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Variability of Sediment Yield from a High Mountain Catchment, Central Spanish Pyrenees

Bernardo Alvera

Instituto Pirenaico de Ecología, CSIC,
Apartado 64, 22700-Jaca, Spain.
balvera@aragob.es

José M. García-Ruiz

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

Abstract

The Izas experimental catchment is located in the high Gállego Valley, Central Spanish Pyrenees, in an environment strongly affected by the presence of snow during at least six months of the year. Discharge and sediment transport variability are closely linked to snowmelt and to intense autumn rainfalls. Following 11 yr of data collection, the seasonal and interannual variability of sediment transport has been estimated, as well as the relative importance of bedload, suspended sediment and solutes. The results obtained show that the total sediment yield is relatively low (between 200 and 320 t km^{-2} yr^{-1}) and that solutes represent more than 60% of the sediment exported. Bedload, which in other mountain catchments reaches a great quantity, represents here, in general, less than 30% of the total sediment yield. Seasonal and interannual sediment transport variability is very high, mainly depending on the intensity of autumnal rainfalls.

Introduction

A number of small and medium-sized catchments have been monitored in the last few decades in order to quantify runoff and sediment transport and to understand the functioning of the factors explaining their hydrological and sedimentological variability (i.e., Hayward, 1980; Caine and Swanson, 1989; Tropeano, 1991; Bogen, 1995; Batalla et al., 1995; Gintz et al., 1996; Rickenman, 1997; Lenzi et al., 1999). The nature of the sediments, including spatial and temporal variability, allow us to understand the functioning of natural and disturbed systems and to detect the existence of problems in environmental conservation.

Most monitored basins are located at low and medium altitudes (Walling, 1991), due to both accessibility and the interest of studying environments directly affected by human activities and land-use changes. Much less information exists on high mountain catchments, due above all to the difficulties of obtaining data on precipitation, runoff and sediment transport in winter and spring. High mountains are subject to a variety of geomorphic processes, especially those linked to freeze-thaw, debris avalanches, debris flows, and other mass movements, resulting in, generally, high rates of sediment yield and in the formation of specific deposition forms such as debris cones and alluvial fans (see, e.g., Caine, 1974; Barsch and Caine, 1984). Nevertheless, the link between sediment supply from hillslopes and valley-floor is not yet well understood, and little information exists on the relative proportion of different types of sediment exported (suspended sediment, solutes, bedload). With this in mind, a small catchment in the Spanish Pyrenees was instrumented in 1987 by the Pyrenean Institute of Ecology for studying the relationships between rainfall, water discharge and sediment transport. In this paper the interannual and seasonal variability of sediment transport is studied from 1987–88 to 1997–98, as well as the relationships between bedload, suspended sediment and solutes. We especially emphasize the variability of bedload, which is generally considered to be the main component of the sediment balance in mountain streams. Previous studies in the Izas catchment highlighted the temporal variability of the coarse sediment (Martínez-Castroviejo et al., 1991), the importance of solutes and their inverse relationship to the discharge (Díez et al., 1991) and, finally, the location of sediment sources during low-frequency events (Díez et al., 1988).

The Izas Catchment

The Izas catchment is located in the upper Gállego River valley, in the Central Spanish Pyrenees (Fig. 1), at an altitude which ranges between 2060 and 2280 m a.s.l. It has an area of 0.33 km², with steep gradients (between 25 and 30°) in the upper part of the catchment; gentle slopes prevail in the lower part, dominated by fluvial and colluvial sediments. Bedrock consists of densely fractured Carboniferous slates. The mean gradient of the ravine is 20% and the width is 1.10 m.

Solifluction is very active in deep soils in the middle and lower sections of shady slopes (Del Barrio and Puigdefábregas, 1987), while terracettes develop on the degraded soil of south-facing slopes (García-Ruiz et al., 1990). Nevertheless, terracettes do not seem to contribute to the sediment output because they are, in general, disconnected from the fluvial system. A dense and very steep gully system has developed on slates close to the western divide. This small area (1.5 ha) is the most important sediment source for the main channel (Díez et al., 1988).

Mean annual temperature is around 3°C. Total rainfall is 1900 mm and most of it falls between October and May. During the cold season all the precipitation in the Izas catchment falls as snow, which covers the catchment until June.

The whole catchment is located above the upper forest limit, artificially lowered during the Middle Ages in order to increase the extent of summer pastures (García-Ruiz et al., 1990). Subalpine and alpine grasslands cover most of the slopes. *Festuca eskia* occupies the drier areas, while *Nardus stricta* dominates the wetter ones (Del Barrio et al., 1997). Extensive summer pasturing is the only human related activity.

Equipment and Methods

The equipment used in the Izas catchment mainly consists of a gauging station (V-notch weir) with a pressure transducer

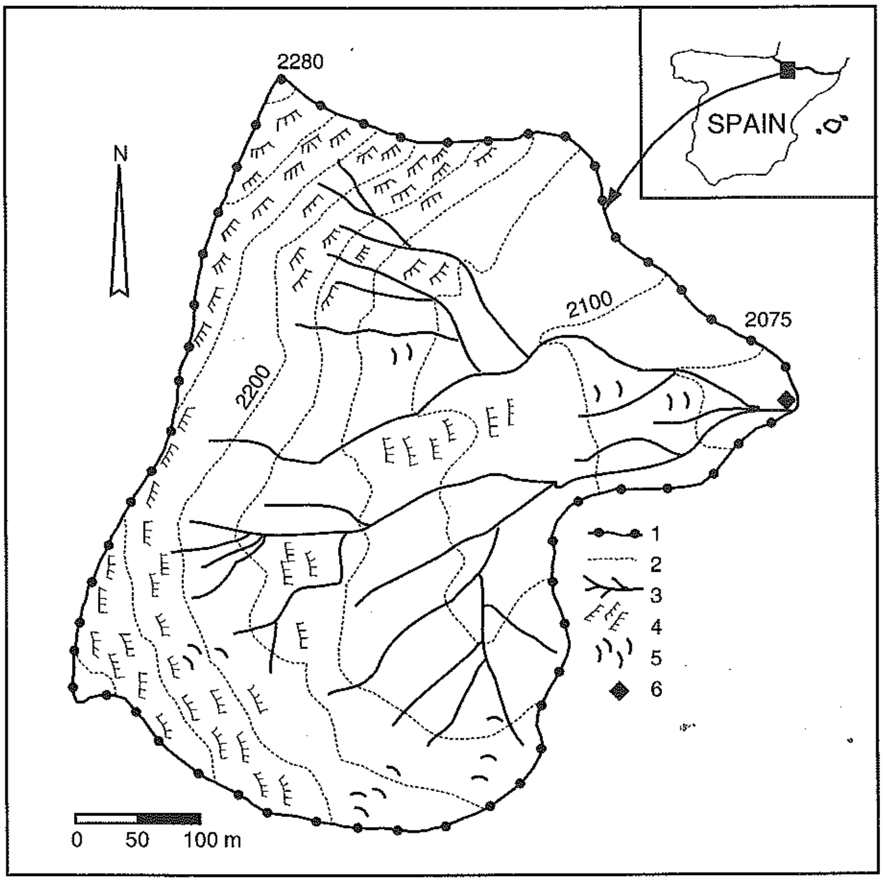

FIGURE 1. The Izas catchment. 1: Main divide. 2: Contour levels. 3: Fluvial network. 4: Terracettes. 5: Solifluction lobes. 6: Location of the measurement site.

and a thermistor recording the height and the temperature of runoff water. Sediment transport is monitored by means of a slot-trap for bedload, an automatic water sampler for suspended and dissolved solid concentrations, a conductivimeter, and a turbidimeter which after calibration allows the evaluation of suspended sediment concentration.

The bedload trap is a rectangular hole dug into the bed and lined with concrete. The approximate trapping capacity is 600 to750 kg, sufficient for collecting all the bedload carried out during a rainstorm, except in some infrequent events when the coarse sediment transport is so large that most of the gravel passes over the trap. Even in this case the problem is partially solved by the presence of a small dam just downstream of the trap. Periodically, mainly after heavy rainstorms and during snowmelt (May–June), the trap is emptied and the sediment weighed and sieved.

An automatic weather station records information on air temperature, relative humidity of air, global radiation, velocity and direction of wind, and precipitation.

Results and Discussion

MAIN FEATURES OF THE HYDROLOGIC REGIME

After 11 yr of study, the most important features of the hydrological regime are well known, in spite of several disturbances of the gauging station data logging. The evolution of water discharge through the hydrological year is typical of the Pyrenean high mountain rivers, affected by a strong influence of snow (García-Ruiz et al., 1985) (Fig. 2). During winter the discharge is very low and steady, since precipitation is retained in solid form. The progressive increase in temperature from the beginning of April causes a swift rise in discharge, which shows daily oscillations according to temperature fluctuations between day and night. Every day the hydrographs show a characteristic wave pattern (Alvera and Puigdefábregas, 1985; Puigdefábregas and Alvera, 1986) with gentle contrasts (Fig. 3). At the end of June the discharge is very low again, after the exhaustion of the snowpack.

From the the end of June the catchment is mainly free of snow, and discharge fluctuations are directly related to precipitation. This last period is characterized by very short and intense rainstorms in summer as well as heavy rainfalls of two or more days duration in autumn.

To summarize, three hydrologic periods can be clearly distinguished: (1) winter, with a very low and regular discharge; (2) spring, with high discharges during several weeks, and daily oscillations, thus confirming the strong influence of snow accumulation and melting; (3) the rest of the year, marked by fluctuations in the pluviometric regime (García-Ruiz et al., 1986).

SEDIMENT OUTPUTS

The period between 1987–88 and 1997–98 (with the absence of data in 1989–90) is insufficient for calculating reliable average values for sediment transport, due to its high interannual variability. However, a clear trend can be obtained with the available information.

Sediment outputs show important interannual variations. Table 1 includes information for the four best years of record. For the remaining there are some gaps in suspended sediment and solutes data, but they can be extrapolated due to their good relation to the discharge.

In years with high intensity and volume of precipitation,

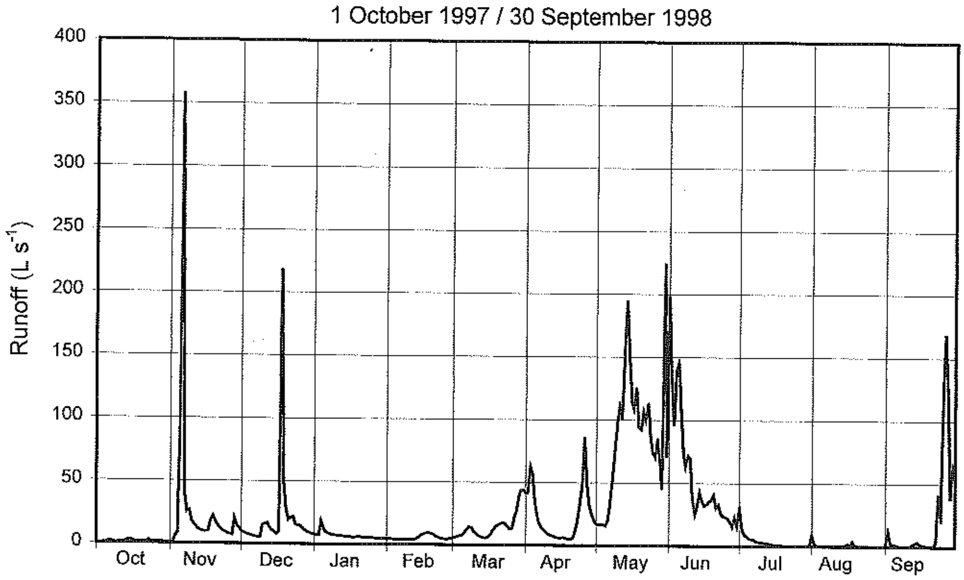

FIGURE 2. Daily discharge series in the Izas catchment during the hydrological year 1996–1997.

bedload can represent a very high proportion of the total sediment output. This is the case for 1987–88, when heavy rainfalls occurred in October 1987, during which around 17 t of coarse bedload (85% of the total) were weighed, while suspended sediment weighed 0.75 t and solutes were calculated in 2 t. (Díez et al., 1988). This is also the case for the year 1997–98, where a very stormy autumn explains the record of 23.3 t of bedload (25 t during the whole year), increasing the proportion of bedload until 23%. In these cases precipitation in 24 h (166 and 220 mm respectively) corresponds to a 10- and 150-yr return period.

In years without heavy, unfrequent rainstorms, bedload represents even less than 5% of the total sediment outputs, while solutes are around 80 to 85% and suspended sediment between 10 and 20%. Thus sediment transport for each type of sediment can show large ranges of variability:

- Solutes, between 60 and 85% of the total.
- Suspended sediment, between 5 and 20%.
- Bedload, between 1 and 30%.

An extreme event (such as that of October 1987) has many consequences in the sediment balance in the short term. Thus, although values of bedload outputs are most of the years under 20%, a low frequency event increases the average value very much. Likewise, mobilization of a great volume of coarse sediment during one intense rainstorm causes an exhaustion of bedload, in such a manner that a rainfall of similar intensity occurring only a few days later carries lower quantities of coarse sediment. In the case of October 1987, a first heavy rainfall transported 17 t of bedload, but a second rainstorm which occurred 1 wk later was only able to carry 0.48 t, in spite of a similar peak flow. The effect of exhaustion was apparent for several years, as Figure 4 suggests, because between 1988 and 1992 very low values of bedload were recorded in comparison to the rest of the study period. Nevertheless, it is important to take into account that during this period the intensity of maximum precipitation in 24 h was relatively low (Table 2). Exhaustion processes were already stated in the Torlesse basin, New Zealand, by Hayward (1980), who also emphasized the fact that most of the sediment was carried out only during few events.

The mean annual sediment transport is difficult to assess, due to the great variability of bedload, which depends not only on the intensity of autumn rainfalls but also on the availability of sediment in the fluvial bed. In 1988–89, without intense rain-

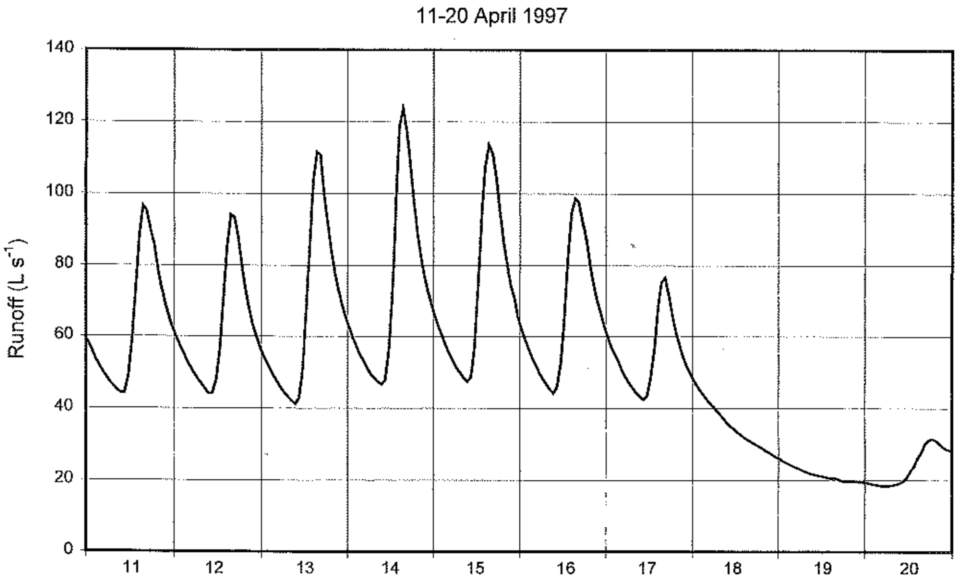

FIGURE 3. Hourly fluctuations of the discharge in the Izas catchment during 10 consecutive days in springtime (from 11 April 1997 until 20 April 1997).

TABLE 1

Sediment outputs from the Izas catchment in four selected years (in tonnes)

Hydrological year	Solutes	Suspended sediment	Bedload	Total
1992–93	56 (79%)	12 (17%)	3.3 (4%)	71.3
1993–94	60 (79%)	14 (18%)	2.3 (3%)	76.3
1996–97	60 (85%)	7 (10%)	3.3 (5%)	70.3
1997–98	69 (63%)	16 (14%)	25.0 (23%)	110

TABLE 2

Total and maximum 24-h precipitation (P) in autumn and summer

Hydrological year	Total P (mm)		Max. P in 24 h (mm)	
	Autumn	Summer	Autumn	Summer
1987–88	818	*	166	*
1988–89	265	*	73	*
1989–90	*	*	*	*
1990–91	455	*	60	*
1991–92	343	*	70	*
1992–93	626	405	90	103
1993–94	538	360	92	70
1994–95	632	287	167	70
1995–96	412	462	160	40
1996–97	359	532	70	93
1997–98	394	530	220	76
1998–99	158	730	26	150

* No data available.

storms in autumn, bedload represented 1% of the total sediment output. In 1992–93 bedload amounted to 4% of the total sediment yield. In the exceptional year of 1987–88 coarse material represented around 40%, while for 1997–98, with a very rainy autumn, a proportion of 23% was been obtained. Due to this variability, total sediments carried out oscillate in a broad range between 66 and 110 t yr^{-1}, with a sediment yield varying between 200 and 320 t km^{-2} yr^{-1}, for a catchment of 0.33 km^2.

THE SEASONAL VARIABILITY OF BEDLOAD TRANSPORT

The Izas catchment is characterized by an important seasonal variability of bedload outputs (Fig. 5). The snowmelt period includes April, May, and June. It also includes the coarse sediment transport measured during winter, the values of which can be considered as insignificant due to minimal discharges and the absence of fluctuations for several months. Available information on sediment transport during winter in 1987–88 and 1988–89 (75 and 10 kg, respectively) confirms that during the coldest season bedload transport is negligible. This is why the emptying of the sediment trap at the end of winter has not been considered so necessary, thus reducing the problems linked to winter and spring accessibility to the catchment.

The results obtained show that the contribution of each season to the bedload balance varies considerably from year to year. Snowmelt period is quite regular, with relatively low values: discharge, though at high levels, is unable to mobilize large quantities of bedload, because daily peak flows show a gentle increase. Furthermore, as snowmelt is a very regular hydrologic process year after year, there are no important interannual differences. In fact, in relative terms, snowmelt always contributes less than 16% to the annual bedload transport, and, in absolute terms, the figures of bedload outputs are always below 600 kg each year.

The hydrological behavior of the Izas River in summer and autumn depends on the intensity of rainstorms in each season. For most years bedload recorded amounts are greater in autumn than in summer. The reason for this behavior is that, in general, autumn rainstorms are more intense and longer than in summer (García-Ruiz et al., 2000) and, as a consequence, they produce hydrographs with higher peak flows. Furthermore, although some summer rainstorms can be very erosive and even catastrophic (White et al., 1997), they generally fall over dry soil. Exceptionally, during dry autumns, summer rainstorms become responsible for a greater proportion of gravel carried out. In contrast, summers with few rainstorms of low intensity show very low values of bedload transport.

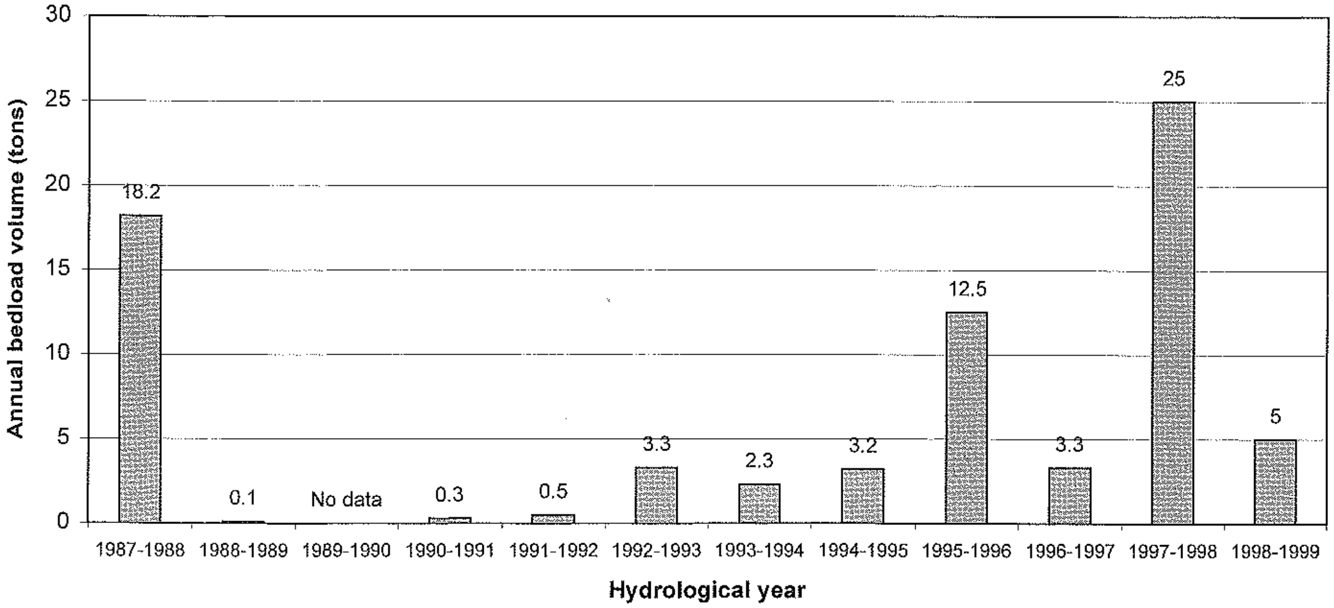

FIGURE 4. Bedload outputs from the Izas catchment between 1987–88 and 1997–98.

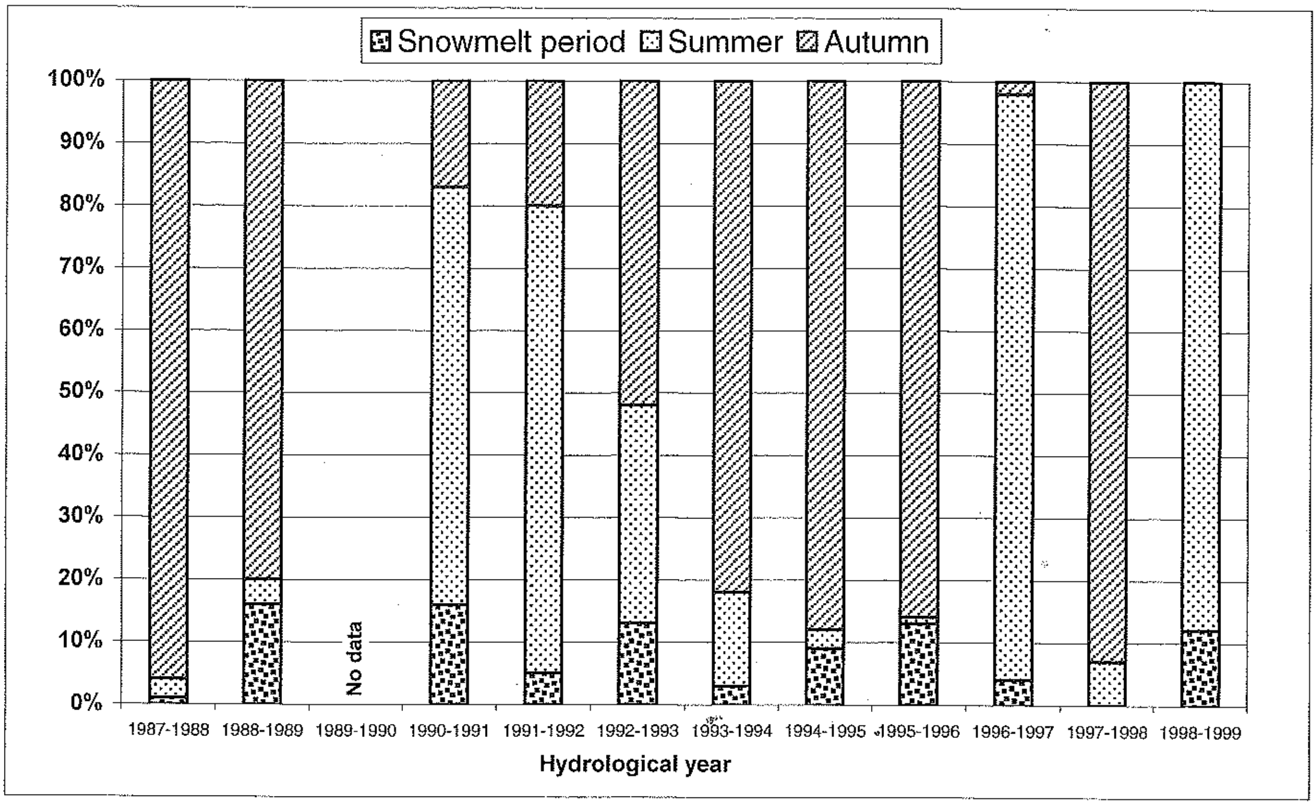

FIGURE 5. Seasonal distribution of bedload outputs.

The study of relations between rainfall and bedload transport in autumn shows that total precipitation in 2 mo (October–November) explains 59% ($r^2 = 0.59$) of the bedload amount (the correlation coefficient, $r = 0.77$, is significant at the 99% level). If maximum daily precipitation during both months is considered, the coefficient of determination reaches 88%. Finally, if the maximum precipitation corresponding to 24 consecutive hours is considered, then the coefficient of determination reaches 93% (Fig. 6). Then, only 7% of the bedload variability in autumn depends on other factors. Residuals are probably related to the time necessary for the retrieval of gravel in the channels.

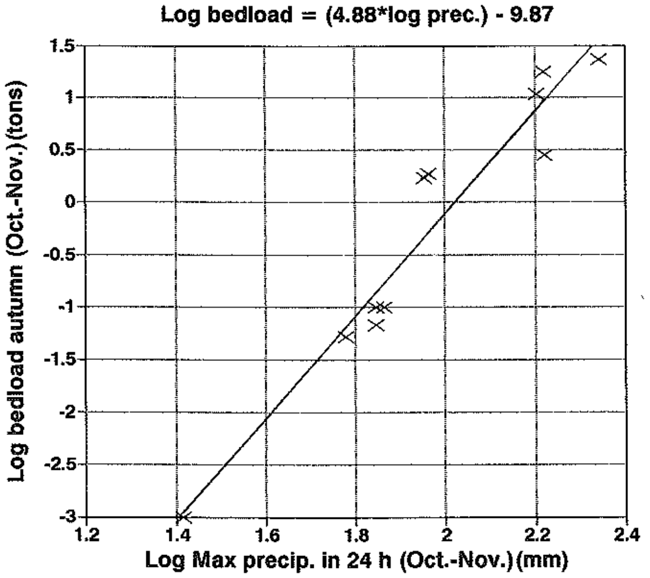

FIGURE 6. Relationship between maximum precipitation in 24 h (October–November) and total bedload carried out in autumn.

Most of bedload carried out ranges between 2 and 8 mm in diameter (*a* axis), representing around 60% of the total weight, while clasts of more than 30 mm in diameter rarely amounts more than 10% (Martínez-Castroviejo et al., 1991). However, grain size distribution also shows a high variability according to the intensity of peak flows. Thus, during the 13 October 1987 flood, clasts of more than 30 mm in diameter represented 13.6%, but only 1.4% during the 8 June 1988 flood ($D_{90} = 38$ and 13.7 mm, respectively).

SOLUTES

The study of solute outputs (both from electric conductivity and from water samples during floods) demonstrates that solute concentration is related to the volume of discharge. Thus, in the 1997–98 hydrological year ($r = 0.860$ for $n = 365$), an inverse relationship has been obtained between discharge and concentration of ions. However, not all the ions behave in the same way. Díez et al. (1991) demonstrated that the general pattern (more discharge equals less solute concentration) is only followed by solutes that come from the bedrock or the deeper soil horizons, such as sodium, magnesium and silica, and this is why they dilute with increasing discharge. The contrary occurs in the case of dissolved phosphorus concentrations. These rise with increasing streamflow, because phosphorus comes from the soil surface (litter and animal excrements), where it is directly taken by overland flow (Puigdefábregas and Alvera, 1986). The behavior of other solutes (potassium and nitrate) is very unstable, with no clear explanations.

Conclusions

The hydrological and geomorphological behavior of subalpine and alpine environments of the Central Spanish Pyrenees are relatively well represented by the Izas catchment. Most of the hillslopes of the catchment are covered by grasslands and the most active sediment sources occupy a very limited extent. Some of the most active, high mountain geomorphic processes are not represented (avalanches and debris flows), although this does not affect the outcome because in other Pyrenean valleys such processes tend to be partially or totally disconnected from the fluvial network. At present, human activities have hardly any hydromorphological significance (García-Ruiz and Valero, 1998).

The following conclusions can be stated from the previous results:

(1) Sediment transport shows great annual and seasonal variability, depending on the total precipitation and its intensity. For example, during the snowmelt period, bedload is hardly represented, while solutes play a very important role. In contrast, during the autumn bedload can be the dominant sediment carried out. The variability can be so great that a peak flow caused by a 30-min summer rainstorm is able to carry out more suspended sediment than that exported during the whole snowmelt period (Díez et al., 1988). Rickenmann (1997) suggests that this temporal variability is related to the limited availability of sediment, to the large grain size distribution and to the irregular channel geometry (see also Reid et al., 1985; Tacconi and Billi, 1987; Bogen, 1995; Lenzi et al., 1999).

(2) Solutes represent more than 2/3 of sediment outputs, thus suggesting the importance of the biological activity in alpine environments and, especially, the high weathering rate of slate. Solutes become almost the unique type of sediment exported during the snowmelt period. This result confirms that obtained by other authors in different environments (see Walling and Webb, 1986; Caine and Swanson, 1989; Llorens et al., 1997).

(3) Bedload represents, in general, less than 30% of sediment outputs in the Izas catchment. Its absolute and relative importance directly depends on the intensity of autumn rainfalls. When rainfall events are relatively infrequent (more than 10-yr return period), then bedload represents a very important part of sediment yield, as in the 1987–88 hydrological year. Nevertheless, after an exceptional event, bedload shows clear depletion signs, confirming the great uncertainty of all the equations for bedload prediction (Gomez, 1987). It is important to note that in most of the catchments studied, bedload shows a great variability in relation to total sediment outputs. Thus, Lenzi et al. (1989) report that in mountain rivers the proportion of bedload ranges between 10 and 80% (e.g., Milhous and Klingeman, 1973; Hayward, 1980; Bathurst et al., 1987; Gomez, 1987; Whittaker, 1987; Batalla et al., 1995), while in lowland rivers it ranges between 5 and 20% (Walling and Webb, 1981, 1987), and even less in catchments occupied by agricultural terraces (Llorens and Gallart, 1990; Llorens et al., 1992, 1997).

(4) Total sediment yield varies between 66 and 110 t yr^{-1}, resulting in a rate of 200 to 320 t km^{-2} yr^{-1}. From a worldwide perspective, values of sediment yield from catchments vary between 2 t km^{-2} yr^{-1} (and even less) and more than 10,000 t km^{-2} yr^{-1} (Walling, 1991). For mountain rivers, variability is also very high, depending on catchment size, lithology, channel characteristics and dominant geomorphic processes. Duck and MacManus (1994) reported a mean value of 50.9 t km^{-2} yr^{-1} from sediment accumulated in a reservoir of western Scotland: In the case of the Torlesse catchment (New Zealand), Hayward (1980) reported a mean sediment yield of 30 t km^{-2} yr^{-1}. Values estimated for the Izas catchment are somewhat higher, probably due to the good integration of the small badland area into the fluvial network, and also to the intensity of summer and autumn rainstorms.

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