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Sediment deposition in the Barasona reservoir (central Pyrenees, Spain): temporal and spatial variability of sediment yield and land use impacts

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Abstract A sedimentological study of the Barasona reservoir (central Pyrenees, Spain) illustrates the variability of depositional dynamics in the Esera-Isábena drainage basin through time and space. A preliminary chronology based on flood events recorded in the reservoir indicates changes in sediment yield during the last four decades. Coupled reservoir-drainage basin sediment studies have enabled sediment sources and sediment production risk areas to be identified and, the assessment of the relative role of natural (topography, drainage network, lithology, and hydrology) and human (land use) factors influencing sediment yield, delivery and deposition.

INTRODUCTION

Soil erosion processes are an important influence on sediment delivery to reservoirs and consequent loss of water storage capacity. Lake and reservoir sediments have been frequently used to reconstruct records of catchment processes (Dearing & Foster, 1993) and the quantification of sediment accumulation in reservoirs has proved to be a reliable means of estimating average erosion rates in their drainage basins. In this paper we present the preliminary results of a sedimentological study of a mountain drainage basin and reservoir in the Spanish Pyrenees. Using these methods we have improved the resolution of the reconstructed depositional history of the reservoir, and contributed to a better understanding of temporal and spatial variability in catchment processes, and the relative importance of anthropogenic and natural factors.

THE ESERA-ISABENA RIVER BASIN AND THE BARASONA RESERVOIR

In the Spanish Pyrenees, many rivers that run through rugged topography and erodible soils and rock formations have been dammed in the foothills. The Barasona reservoir in the Esera-Isábena drainage basin, central Pyrenees (Fig. 1A) provides a case study for an integrated investigation of reservoir drainage basin dynamics. The basin is characterized by heterogeneous topography and lithology and contains several WNW-ESE trending geologic units (Fig. 1B, C). The climate is of a mountain type, and is cold and wet with both Atlantic and Mediterranean influences, and strong north-south gradients. Annual precipitation and average temperature range from more than 2000 mm year^{-1} and 4°C respectively in the headwaters, to less than 500 mm year^{-1} and 12°C at the reservoir. Both the Esera and Isábena rivers have

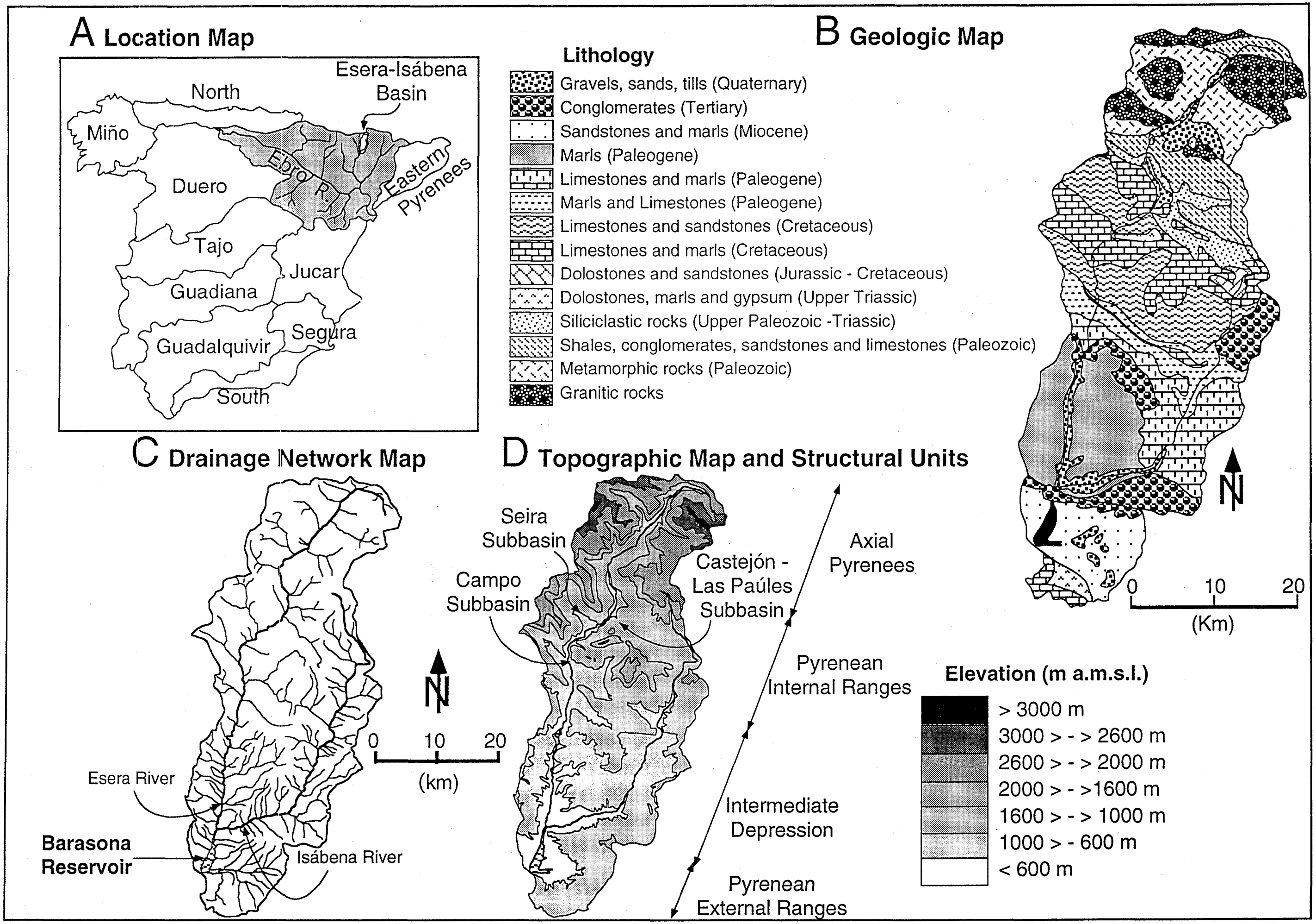

Fig. 1 The Esera-Isábena basin and the Barasona reservoir. A. Location map. The Esera-Isábena basin forms part of the Ebro River basin, one of the largest river basins in Spain. B. Geologic map (after Riba, 1972). C. Drainage network map. D. Topographic map and structural units.

transitional hydrologic regimes characterized by two periods of high flows, during late spring/early summer (snow melt) and late fall (Mediterranean rains). According to available historical and hydrological evidence there have been eight major floods in the Esera-Isábena basin since 1892. The floods are caused by three different mechanisms i.e. late spring/early summer snow melt and heavy rains (1925, 1960, 1971, 1977), summer thunderstorms (1963), and late autumn heavy rains (1960, 1963, 1965, 1977, 1982, 1984, 1996).

The reservoir, one of the oldest in Spain (1932), has lost one third of its initial water capacity (71×10^6 m^3). The specific sediment yield of the 1224 km^2 basin has been estimated as 350 t km^2 $year^{-1}$ (Sanz Montero *et al.*, 1996). Variations in drainage network pattern (Fig. 1C) and lithology (Fig. 1B) have been proposed as key factors in explaining intrabasin contrasts in sediment yield (Fargas *et al.*, 1996). In this paper we test this hypothesis and also the relationship between land use and sediment delivery.

METHODS AND DATA

Twenty two cores and sediment sections, up to 4 m long, were described and correlated using lithology, mineralogy and sedimentary structures (Fig. 2A and C). Suspended sediment and river bed sediments were sampled after the winter 1996 floods (28 February 1996) in the Esera and Isábena rivers. Samples of 1 litre were collected at approximately 10 cm from the stream bed, and filtered in the laboratory to calculate suspended sediment concentration (SSC). Mineralogy was determined by a Siemens D-500 diffractometer. Composition percentages were calculated using relative reflectance factors and are therefore semiquantitative. Flow values for the Isábena and Esera rivers were provided by the Confederación Hidrográfica del Ebro, and land use maps were based on data derived from Manrique *et al.* (1987).

RESULTS AND DISCUSSION

Sedimentation in the Barasona reservoir

The two main depositional environments in the Barasona reservoir are firstly, deltas developed at the mouth of the Esera River and close to the dam wall, and secondly, pelagic plains (Valero-Garcés *et al.*, 1996). Sediment thickness varies from 2 m in the littoral areas, to more than 4 m in the Esera delta, 6 m on the pelagic plain, and a few tens of metres in the dam wall delta. Sediments are admixtures of calcite, quartz, illite, chlorite and minor amounts of kaolinite, feldspar, dolomite, and pyrophyllite. The organic matter content ranges between 2-5%. The silt fraction is dominant, but sand layers also occur, specially close to the mouth of the Esera River.

Sediments are primarily of allochthonous origin, and deposition is dominated by physical processes. Changes in the river flows exert a major control on the depositional dynamics. Upward fining sequences, up to 30 cm thick and composed of sand, silt, and clay define major flood episodes in the reservoir. At the Esera River mouth (profile B-21, Fig. 2C) more than 50% of the sediments are sandy silts and

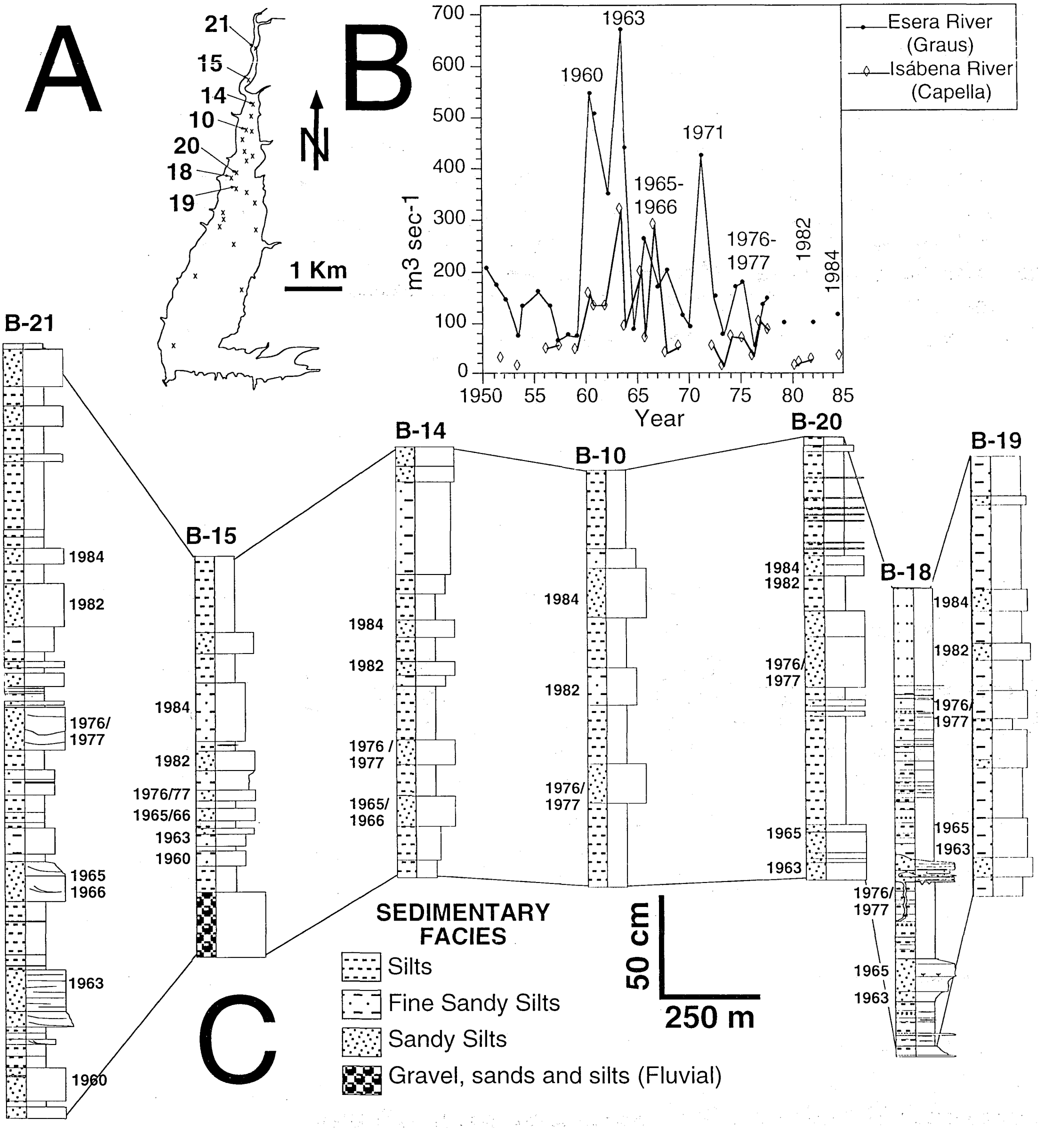

Fig. 2 Sediment core correlation and a tentative chronology for deposition in the Barasona reservoir. A. Location of the sediment cores. B. Maximum instantaneous flow values in the Esera and Isábena rivers during each year at the gauging station closest to the reservoir. C. Selected sediment cores and a tentative correlation between sand layers and flood events.

sands accumulated during floods. The occurrence of sand layers in cores from the central areas of the reservoir (Fig. 2C) indicates that tractive processes still function in that area. In contrast to other reservoirs, where authigenic processes are very significant (Cobo Rayán *et al.*, 1996), our data support a depositional model with major flood events as the main agents of reservoir sedimentation.

A relative depositional chronology can be constructed by comparing the known floods in the basin (Fig. 2B) with the sandy layers described in core B-21 (Fig. 2C).

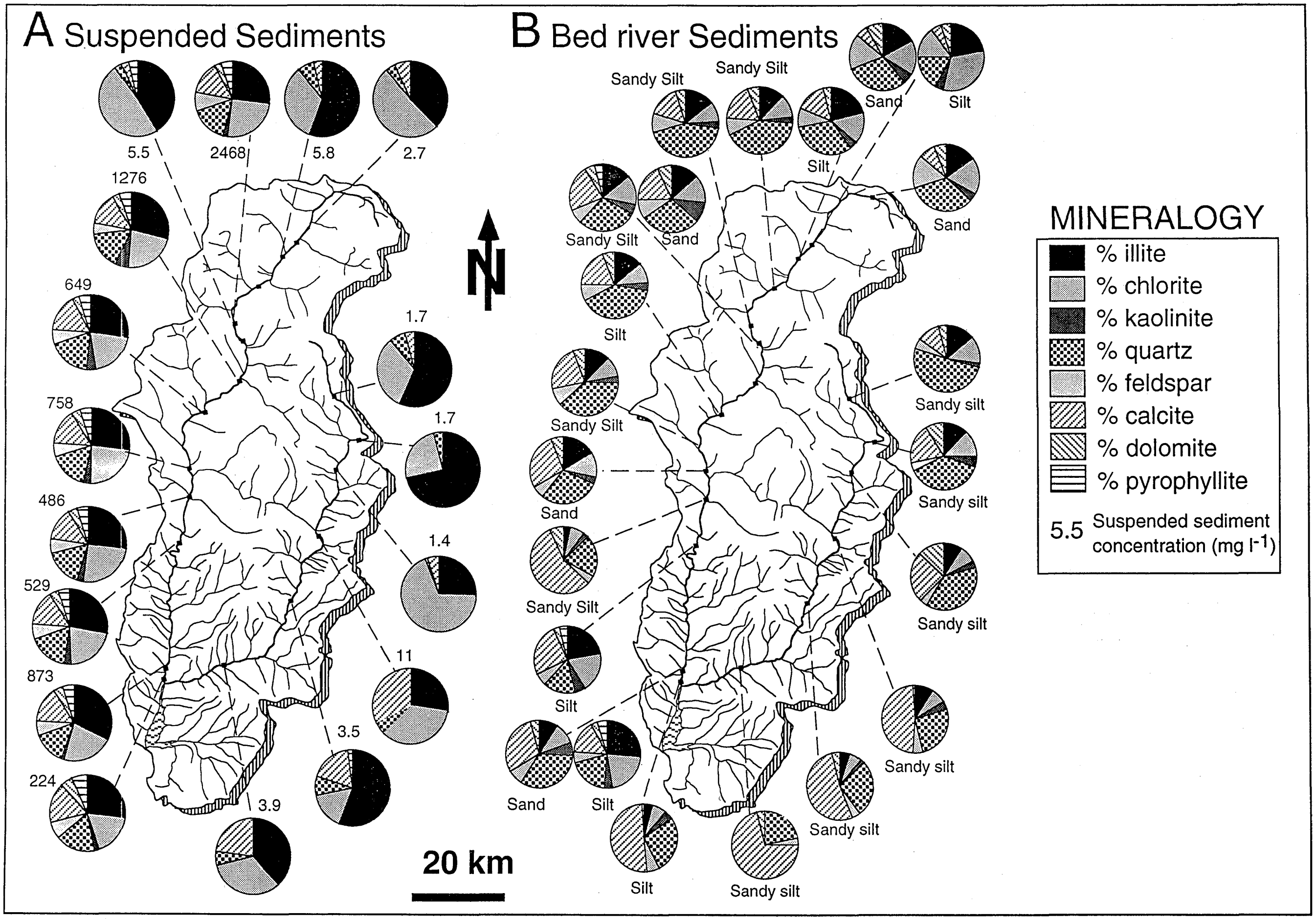

Fig. 3 The winter 1996 flood sediments (sampled 28 February 1996): A. suspended sediment concentration and composition B. River bed sediment composition.

We have ascribed the sand layer at the bottom of the profile, characterized by the coarser grain size, higher quartz content, and presence of the largest tree branches, to the largest flood (1960). According to this relative chronology, three periods can be distinguished in the Esera delta of the Barasona reservoir. Sedimentation rate was high during the early 1960s (more than 1.5 m of sediment was deposited in less than 10 years), decreased during the 1970s (up to 1 m in about 10 years) and increased subsequently during the 1980s and 1990s (about 1.5 m in 15 years), but without reaching the values of the 1960s. Taking into account that most of the sediment is deposited during floods and that these events were more frequent during the 1960s, we speculate that these changes in sediment yield have been caused by changes in flood frequency. A definitive chronology will be established using radioisotope analyses, which are currently in progress.

The winter 1996 floods

The floods of 1995-1996 occurred during a period of increased precipitation extending from late fall to winter (December 1995-February 1996). A preliminary sampling programme was undertaken at the end of that flood period. Our results, although not based on a comprehensive survey, clearly indicate that the Esera River delivers most of the suspended sediment to the Barasona reservoir (Fig. 3A). Suspended sediment concentrations in the inflow to the reservoir were 50 times higher in the Esera River (224 mg l^{-1}) than in the Isábena River (3.9 mg l^{-1}). The mineralogy of the river sediments reflects not only their grain size distribution but also the heterogeneous lithology of the source areas (Fig.1B and Fig. 3) Clay minerals are more abundant in the Isábena River suspended sediment due to the lower flow of this river. Quartz is generally dominant over calcite on the Esera River, whereas the opposite is true for the Isábena River. Feldspars are more abundant in sediment from the Esera River, especially in the upper valley where granitic rocks outcrop.

Sediment yields as inferred from SSC values and river sediment mineralogy (Fig. 3A and B) show a distinctive geographic distribution. We define four areas in the Esera basin (the headwaters, the Castejón de Sos Depression, the Campo-Seira intramountain Depressions, and the Intermediate Depression), and three in the Isábena basin: northern, intermediate, and southern.

The Esera River basin Suspended sediment concentrations in the headwaters of the Esera River were below detection limits but increased to 6 mg l^{-1} downstream. A heavy snowpack covered the landscape and effectively reduced soil erosion. Pyrophyllite appears in all samples downstream of where tributaries draining sedimentary Palaeozoic rocks join the Esera River. The Lower Devonian low grade metamorphic shales are the only pyrophyllite-rich rocks outcropping in the basin (up to 25% of total clay minerals; Valero-Garcés *et al.*, 1996), and consequently, we identified them as the only source area for this mineral. One of the samples is unusual in terms of both sediment concentration (2468 mg l^{-1}) and mineral composition (higher amounts of carbonate and quartz), and is more similar to the composition of silt from the Esera River bed (Fig. 3B). Because the sample was taken in an area where the river is very shallow, we explain this anomaly as the result of a higher proportion of coarser particles transported by saltation and as bed load.

We interpret the low SSC in the northern Esera basin as being the result of lower erosion rates. The snow covered landscape would be a significant factor in limiting erosion during the winter months. Land use would also favour low sediment yields (Fig. 4). Most of the land is grassland (>50%), which helps to prevent soil erosion throughout the year (Ruiz Flaño, 1993), and the percentage of cultivated land is small (<10 %) (Manrique *et al.*, 1987).

The mineral composition of the suspended sediment changes markedly downstream, after the river enters the Castejón de Sos sub-basin. The suspended sediment concentration is very high (1276 mg l^{-1}), and its quartz and calcite content increases up to 20% for each. A higher sediment yield would be favoured by the increase in cultivated land (up to 50%), and the decrease in grassland (<50%) (Fig. 4).

Suspended sediment concentrations decrease in the Intermountain Depressions of Seira and Campo (650-750 mg l^{-1}), but the mineral composition remains similar. Tributaries drain carbonate terrains from the Internal Ranges and calcite correspondingly increases and quartz decreases in the river sediments. Although SSC values in the streams were low (below detection limits), sediment in the channels shows a distinctive mineral composition, characterized by a higher calcite content than the Esera River (Fig. 3B). Due to the rugged topography, both cultivated land (up to 25%) and grassland (<10%) decrease, and forest reaches the highest percentages in the basin (>70%) (Fig. 4). Again, human impact appears to be significant in explaining the slight decrease in suspended sediment concentrations.

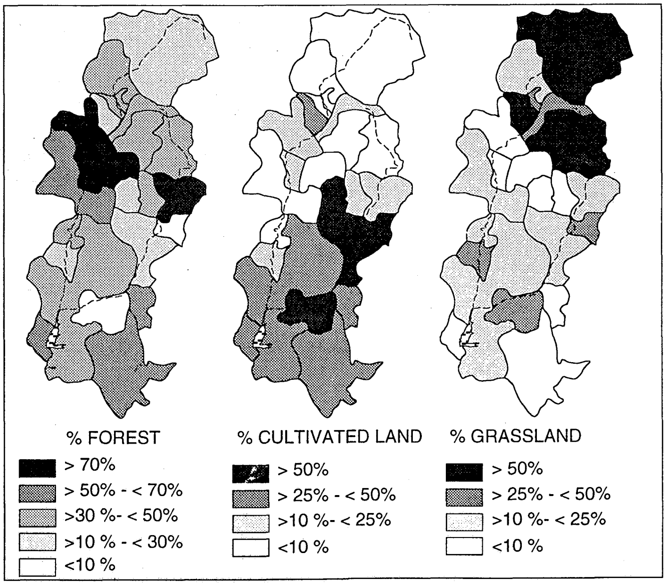

Fig. 4 Land use in the Ribagorza region (after Manrique *et al.*, 1987).

In the southern Esera basin, SSC values decrease (<500 mg l^{-1}) with no change in mineral composition. River bed sediment, however, contains more calcite and clay minerals, as the rivers pass through limestones and marls (Figs 1B and 3B). High sediment yield values would be expected as cultivated land has the highest percentages in the Esera basin (up to 50%). However the high forest cover (up to 50%) and other natural factors (lower slopes) could reduce sediment yields.

The Isábena River basin Suspended sediment concentrations are much lower in the Isábena River (up to 11 mg l^{-1}) than in the Esera River, and the mineral composition is characterized by a predominance of clay minerals (illite and chlorite) and calcite. Dolomite and quartz are less abundant. Kaolinite only occurs in the river bed sediment, and pyrophyllite is absent from all but one sample. The northern areas of the Isábena basin show the lowest SSC (1.4-1.7 mg l^{-1}). Mineralogy is dominated by illite (60%) and chlorite (30%) and the carbonate content is very low due to the mostly siliciclastic composition of the outcropping rocks. The large amount of chlorite and the increase in dolomite in one of the samples represents a response to the local occurrence of Jurassic dolostones and Lower Cretaceous sandstones and siltstones (Fig. 1B). The higher SSC value in the intermediate areas (11 mg l^{-1}) parallels a high calcite content in suspended (25-35 %) and bed load (almost 50%) sediment. Finally, suspended sediment concentrations in the southern part of the Isábena basin are lower (3.5-3.9 mg l^{-1}) and the calcite content slightly decreases, although the calcite content greatly increases in the river bed sediment (>50%). Compared to the Esera River, calcite clearly dominates the Isábena sediment in the southern areas of the basin. Although both rivers pass through the same geological formations, a lateral facies change (lacustrine carbonates are more abundant to the East; Riba, 1972) explains this mineralogical dissimilarity.

The good relationship between land use and the pattern of SSC values confirms human impact as a significant influence on sediment yield. The low SSC in the Upper Isábena River reflects the lower percentage of cultivated land (<10%), a relatively high forest cover (50-70% in the Laspaules sub-basin and >70% in the Internal Ranges) and the highest percentage of grassland (>50 %) (Figs 3B and 4). The highest SSC value occurs in the area of the Isábena basin with the highest proportion of cultivated land (>50%) low forest cover (10-30%) and grassland cover ranging from less than 10% to up to 50%. The intermediate values found in the southern part reflect the high proportion of cultivated land (50%), the lowest forest cover (<10%) and a large grassland range (10-50%).

Time and space variability and natural *vs* human impact

An attempt to identify sediment source areas has been made using distinctive minerals (feldspar, kaolinite, dolomite, calcite) as tracers. The presence of pyrophyllite characterizes floods that transport sediment from the headwaters of the Esera River. Our results agree with the critical sediment source areas identified by Fargas *et al.* (1996) using drainage density and lithology. The areas considered to be of low sediment production risk (Upper Esera and Isábena valleys) provided low SSC during the winter 1996 floods whereas the areas of severe risk (Internal Ranges) had the highest SSC values in both rivers. The southern areas considered to be of moderate risk correspond with intermediate SSC values.

Although physical factors such as topography, lithology and drainage patterns appear to exert a major control on soil erodibility, our study demonstrates the importance of human activity through changes in land use. However, most of the sediment load is transported to the Barasona reservoir during flood events, which underlines the importance of the hydrologic regime of the rivers. The observed intrabasin contrasts in sediment yield, and the inferred changes in erosion rate during the last decades, illustrate the variability of depositional processes in mountain basins. A better understanding of the temporal and spatial variability of depositional processes is needed for improved management of the limited soil and water resources and to reduce reservoir sedimentation problems.

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