Pirineos, **135**: 39 a 54, JACA, 1990

BED LOAD SIZE DISTRIBUTION AND FLOW CONDITIONS IN A HIGH MOUNTAIN CATCHMENT OF CENTRAL PYRENEES[1]

RICARDO MARTÍNEZ-CASTROVIEJO*

SUMMARY.- The bed load size distribution caused by different types of flow are compared in a high mountain catchment located in the upper Gallego river basin (Central Spanish Pyrenees). Three kinds of hydrologic events could be defined: those triggered by heavy autumn rainfalls, those originated by isolated summer rainstorms and those promoted by snowmelting. Each one is characterized by a peculiar bed load size distribution. Thus, it could be demonstrated that the coarser fractions, above 30 mm in diameter, are up to six times more abundant, in percentage of total weight, in transports caused by heavy rainfalls than in the material collected after snowmelt flows. In its turn, bed load mobilized by snowmelt flows is mainly composed by medium and fine gravel, from 2 to 8 mm. These may amount up to 60 % of total weight of bed load. The reasons for these so different size distributions are discussed.

RESUMEN.- En una cuenca de alta montaña localizada en el alto valle del río Gállego (Pirineo central) se comparan las distribuciones por tamaños de los acarreos movilizados por diferentes tipos de caudal. Tres tipos de eventos hidrológicos han podido ser caracterizados: los ocasionados por intensas lluvias de otoño, los originados por tormentas estivales aisladas y los producidos por la fusión de la nieve acumulada durante el invierno. Se concluye que cada uno de ellos lleva asociada una distribución por tamaños típica de la carga de fondo. Así, se ha comprobado que las fracciones más gruesas consideradas -superiores a los 30 mm. de diámetro- son hasta seis veces más abundantes -en porcentaje sobre el peso total- en las exportaciones causadas por lluvias de gran intensidad que en las generadas por caudales de fusión. A su vez, las descargas ocasionadas por la fusión arrastran principalmente gravas de calibre medio y fino -entre 2 y 8 mm- que llegan a suponer el 60 % en peso del volumen movilizado. Este artículo discute las razones que provocan tales desigualdades en la composición granulométrica de la carga de fondo.

---

* Instituto Pirenaico de Ecología. Campus de Aula Dei. Apdo. 202 ZARAGOZA.

[1] Received December, 1990.

RÉSUMÉ.- Dans un bassin de haute montagne placé sur le Haut Gállego (Pyrénées aragonaises) on mis en rapport la distribution por tailles de la charge de fond mobilisée par divers types de débit. Nous avons caracterisé trois types d'épisodes hydrologiques: en relation avec les precipitations les plus intenses de l'automne, avec quelques orages d'été et avec la fonte des neiges. Chaque épisode hydrologique est en rapport avec une distribution por tailles de la charge de fond. Ainsi, nous avons observé que les graviers les plus grossières considerées (> 30 mm) ils sont jusqu'à six fois plus abondantes -en % sur les poids total- dans les exportations occassionnées par précipitations très intensives que dans les occassionnées par débits de la fonte. Après, les exportations occassionnées par la fonte de la neige sont en rapport avec le transport de graviers de taille moyenne -comprise entre 2 et 8 mm-, ce que suppose jusqu'à le 60 % en poids du volume mobilisé.

Key-words: *Bed load transport, bed load composition, flow conditions, Central Pyrenees.*

From a geoecological point of view, rivers are a reliable basis source for understanding the overall functioning of ecosystems incorporating geologic, geomorphologic, biogeographic and human activity information (MARTINEZ-CASTROVIEJO, 1989). Generally, the connection between river state and morphology and its environment is quite clear, particularly in mountain basins where events follow one another swiftly and where the drainage channels have available excess of energy to adjust themselves quickly. A great part of the information supplied by a river system can be extracted from the volumetric and temporal analysis of one of the consequences of such a functioning, that is, the sediment transport.

Most of authors agree that bed load transport processes are complex (KLINGEMAN & EMMET, 1982; BILLI & TACCONI, 1987; BATHURST, 1987). The recent literature on fluvial geomorphology devotes many pages to the improvement of sample techniques and analysis of the transported material, especially of the bed load (e.g. LEOPOLD & EMMET, 1976; KLINGEMAN *et al,* 1979; EMMET, 1979; KLINGEMAN & EMMET, 1982; TACCONI & BILLI, 1987; CHURCH *et al,* 1987; HUBBEL, 1987 etc.) The development of these techniques has been the main source of advances known in the theory of fluvial transport throughout the last ten years. Thus, some of the mechanisms that govern the sediment transport can be described (JACKSON & BESCHTA, 1982; CARLING, 1987) as well as the implications of bed state and bed morphology for sediment mobility (WHITE & DAY, 1982; HAYWARD, 1980) and other aspects of the transport itself, such as the sediment movement in pulses (REID *et al,* 1985; SCHICK *et al,* 1987). Nevertheless, the most common application of this new knowledge is the establishment of sediment budgets at the catchment scale (e.g. TRIMBLE, 1983; ROBERTS & CHURCH, 1986; DUIJSINGS, 1987).

Although most of efforts have been centred on getting the quantity of material mobilized under certain channel and basin conditions, little attention has been paid to sediment quality. The assessment of bed load composition and their relation to flow conditions must complete present knowledge on transport processes and mechanics. The main problem for assessment is the need for a wide range of flows. High mountain catchments offer this best, with autumn floods, spring snowmelt discharges and base flow in winter, and this work has been carried out in one of them: the Izas catchment. In a former paper, (MARTINEZ-CASTROVIEJO *et al,* in press), the general features of the total bed load transport at Izas were stated; now, our objective is to look for seasonal contrasts in the size distribution of bed load and to explain them according to the hydrologic behaviour of the basin.

1. Study area

The Izas catchment is located in the upper Gallego river valley, in the Spanish central Pyrenees (Fig. 1). It has an area of 0.22 km^2; its lowest point is sited at 2,060 m. a.s.l., and the highest point is sited at 2,280 m a.s.l. Bedrock consists of densely fractured Carboniferous slates. In its upper part, the basin is drained by a dense and very steep gully system. Mass movements are the dominant processes: solifluction, formation of terracettes and soil creep. Terracettes are common on degraded soils of sunny slopes whose gradients range from 25 to 30°, while solifluction lobes are present on deeper soil areas in the middle and lower sections of shady slopes (GARCIA-RUIZ & PUIGDEFABREGAS, 1982; DEL BARRIO & PUIGDEFABREGAS, 1987). Although these landforms are still very active, they do not appear to contribute to the sediment output because they are disconnected from the fluvial system. The network has a high density (16 km km^{-2}, DIEZ *et al,* 1988). Along the channels, bedrock reaches alternate with alluvial reaches, where the channel erodes older fan deposits.

The mean annual temperature of the basin is around 4°C and total rainfall is over 1600 mm. In winter, the whole basin is enclosed by the 0° C winter isotherm, so precipitation in that season, which is the most important of the year, falls as snow (GARCIA-RUIZ *et al,* 1985). Above the tree line, alpine grasslands cover most of the slopes. *Festuca eskya* occurs on drier slopes and *Nardus stricta* in the wetter areas. Low density summer pasturing of sheep and cattle is the only human activity.

2. Equipment and methods

Izas catchment is equipped with a gauging station consisting of a pressure transducer connected to a data logger, several rain gauges, a propane heated snow gauge, an autographic rain recorder and a lot of thermometers connected to the data logger. Sediment transport is monitored by means a slot-trap for bed load and an automatic water sampler for suspended and dissolved solids concentration. The bed load trap is simply a cube dug in the bed of the stream and lined with concrete. The approximate trap capacity is 1,000 kg which normally is enough to trap the total bed load movement during individual flood events. Its capacity was exceeded during one exceptional event. On that occasion, bed load was deposited in the stilling area of the gauging station which is just downstream of the trap.

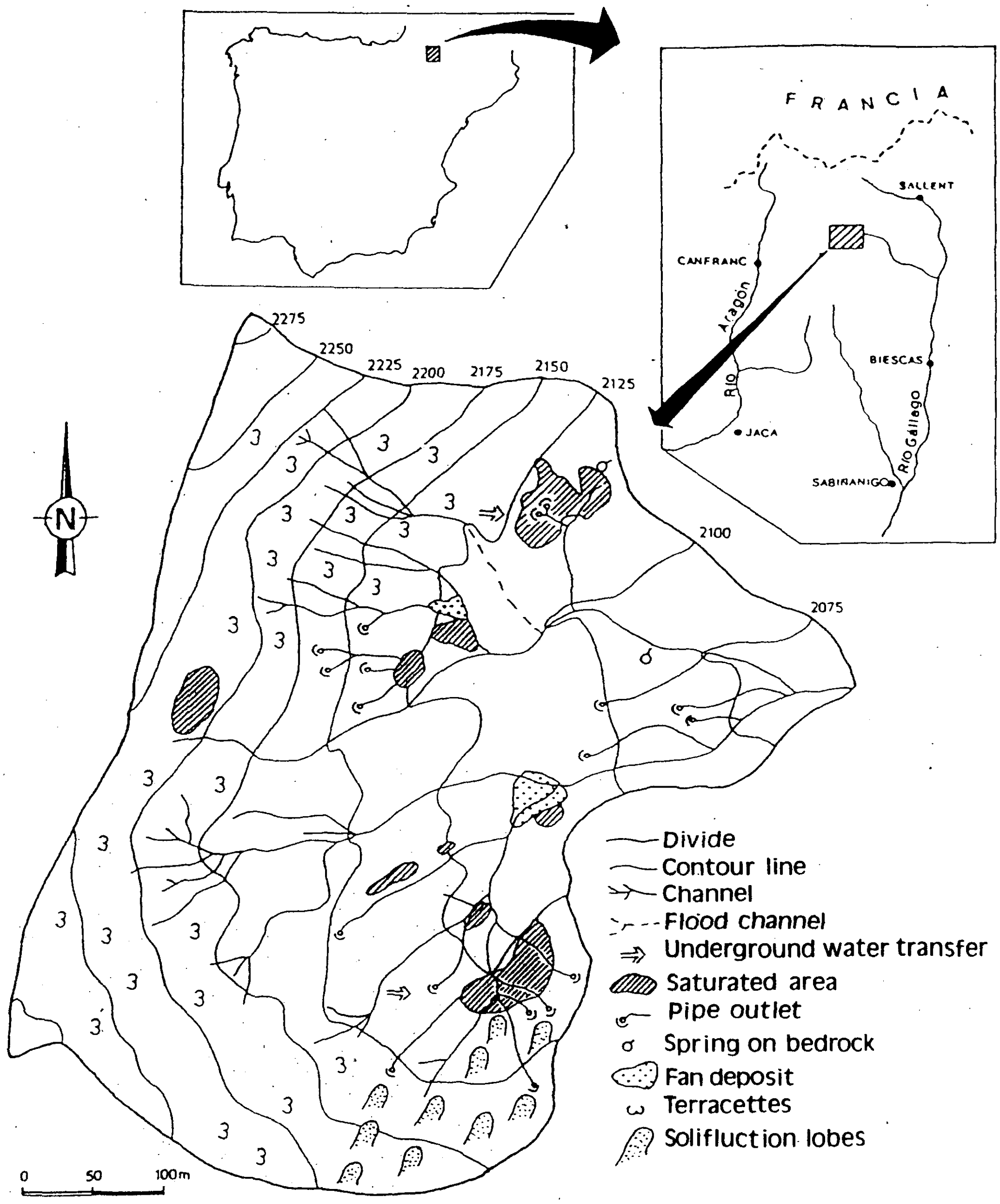

Fig. 1. The Izas catchment study area.

Periodically, mainly after heavy rainstorms and during the snowmelt (May-June), the trap was emptied and the volume of sediments weighed. If the volume obtained was not very large (less than 100 kg), all of it was taken to the laboratory for analysis. For more than 100 kg a proportional sample was obtained. In the laboratory, we sieve the bed load material to obtain the size distribution. In some cases, all particles with diameter below 0.5 mm have been rejected because it was believed that they were related to suspended sediment transport rather than to bed load; their deposition in the trap may be caused by energy losses created by the trap itself. We have available information from October 1987 to June 1989, although during the winter, with the basin completely covered by a snow mantle up to 4 m thick, there was virtually no water discharge and it was not possible to empty the trap. Thus, all the material transported during the winter is grouped in the first sample obtained in spring (in the middle of May).

Table 1 summarizes the most outstanding climatic and hidrological aspects of the sixteen recorded events throughout the study period. Disturbances to the gauging station data logging were associated with electrical storms, causing a break in the water discharge data series, but rainfall characteristics and distribution help us to interpret the hydrologic regime.

TABLE 1.
Hydrological and climatic conditions of the recorded events.

Date of collection	Lenght of the period (days)	Total rainfall (mm)	Maximum rainfall (1) (mm)	Mean discharge (l/s)	Maximum discharge (l/s)	Total bedload (kg)	Type of event
1-13 October 1987	13	392.5	133	109.7	832	≈17,000	A
21 October 1987	8	295	129	197.1	616.6	476.8	A
19 May 1988	211	Snow	Snow	96.1(2)	165(2)	70.9	S
1 June 1988	12	74	18	131.7	220	24.9	S
8 June 1988	7	6.7	6.7	130.7	190	41.0	S
22 June 1988	14	167.4	40	121.3	240	41.9	S
7 July 1988	15	228.5	95	180*	600*	435.3	A
27 July 1988	20	37	35	19.3	21(3)	13.5	A
19 August 1988	23	62	31	2*	10*	58.5	A
7 September 1988	19	26	23.6	1.2*	4.5*	1.1	Ss
13 October 1988	36	67.7	35	0.6*	10.2	1.1	Ss
25 October 1988	12	121.4	66	21.5*	75	26.4	A
10 November 1988	16	93	68.2	13.4	95	72.3	A
16 May 1989	187	Snow	Snow	97.5(2)	173.8(2)	9.9	S+A?
8 June 1989	23	87.7	23	83.2	162.2	7.6	S
15 June 1989	7	36.8	14.3	41.3	50.0	2.6	S

A: heavy rainfall
S: snowmelt flow
Ss: isolated summer storm
(1) In 24 hours
(2) Since May,1
(3) Rainfall peak in the middle of the snowmelt flow falling-limb. First day of the period: 63.1 l/s.
* Estimated data.

TABLE 2.

Size distribution of bed load (as percentage of total by weight). For hydrological considerations of events, see Table 1.

FRACTIONS	13-X-87	21-X-87	19-V-88	1-VI-88	8-VI-88	22-VI-88	7-VII-88	27-VII-88
>30 mm	13.590	10.090	2.760	1.710	2.780	1.360	8.870	6.200
15-30	16.250	14.330	9.930	7.610	11.400	12.080	16.230	10.140
8-15	13.980	13.600	14.090	11.980	14.600	16.080	13.720	11.710
4-8	26.130	29.070	32.650	34.350	27.650	27.590	26.500	28.830
2-4	18.780	21.200	26.920	30.780	25.070	26.930	21.570	25.440
1-2	8.400	8.780	10.970	11.910	14.790	13.540	10.110	13.130
0.5-1	1.850	7.870	1.940	1.310	2.970	2.750	2.160	3.660
0.25-0.5	0.498	0.489	0.350	0.190	0.470	0.420	0.470	0.710
0.125-0.25	0.203	0.193	0.102	0.060	0.102	0.111	0.132	0.105
0.063-0.125	0.131	0.136	0.076	0.039	0.065	0.060	0.086	0.027
< 0.063	0.187	0.240	0.222	0.055	0.100	0.083	0.143	0.027
T.B.T.	17,000,000	476,800	70,899	24,944	41,037	41,954	435,300	13,460

FRACTIONS	19-VIII-88	7-IX-88	13-X-88	25-X-88	10-XI-88	16-V-89	8-VI-89	15-VI-89
>30 mm	5.130	0.000	3.950	6.460	3.280	12.540	1.530	2.010
15-30	9.410	11.970	14.220	11.070	11.830	10.640	8.110	10.980
8-15	11.950	9.500	9.760	12.650	13.050	9.280	9.790	9.360
4-8	29.730	26.440	26.030	27.790	28.830	24.470	30.400	30.600
2-4	27.880	26.030	23.420	25.620	27.400	27.780	36.540	28.980
1-2	12.490	18.120	16.550	13.030	12.250	13.680	12.050	15.180
0.5-1	2.700	6.220	4.960	2.740	2.500	1.430	1.380	2.470
0.25-0.5	0.472	1.450	0.790	0.416	0.457	0.118	0.126	0.304
0.125-0.25	0.122	0.130	0.139	0.093	0.156	0.023	0.032	0.050
0.063-0.125	0.059	0.046	0.056	0.047	0.098	0.012	0.016	0.035
< 0.063	0.058	0.084	0.121	0.084	0.096	0.034	0.033	0.038
T.B.T.	58,466	1,076	1,076	26,424	72,260	9,945	7,603	2,602

T.B.T.: Total bed load transported (in gr).

3. Bed load size distributions

Bed load size distributions are a very good reference to assess the flow conditions that promoted their transport. Every particle of bed material responds to different initial motion thresholds clearly realted to particle size. This relationship is expressed in the Shields formula (SHIELDS, 1936):

$$\tau = 0.06\,(\gamma_s - \gamma)\,d \qquad \text{(equation 1)}$$

where

τ: shear stress ($N.m^{-2}$)
γ_s: specific weight of sediment particle ($N.m^{-3}$)
γ: specific weight fo water ($N.m^{-3}$)
d: particle diameter (mm)

When the shear stress supplied by discharge exceeds largely the critical value, particle may reach a new threshold and it leaves off contacting frequently with bed to be carried in suspension. Only between these two thresholds material behaves as bed load and falls into the trap. Table 2 shows the size distributions obtained in all transport events. Figure 2 shows the evolution of the most significant fractions together with hydrographs, total bed load and daily rainfall throughout the study period.

A simple statistical approach reveals very interesting aspects. A coefficient of variation for each fraction has been used to describe its susceptibility to vary in different events. The results can be seen in Table 3. Lowest values are registered for fine and very fine gravel (2-4 and 4.8 mm) while coefficients of variation increase towards both extremes of the series. The most unstable sizes on flow conditions appear to be the extreme ones. Differences between typical size distributions according to magnitude of events will be reflected by these size fractions.

TABLE 3.
Coefficient of variation of the most significative size fractions.

FRACTIONS	Mean	St. dev.	CV (%)
> 30 mm	5.10	4.20	82.353
15-30	11.60	2.50	21.552
8-15	12.10	2.00	16.529
4-8	28.60	2.60	9.091
2-4	26.30	4.10	15.589
1-2	12.80	2.60	20.313
0.5-1	2.70	1.30	48.148

Another analysis consisting of affinities and incompatibilities between fractions helps to relate them to flow conditions. To obtain such behaviours, a matrix correlation of percentages of total for every fraction has been carried out (Table 4). Correlation coefficients are not as important as sign. A direct correlation implies affinity between fractions, a tendency to be mobilize with the same type of flow. On the contrary, inverse correlations mean incompatibility, so increasing percentages in one fraction imply decrease in the other. Table 4 shows that all fractions correlate positively with the nearest in the series, but they lose their affinity towards more and more unlike sizes. More specifically, coarsest particles, above 8 mm, behave in a rather similar way to the smallest ones, while medium sizes correlate negatively both with coarse and small material. This can be graphically followed in Figure 2.

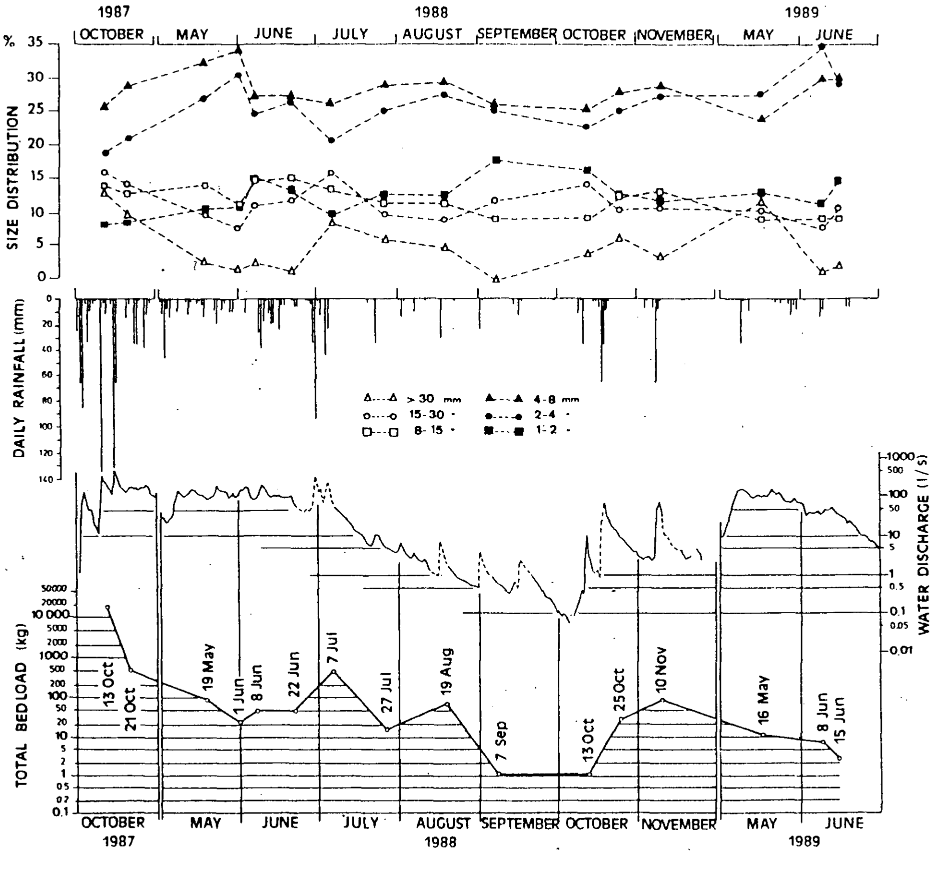

Fig. 2. Total bed load, water discharge and size distribution of bed load throughout the study period (winters excluded). Long periods in which the trap remained empty are not plotted. Dashed line: estimated data.

TABLE 4.
Correlation matrix between the different size fractions considered.

FRACTION	> 30	15-30	8-15	4-8	2-4	1-2	0.5-1	0.25-0.5	0-125-0.25	0.063-0.125	< 0.063
> 30 mm	1.000	.543	.147	-.499	-.608	-.590	-.374	-.219	.330	.420	.344
15-30	.543	1.000	.317	-.643	-.872	-.255	.194	.331	.739	.703	.605
8-15	.147	.317	1.000	.099	-.453	-.573	-.297	-.153	.518	.662	.573
4-8	-.499	-.643	.099	1.000	.520	-.224	-.380	-.364	-.268	-.095	-.012
2-4	-.608	-.872	-.453	.520	1.000	.283	-.225	-.386	-.798	-.737	-.656
1-2	-.590	-.255	-.573	-.224	.283	1.000	-.752	.511	-.368	-.627	-.550
0.5-1	-.374	.194	-.297	-.380	-.225	.752	1.000	.928	.257	-.117	-.103
0.25-0.5	-.219	.331	-.153	-.364	-.386	.511	.928	1.000	.472	.133	.110
0.125-0.25	.330	.739	.518	-.268	-.798	-.368	.257	.472	1.000	.907	.714
0.063-0.125	.420	.703	.662	-.095	-.737	-.627	-.117	.133	.907	1.000	.846
< 0.063	.344	.605	.573	-.012	-.656	-.550	-.103	.110	.714	.846	1.000

The affinity of some of the size distributions is not inconsistent with flow conditions. Such affinities allow us to gather the distributions in three groups: that of bed load triggered by major hydrological events, that tiggered by the minor ones and that by snowmelt flows (Table 5). Only one event remains outside of this classification: that of May 16th, 1989, whose size distribution is very far away from the group in which it should be. No doubt, such a bed load is related to more than one type of flow, rainfall peaks in the last days of autumn 1988 and snowmelt discharges during spring 1989.

TABLE 5.
Mean bed load composition for the 2-year period and for the groups typified according to flow conditions.

	Period	Period (1)	Heavy rainfalls	Summer storms	Snowmelt flows
> 30	13.184	7.086	13.301	1.975	2.260
15-30	16.084	13.880	16.145	13.097	10.360
8-15	13.946	13.500	13.950	9.630	13.900
4-8	26.287	28.360	26.244	26.235	30.550
2-4	19.083	23.090	18.990	24.729	27.440
1-2	8.537	10.350	8.490	17.335	12.600
0.5-1	1.870	2.140	1.866	5.591	2.240
0.25-0.5	.495	.460	.497	1.120	.359
0.125-0.25	.199	.148	.200	.135	.091
0.063-0.125	.129	.098	.129	.051	.066
< 0.063	.186	.168	.186	.102	.133

(1) Mean of the period excluding the extraordinary event of 13 October, 1987.

Table 5 shows mean size distributions for the three groups. It has been carried out with absolute amounts of each fraction. Annual mean has been obtained in the same way. The annual mean excluding the flash flood of October 13th, 1987 is also shown in Table 5 and it proves how an extraordinary event may affect the whole study period. Both averages include the bed load collected on May 16th, 1989.

Figure 3 presents the cumulative curves corresponding to the mean size distributions. Those corresponding to bed load transport caused by heavy autumn rainfalls, on the one hand, and by isolated summer storms, on the other, are a substantial distance apart at all times. Coarser materials are less important in the minor events, as shown by a displacement to the left. The bed load caused by snowmelt discharges follows an intermediate way between the former two. In the coarser fractions it is very close to that of the isolated summer rainstorms, but reaching the fines it leaves this curve to behave similarly to the major events. The evolution of these three patterns confirm the existence of three kinds of bed load closely related to the type of flow that originated them.

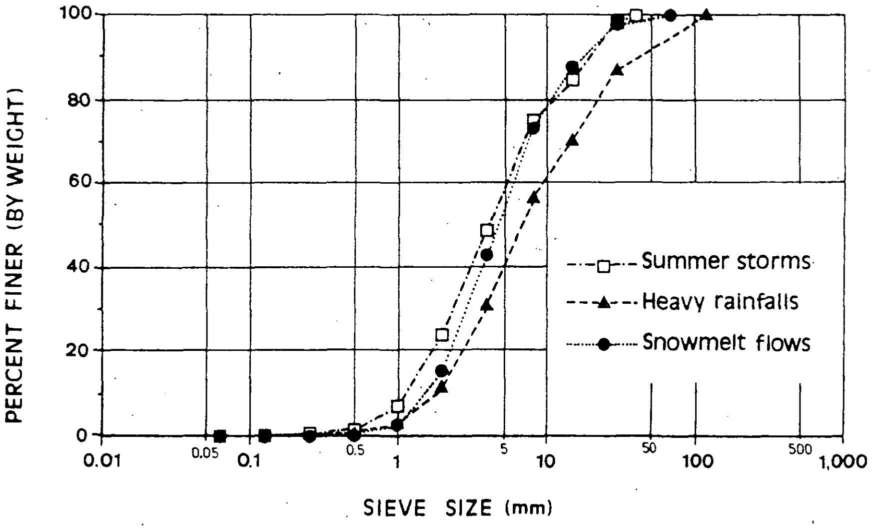

Fig. 3. Comparison of cumulative curves corresponding to the three kinds of typified events.

4. Water discharge and bed load size distribution

Results obtained with the coefficient of variation of each size fraction and the analysis of the affinities and incompatibilities between them may be applied to the size distributions. So, patterns of mobility for different sizes in every kind of event are achieved and related to the type of hydrograph.

Coarser fractions, and more specifically that >30 mm, account for low percentages of the total transported material throughout the whole study period. They are markedly more abundant in those events caused by heavy rainfall. In that cases, sizes above 8 mm may amount up to 44 % by weight of total, 13,3 % for the >30 mm fraction. On the contrary, particles reaching 30 mm in diameter are absent in isolated summer events, with values below 4 % of total. Similar amounts are recorded for snowmelt flows, never reaching 3 %, while sizes above 8 mm only average 26 % of total by weight.

The movement of the coarsest particles appears to be related to the same mechanisms that trigger the greatest bed load transports. Figure 2 shows how the evolution of the >30 mm size fraction is almost parallel to that of the total bed load, at least throughout most of the study period.

Shields critical shear stress (eq. 1) is a direct relationship of the particle diameter. So, the shear stress required to put in motion the coarse particles is the highest one. Such a threshold can be surpassed only by the energy gradient created by flash floods and the peak discharge that accompanies them. The same explanation applies to the low percentages of coarse mateial in snowmelt flows and minor summer events: the rise in discharge is too small to reach the shear stress required by the largest sizes.

On the other hand, medium sizes (from 2 to 8 mm) account for most of bed load in all samples. It can be deduced that their movement is guaranteed with any kind of flow; these size fractions exhibit the minimum coefficients of variation throughout the study period. Nevertheless, the massive entrainment of fine and very fine gravel seems to be related to snowmelt flows, when they may represent up to 65 % of total, with and average value of 58 %. Events caused by summer and autumn rainfalls amount for 45 % and 51 % on average respectively. Minor pulses of meltwater during snowmelt, which are unable to mobilize great quantities of coarse and medium gravel, can entrain smaller materials in a massive manner because of relatively high discharges. The recurrence of these minor peaks throughout the snowmelt period, some of them promoted by rainfall with peak discharges lowered by snow mantle absorption, provides the energy gradient enough to put in motion that sizes.

In rainfall events, the greater presence of other size fractions, mainly coarser, reduces the percentages of medium sizes, though they are still the majority.

The smallest sizes, less than 2 mm in diameter, are the minor part in all the distributions. They define events caused by isolated summer rainstorms because of their increased presence in bed load, which may be up to 24 % of total by weight. Those less than 1 mm amount 7 % as contasted with 2.9 % in the other two kind of flow conditions.

It is raher amazing to see how particles below 0.25 mm are more abundant in bed load associated with heavy autumn rainfalls than in any other type of event. Moreover, they are almost absent during snowmelt discharges. In both cases, flow conditions appear to be the responsible. In the rising-limb of a hydrograph, most of these particles are carried by flow in suspension. However, such a peak implies a falling-limb and, in consequence, the vertical components of flow turbulence disappear. So, suspended material begins to become bed load. This moment may be dalayed because particles keep some inertia in the manner that the stress required to keep them in motion is less than that to initialize it (LEOPOLD *et al,* 1964). Deposition related to the decrease in discharge may take days.

On the other hand, the former mechanics does not occur in snowmelt flows. Once in motion, the smallest sizes are suspended load. The lag of sharp falling-limbs in the hydrograph together with high discharges maintained through several weeks avoid their deposition into the trap.

5. Explanation and conclussions

Differences in bed load size distributions depending on the type of flow are explained according to inherent characteristics of transport processes and sediment supply. This is clear analyzing attributes and consequences of snowmelt and rainfall flows in a high mountain catchment. Thus, major flows are commonly caused by snowmelt, but larger bed load transport events, with higher percentages of coarse gravel, occur when autumn rainfalls promote sudden peak flows in a few hours or even minutes. KLINGEMAN and EMMET (1982) argued that such an inconsistent relation between water discharge and bed load transport lies in great spatial variabilities in the availability of transportable bed material along a river's longitudinal axis. No doubt, bed material composition and organization disturb sediment transport processes in ways still under study. Nevertheless, other reasons must also be taken into account to explain such great variations in size distribution depending on flow origin. The similar distributions within each of the three groups defined above allow us to state that major differences are due to hydrologic conditions rather to changes in bed state, this being in part responsible for the within group variation. Coarse gravel mobilization is related not only to absolute water discharge, but also to the energy gradient created in the rising-limb of a flood peak. Thus, the initial motion of the coarsest fraction coincides with the shock wave of the flood.

On the other hand, sediment supply plays an important role in the total bed load transport. Some authors have pointed out the seasonal and interstorm variations of bed load, especially in rivers dominated by snowmelt regimes (BATHURST, 1987). According with that, erosion by overland flow during autumn rainstorms supplies an additional amount of sediment to the channel, which does not occur during a snowmelt flood. However, once into the main channel, stream power selects the material liable to be transported, remaining the rest stored in variable size and morphology depositional features. In fact, an increase in the supply of a given size fraction (e.g. coarser than 30 mm) from the slopes does not imply *per se* an increase in its percentage on total bed load.

Acknowledgements. The author would like to thank Dr. J. A. A. Jones, from the Institute of Earth Studies, Aberystwyth (Wales) in reviewing the manuscript and discussing the results. The work was funded by the research project "Channel dynamics in central Pyrenees" and ultimately supported by the Spanish Institute for Nature Conservation through the major programme LUCDEME.

References

BATHURST, J. C. (1987).- Measuring and modelling bedload transport in channels with coarse bed materials. In: RICHARDS, K. S. (Ed.) *River channels. Environment and Process,* Institute of British Geographers, Oxford. 272-294.

BILLI, P. & TACCONI, P. (1987).- Bedload transport processes monitored at Virginio Creek measuring station, Italy. In: GARDINER, V. (Ed.) *International Geomorphology 1986.* Proc. 1 st. Conference. Part. 1 Wiley. 541-547.

CARLING, P. A. (1987).- Bed stability in gravel streams, with reference to stream regulation and ecology. In: RICHARDS, K. S. (Ed.) *River channels. Environment and Process,* Institute of Britsh Geographers, Oxford. 321-347.

CHURCH, M. A.; McLEAN, D. G. & WOLCOTT, J. F., (1987).- River bed gravels: sampling and analysis. In: HEY, R. D.; BATHRUST, J. C. & THORNE, C. R. (Eds.) *Sediment transport in gravel-bed rivers.* Wiley. Chichester. 43-88.

DIEZ, J. C.; ALVERA, B.; PUIGDEFABREGAS, J. & GALLART, F. (1988).- Assessing sediment sources in a small drainage basin above the timberline in the Pyrenees. *Sediment Budget.* IAHS, Pbl. n.º 174, 197-205.

DUNNE, T. (1978).- Field studies of hillslope flow processes. In: KIRKBY, M. J. (Ed.) *Hillslope Hydrology.* Wiley. Chichester. 227-293.

EMMET, W. W. (1979).- A field calibration of the sediment trapping characteristics of the Helley-Smith bedload sampler. *Open-file Report.* United State Geological Survey. 79-411.

GARCIA-RUIZ, J. M. & PUIGDEFABREGAS, J., (1982).- Formas de erosión en el flysch eoceno surpirenaico. *Cuadernos de Investigación Geográfica* VIII (1 y 2). 85-128.

GARCIA-RUIZ, J. M. & PUIGDEFABREGAS, J., (1985).- *Los recursos hídricos superficiales del Alto Aragón.* Instituto de Estudios Altoaragoneses. Diputación Provincial de Huesca. 224 pp.

HAYWARD, J. A., (1980).- *Hydrology and stream sediment from Torlesse stream catchment.* Spec. Publ. 17. Tussock Grasslands and Mountain Land Institute. Lincoln College. Canterbury, New Zeland. 236 pp.

HUBBEL, D. W. (1987).- Bedload samplig and analysis. In: HEY, R. D.; BATHRUST, J. C. y THORNE, C. R. (Eds.) *Sediment transport in gravel bed rivers.* Wiley. Chichester. 89-118.

JACKSON, W. L. & BESCHTA, R. L., (1982).- A model of two-phase bedload transport in an Oregon Coast Range stream. *Earth Surface Processes and Landforms,* 7. 517-527.

KLINGEMAN, P. C.; MILHOUS, R. T. & HEINECKE, T. L., (1979).- Oak creek vortex bedload sampler. *Oak Creek Sediment Transport Report F2.* Water Resources Research Institute, Oregon State University.

KLINGEMAN, P. C. & EMMET, W. W. (1982).- Gravel bed load transport processes. In: HEY, R. D.; BATHURST, J. C. & THORNE, C. R., (Eds.). *Gravel-bed rivers.* Wiley. Chichester. 141-179.

LEOPOLD, L. B.; WOLMAN, M. G. & MILLER, J. P., (1964).- *Fluvial Processes in Geomorphology.* Freeman, San Francisco. 522 pp.

LEOPOLD, L. B. & EMMET, W. W., (1976).- Bedload measurements, East Fork River, Wyoming. *Proceedings of the National Academy of Science,* USA. 73 (4), 1000-1004.

MARTINEZ CASTROVIEJO, R., (1989).- Advances in fluvial geomorphology of mountain environments. *Pirineos* 132, 65-88.

MARTINEZ CASTROVIEJO, R. & GARCIA-RUIZ, J. M. (in press).- Coarse sediment transport in an experimental high mountain catchment of Central Pyrenees, Spain. *Zeitschrift für Geomorphologie. Suppl. Band.*

REID, I.; FROSTICK, L. E. & LAYMAN, J. T., (1985).- The incidence and nature of bedload transport during flood flows in coarse-grained alluvial channels. *Earth Surface Processes and Landforms,* 10 (1), 33-44.

ROBERTS, R. G. & CHURCH, M., (1986).- The sediment budget in severely disturbed watersheds, Queen Charlotte Ranges Brittish Columbia. *Canadian Journal of Forest Research* 1 (5), 1092-1106.

SCHICK, A. P.; LEKACH, J. & HASSAN, M. A., (1987).- Bedload transport in desert floods: observations in the Negev. In: THORNE, C. R.; BATHURST, J. C. & HEY, R. D. (Eds.). *Sediment transport in gravel-bed rivers.* Wiley. Chichester. 617-642.

SHIELDS, A., (1936).- Anwendung der Ahnlinchkeitsmchanik und Turbulenza forschung and die Geschiebebewegung. Rep. 26, Mitteil Prenss. *Versuchanst Wasserban und Schiffsban.* Berlin.

TACCONI, P. & BILLI, P., (1987)O.- Bed load transport measured by the vortex-tube trap on Virginio Creek, Italy. In: HEY, R. D.; BATHURST, J. C. & THORNE, C. R. (Eds.). *Sediment transport in gravel-bed rivers.* Wiley. Chichester. 583-616 pp.

WHITE, W. R. & DAY, T. J., (1982).- Transport of graded gravel-bed material. In: HEY, R. D.; BATHURST, J. C. & THORNE, C. R. (Eds.). *Gravel-bed rivers.* John Wiley & Sons. Chichester, 181-223.