Assessing sediment sources in a small drainage basin above the timberline in the Pyrenees

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Abstract Most of the geomorphic work performed in the Izas basin is used to change its shape, and only a small part of the material moved is exported from it. Mass wasting is very active on the hillslopes, but is disconnected from the drainage network and its work cannot be expressed in terms of sediment yield. The drainage system itself, including the pipe network, is usually the main source of the sediment that it transports, but this is primarily coarse material produced by cutting gorges and which is partially accumulated in depressions. Intense summer rainstorms are able to partially integrate the efficient sediment yielding hillslope and the fluvial processes, but their role is uncertain, because we do not know the recurrence interval of such storms. Under these conditions, chemical weathering and dissolved transport seem to be the most effective mechanism for export of material from the basin.

Evaluation des sources de sédiments dans un petit bassin versant au dessus de la limite de la forêt dans les Pyrénées

Résumé La plupart du travail morphologique dans le bassin de Izas correspond à l'évolution des formes, et uniquement une petite partie des matériaux mobilisés est exportée en dehors du bassin. Les mouvements de masse sont très actifs sur les versants, mais ils ne sont pas en liaison avec le réseau de drainage et leur activité ne peut donc pas être exprimée sous forme de perte de sédiments. Le réseau de drainage correspond normalement à la source des sédiments transportés, mais ces sédiments sont surtout des matériaux grossiers produits par l'entaille des ravines et ils sont accumulés en partie dans les dépressions. Des averses d'été sont capables de produire des processus d'érosion et d'écoulement sur les versants, bien connectés avec le réseau et qui sont bien efficaces pour le transport lointain des sédiments fins, mais, faute d'une bonne connaissance de la fréquence de ces événements, nous ne pouvons pas calculer leur contribution au bilan. Dans ces conditions, l'altération chimique et le transport de solides dissous semble bien être le mécanisme le plus efficace d'exportation de matières en dehors du bassin.

INTRODUCTION

Sediment transfer pathways between hillslopes and channels in alpine grasslands are poorly understood. Most workers agree that slope processes, dominated by mass wasting, are almost disconnected from the channel system (Kotarba *et al.*, 1987), the major sediment source being bank collapse within the drainage system itself (Threlfall, 1986). Other secondary sediment sources can be dry tundra areas (Bovis, 1978), or mass movement scars (Puigdefàbregas & Alvera, 1986).

The aim of this paper is to present a qualitative description of the geomorphic processes observed in a small alpine drainage basin, and an estimate of their relative contribution to the sediment budget, assessed with the help of two sets of data obtained respectively during a daily snowmelt pulse and a summer rainstorm. This work has been performed in order to establish a monitoring design adequate for obtaining a full sediment budget.

THE STUDY SITE

The Izas basin (Fig. 1) lies on the southern slope of the central Pyrenees, at coordinates 0° 25' W, 44° 44' N, in the province of Huesca (Spain). It covers 0.22 km² from 2060 to 2280 m a.m.s.l., and is developed on siliceous poorly metamorphosed Carboniferous slates which are discontinuously covered by till and periglacial slope deposits. Infiltration capacities of the soils, assessed with a ring ponding infiltrometer, range between 0.78 and 6.0 mm min⁻¹, but some stony soils can reach values as high as 18 mm min⁻¹. The mean annual temperature is about 4°C, and the total precipitation is approximately 1900 mm, with at least one-half of it occurring in the form of snow. The basin is covered with alpine grasslands of *Festuca eskya* on the well drained slopes and *Nardus stricta* in the wet hollows.

This basin has been selected to study snowmelt processes and to establish water, solute and sediment balances. A gauging station, consisting of a bed load trap, a weir with a pressure transducer connected to a data logger, and an automatic water sampler, was established at the outlet in March 1987. Other instruments in the basin are an autographic rain recorder fitted with a weekly drum chart, a propane heated snow gauge, an anemometer and several thermometers connected to the data logger.

LANDFORMS AND PROCESSES

The Izas basin has been shaped mainly by glacial morphogenesis during the last cold period of the Quaternary. The landscape is therefore characterized



Fig. 1 The Izas basin and its location.

by steep slopes and gentle hollows or depressions that are being respectively eroded and filled by the present-day morphogenetic processes.

The hillslopes

Terracettes up to 3 m wide are very common on the steep sunny hillslopes $(25-30^{\circ})$ and are developed on stony soils or old periglacial deposits, where frost heaving and sheet wash are active. Frost creep seems to be active especially on the west-facing windward areas, while deeper solifluction occurs on lee slopes wetted by melting of snow patches (del Barrio & Puigdefàbregas, in press). The high infiltration capacities (between 1 and 18 mm min⁻¹) and the filtering effect of the *Festuca eskya* rims, limit the occurrence and geomorphic effectiveness of runoff, the limited sediment entrained being trapped by the dense grass cover of the gentler footslopes. In spite of the active appearance of these areas, their contribution to the basin

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sediment yield seems to be limited to a few steep slopes dissected by streams and to during heavy rainstorms or rainstorms falling on soils previously saturated by snowmelt.

Vegetated solifluction lobes occur mainly on the shady parts of the mid and footslopes. Movement rates measured outside the basin at 1800 m altitude and on the same bedrock lithology showed a mean rate of >40 mm year⁻¹, but the wetter lobes can achieve rates that are twice the former figure (Creus & Garcia-Ruiz, 1977). The transported material is accumulated within footslope depressions.

Some free-fall talus deposits occur on the steep rock walls near the summits and, especially, on the sides of deeply incised stream channels. The latter are the main source of bed load and are active enough to allow us to assume that the discharge of bed load coarser than 10 mm is usually controlled by transport capacity rather than sediment supply.

Hollows and pipes

As areas of convergence of overland and subsurface flow, hollows and depressions become almost permanently saturated and are characterized by peaty or gley soils. Rainstorms can produce pools which persist for several days, fed by groundwater stored in the surficial deposits on the hillslope. Pipes are very common in these areas. Most of them drain the water table, and are well connected to the drainage network. Other common features are scars and exposed patches of bare ground produced by small mudflows.

In a previous study carried out in a similar area (Alvera & Puigdefàbregas, 1984) it has been shown that these saturated hollows are responsible for most of the suspended solids generated during snowmelt conditions.

Field inspection suggests that there are three main sources of sediment: the pipe network and patches of wet bare ground and dry bare ground.

The drainage network

The network exhibits a high density (16 km km⁻²) which can be seen as an expression of the early stage of evolution of the fluvial system. Channel slope and capacity are very discontinuous; steep reaches in bedrock and small gullies cut into periglacial or talus deposits alternate with gentle reaches with narrow channels cut in old alluvium. The continuous changes in slope and coarse sediment availability induce a strong spatial discontinuity in bed load transport. Small terraces cut into the fan deposits that occur in some depressions may reflect the role of extreme floods which could transport large amounts of coarse material.

The permeability of some of the slope and alluvial deposits is high enough to induce discontinuities in channel water conveyance. Two examples of subsurface transference of water, one between channels and another between a channel and a saturated area, have been found. Bank erosion is a common mechanism of sediment supply, but, with the exception of free-fall talus deposits in gorges and old periglacial deposits cut by gullies, the sediment supplied by this process represents old alluvium and does not come from the hillslopes. The classical connection between hillslope soil creep and channel bank erosion, which can be used to establish an approximate sediment budget (Dietrich & Dunne, 1978), cannot, therefore, be applied to this basin.

SOME QUANTITATIVE DATA

Snowmelt pulses

The snowmelt period extends from early April to late June and is characterized by a daily rhythm in the hydrological response. The data obtained for 2 and 3 May 1987 have been selected as representative of these pulsations (Fig. 2). Total suspended solids concentrations were obtained by filtering 1 l samples and subsequent weighing of dry glass microfibre filters. Total dissolved solids concentrations were determined by weighing the residue after evaporation.



Fig. 2 (a) Variation of discharge (Q), suspended solids concentration (SSC), and total dissolved solids concentration (DSC) during a snowmelt pulse. (b) Hysteresis loops evidenced by plots of suspended solids concentration (SSC) and dissolved solids concentration (DSC) vs. discharge (Q) for the same data.

Dissolved solids concentrations values are low ($<40 \text{ mg l}^{-1}$) and they exhibit an anticlockwise hysteresis loop during individual events. This response

is usually associated with areas where groundwater is rapidly affected by infiltration and is well connected to the drainage network (Gregory & Walling, 1973). A decrease in dissolved solids concentrations occurs during the early rising stage, because of a dilution effect, but, when the peak discharge is reached, groundwater has already started to feed streamflow in response to infiltration. The low concentration levels observed subsequently and associated with a second gentle rise of the hydrograph, are not so easily explained. The role of pipeflow and the melting of snow patches deserves further research.

Suspended solids concentrations during the event are very low. The peak value is 2 mg l^{-1} and the total transport for the whole day is 1.92 kg $(8.7 \text{ kg} \text{ km}^{-2} \text{ day}^{-1})$. Their relationship with discharge evidences a clock-wise hysteresis loop. The increase in concentration slightly precedes the discharge rise, but both peaks coincide at a two-hour sampling interval, and there is therefore no evidence of a dilution effect. The second concentration peak occurs during the recession limb of the hydrograph, eight hours after the flood peak, and coincides with the delayed peak of the dissolved solids concentration. Its volume accounts for about 26% of the suspended sediment transported during the 24 hours, or 227 kg km⁻² year⁻¹ if it is extrapolated to the 100 days of snowmelt. These characteristics, together with the field observations, suggest that this second sediment peak could be produced by pipe erosion. Small delayed peaks of suspended sediment concentration have been found previously in other areas (Alvera & Puigdefabregas, 1984) where they have been related to peaks of dissolved solids concentration and to a secondary increase in the level of the water table. Jones & Crane (1984) found lag times between rainfall and peak pipeflow discharge ranging from 5.8 to 11.8 h, and showed that rainstorm induced pipe erosion could account for approximately 15% of the total sediment yield from the basin, or 556 kg km⁻² vear⁻¹, which is more than twice the figure found in the Izas basin.

Estimates of the total solid discharge for the whole snowmelt period amount to 6550 kg of dissolved solids transport, 150 kg of suspended sediment, and somewhat more than 200 kg of bed load. The small magnitude of the suspended sediment load reflects the ineffectiveness of the processes of fine sediment supply, resulting from the disconnection of the mass movements and the fluvial processes.

Rainstorm-induced floods

A short-lived flood was observed on 23 July 1987, subsequent to 7 mm of rain falling during a period of 30 minutes, with an antecedent rainfall of 16 mm in 24 h. By photographic enlargement of the rain recorder chart, the intensity was estimated at 0.8 mm min⁻¹, for the last 4 mm of the event. The flood was too short to be fully recorded by the gauging system and the automatic sampler was out of order. However, some of the authors were at the site and were assisted by several postgraduate students. The water levels on the weir were obtained by direct readings of the transducer response, and the suspended sediment concentrations were estimated with a manual



Fig. 3 (a) illustrates the discharge (Q) and suspended solids concentrations (SSC) for the flash flood of 23 July 1987. Suspended solids value shown in parenthesis is extrapolated (see text). (b) depicts the relationships between suspended sediment concentration (SSC) and discharge (Q) plotted on log paper for the snowmelt pulse (I) and the summer flash flood (II).

turbidimeter, calibrated in the laboratory.

Observed characteristics of this flood are shown in Fig. 3(a). The actual peak was missed (dashed line), and the suspended sediment concentration for the highest value of discharge was not measured directly in the field, but was extrapolated from the concentration versus water discharge linear regression (significant at the 99.9% level). The precise time relationship between rainfall and runoff could not be investigated because of the limited accuracy of the weekly chart of the rain recorder. Although the former limitations preclude exact computations of water and sediment volumes, it is worthwhile to compare the approximate values with those obtained for the snowmelt pulse.

Sediment concentrations are moderately high, and about 25 times greater than those observed during the snowmelt pulse for the same water discharge (Fig. 3(b)). The main mechanisms of sediment production must therefore have been different during both cases. These were runoff stress during snowmelt, and raindrop impact or raindrop-induced runoff water turbulence during the rainstorm. No direct information about sediment source areas is available, but if 400 m³ is taken as the approximate quickflow volume, the partial contributing area for a 7 mm storm would be about 5.7 ha while semipermanently saturated area plus channel area is somewhat less than 1 ha. Since the rainfall intensity was of the same order as the infiltration capacity of some of the soils, Hortonian flow could have provided a significant contribution to quickflow and sediment discharge.

The total suspended sediment transport during this short event was about 220 kg, and therefore more than for the whole snowmelt period. Nevertheless, this storm did not produce a significant bed load discharge. This could not be accurately measured, because the bed load trap was not entirely empty before the event. However, no change in the trapped sediment volume was apparent. The high ratio of suspended to bed load transport is also in accord with the role of rainsplash and sheet wash on the hillslopes.

On 10 October 1987, 98 mm of rain fell during a period of 8 h, with a maximum intensity of 20 mm h⁻¹. This event had a recurrence interval of more than 12 years and produced a total bed load discharge of over 18 000 kg (82 t km^{-2}), which buried the pressure transducer of the gauging station. Dissolved and suspended solid discharges estimated for the whole month were respectively 2000 and 750 kg.

DISCUSSION AND CONCLUSIONS

Unfortunately, the data shown above do not allow us to establish a full sediment budget for the basin, but some tentative guidelines may be advanced. Solid matter output appears to be dominated by dissolved solids loads. Since snowmelt accounts for 50% of the annual runoff, the basin could yield over 13 000 kg year⁻¹, or 60 t km⁻² year⁻¹ of dissolved material. The variation of discharge and dissolved solids concentrations during a daily snowmelt pulse (Fig. 2) suggest a complex pattern of groundwater interaction. The suspended sediment discharge is 40 times less than the dissolved transport during snowmelt conditions. Hillslope runoff is unable to entrain significant quantities of fine material in suspension, and there is a lack of fine fractions in the bank sediments because these represent old alluvium or talus scree and rarely hillslope soil creep material. Under these conditions, pipe erosion can be important and could account for 26% of the suspended sediment load.

Nevertheless, intense summer showers seem to be able to induce Hortonian flow and to export significant amounts of suspended sediment from the hillslopes through the action of raindrop energy. Such an event lasting 30 minutes can export more suspended sediment than the whole snowmelt period. It is therefore impossible to establish a sediment budget without adequate knowledge of the recurrence and consequences of intense rainstorms.

Bed load transport seems to be more limited by transport capacity than sediment supply. High water stages of sufficient duration can therefore transport large amounts of coarse alluvium, as evidenced by several fan accumulations and by the event observed on October 1987. It conforms also with the low ratio between suspended and bed load discharge observed during the snowmelt period. Nevertheless, the great volume moved by the autumn event described above could exhaust some sediment sources and modify the yield for several subsequent years. Acknowledgements This work has been carried out within a research programme of the Consejo Superior de Investigaciones Cientificas, and is to be continued beyond 1988 within an agreement with the Instituto Nacional para la Conservacion de la Naturaleza. We are very grateful to J. M. Garcia-Ruiz and I. Sobron for provision of some data, and to the students of the "High Mountain Geomorphology and Ecology" course for their field support.

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