities, that caused large areas with sheet wash erosion on steep gradients close to the villages. These areas are not always well connected to the fluvial network, and they are contributing areas only during relatively infrequent rainstorm events.

At a large basin scale, sedimentation in the Yesa reservoir provides an erosion rate of 4.1 t ha^{-1} $year^{-1}$. Figure 5 shows how sediment delivery clearly increases as the area considered enlarges, due to the improvement between the interactions between slopes and channels in larger basins, and to the existence of very active sediment sources (bare marl outcrops) in the Aragón basin.

THE TEMPORAL APPROACH: EFFECTS OF LAND USE CHANGE

Investigation of soil erosion and streamflow through time reveals key periods of intense erosion mainly related to the removal of forest cover and farming of steep slopes.

The first evidence of human-induced plant cover disturbances is dated at about 4000 ^{14}C year BP. It is represented by the presence of charcoal and a small decrease in arboreal pollen percentages in some lake and slope records (Montserrat, 1992). The second dramatic erosion period occurred around the 12th century and represents a sudden and very significant lowering of the upper forest belt, in order to enlarge the summer pasture area. At present, the upper forest limit in many Pyrenean valleys reaches only 1600–1700 m, whereas the natural

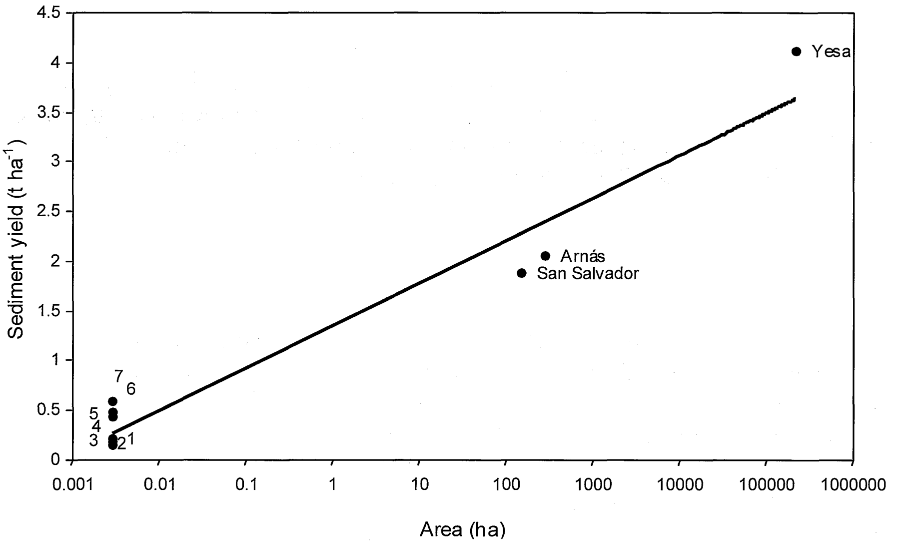

Fig. 5 Relations between area and sediment delivery in the Central Spanish Pyrenees. Plots data. (1) control area; (2) meadow; (3) burnt (old); (4) abandoned; (5) shifting agriculture; (6) cereal; (7) burnt (recent).

forest limit is at about 2200 m. The negative consequences of such a deforestation process were shallow translational landslides and dense rill networks, leaving large areas of the subalpine hillslopes with the bare substratum at the surface. Evidence of this erosion period has also been recorded in high mountain lake sediments (Montserrat, 1992), where increased charcoal percentages are associated with an intense period of soil erosion and a change in plant cover (substitution of trees by grasses).

Between the beginning of the 18th century and the first decades of the 20th century the population increased and all the farming possibilities in the Pyrenees were exploited. Thus, a new soil erosion period occurred, coinciding with the stage of maximum aggradation of the Ebro River delta in the Mediterranean. At the same time, alluvial plains were characterized by bare river bars and very unstable braided channels, suggesting a supply of large volumes of coarse sediment from the hillsides (García-Ruiz & Valero, 1998).

Since the middle of the 20th century farmland abandonment is the most important feature of Mediterranean mountains due to depopulation. This process has been very fast in such a manner that by 1970 all the fields in the hillslopes were already abandoned. As a consequence, the old fields and many overgrazed areas have been re-colonized with scrubs. In addition, government-induced re-afforestation affected many old cultivated areas. These changes in plant cover and land uses caused significant changes in runoff generation and soil erosion. Beguería *et al.* (2003) demonstrated decreasing streamflow in the central Spanish Pyrenees, regardless of climatic oscillations, between 1945 and 1995. The difference between the expected trends in discharge (based on climate) and the actual discharge implies that a non-climatic, time dependent factor has determined the decrease in discharge. Similarly, a decrease in the sedimentation rate has also been observed in large reservoirs in the last few decades (López-Moreno *et al.*, 2003). In relation to that, a clear reduction in sediment sources has been detected, as well as a partial stabilization of fluvial channels and alluvial fans (Gómez-Villar, 1996), now affected by entrenchment and plant colonization.

The study of the effects of different intensity rainfall events demonstrates that, in general, processes linked to rainfall events with return periods of less than 25 years can carry a lot of heterogeneous sediments, but the effects on the landscape are relatively minor. However, the less frequent events (>100-year return period) can introduce very important modification of the landscape, but since they affect a very localized area, they have limited regional importance (García-Ruiz *et al.*, 2002).

CONCLUSIONS

Temporal and spatial interactions in sediment sources, erosion and transport are very complex in the central Spanish Pyrenees, as in other Mediterranean mountains, due to the role of human activities in the triggering of erosion processes and in the evolution of the streamflow. Historical evidence demonstrates the existence of periods with higher sediment yield and transport, resulting in soil erosion, shallow landslides and, as a consequence, braided rivers. The Bronze and Iron Ages, the Lower Middle Age and the 17th–19th centuries seem to have been the most important erosion periods since the mid-Holocene. During those periods sharp differences existed between the human-induced eroded areas and the rest of the territory: the former, occupying around a half of the study area, were directly connected to the fluvial channels through natural and artificial drainage systems; the latter behave in a very moderate way, as the San Salvador catchment does at present, supplying clean waters, even during relatively infrequent rainstorm events.

Farmland abandonment during the second half of the 20th century has introduced very important hydrological and geomorphological changes. The bare, easily erodible marly and clayey outcrops are now the main sediment sources, whereas the old cultivated areas are colonized by scrubs and forests, and remain partly disconnected from the fluvial network.

Acknowledgements Funding for this research was provided by the following projects: HIDROESCALA (REN2000-1789-c04-01/GLO), PROHISEM (REN2001-2268-C02-01/HID) and PIRIHEROS (REN2003-08678/HID), all funded by CICYT, Spanish Ministry of Science and Technology.

REFERENCES

Beguería, S. (2003) Identificación y características de las fuentes de sedimento en áreas de montaña: erosión y transferencia de sedimento en la cuenca alta del río Aragón (Identification and characterization of sediment sources in mountain areas: erosion and sediment transfer in the Aragón river basin). PhD Thesis, University of Zaragoza, Zaragoza, Spain (in Spanish).

Beguería, S., López-Moreno, J. I., Lorente, A., Seeger, M. & García-Ruiz, J. M. (2003) Assessing the effect of climate oscillations and land use changes on streamflow in the Central Spanish Pyrenees. *Ambio* **32**, 283–286.

García-Ruiz, J. M. & Valero-Garcés, B. (1998) Historical geomorphic processes and human activities in the Central Spanish Pyrenees. *Mountain Res. & Develop.* **18**, 309–320.

García-Ruiz, J. M., Martí-Bono, C., Lorente, A. & Beguería, S. (2002) Geomorphological consequences of frequent and infrequent rainfall and hydrological events in Pyrenees mountains, Spain. *Mitigation and Adaptation Strategies for Global Change* **7**, 303–320.

García-Ruiz, J. M., Lasanta, T., Ortigosa, L., Ruiz-Flaño, P., Martí, C. & González, C. (1995) Sediment yield under different land uses in the Spanish Pyrenees. *Mountain Res. & Develop.* **15**, 229–240.

Gómez-Villar, A. (1996) *Conos aluviales en pequeñas cuencas torrenciales de montaña* (Alluvial fans in small mountain catchments). Geoforma Ediciones, Logroño, Spain (in Spanish).

López-Moreno, J. I., Beguería, S., Valero, B &, García-Ruiz, J. M. (2003) Intensidad de avenidas y aterramiento de embalses en el Pirineo Central español (Floods and reservoirs siltation intensity in the Central Spanish Pyrenees). *Ería*, **61**, 159–167 (in Spanish).

Montserrat, J. (1992) *Evolución glaciar y postglaciar del clima y la vegetación en la vertiente sur del Pirineo: estudio palinológioco* (Climate and vegetation glacial and postglacial evolution in the Pyrenean sunny aspects: Palinologic study). Instituto Pirenaico de Ecología, Zaragoza, Spain (in Spanish).

Seeger, M., Errea, M. P., Beguería, S., Arnáez, J., Martí, C. & García-Ruiz, J. M. (2004) Catchment soil moisture and rainfall characteristics as determinant factors for discharge/suspended sediment hysteretic loops in a small headwater catchment in the Spanish Pyrenees. *J. Hydrol.* (in press).