Hydrological and sediment dynamics network design in a Mediterranean mountainous area subject to gully erosion

J. C. BALASCH, X. CASTELLTORT, P. LLORENS & F. GALLART
Institute of Earth Sciences Jaume Almera, PO Box 30102,
08080 Barcelona, Spain

ABSTRACT The Vallcebre basin is the main sediment contributor to the Llobregat basin because of the high geomorphic activity on smectite-rich clays. Two different zones have been instrumented in this basin, respectively representative of old farmed terraced stable areas, and of sediment contributing areas with significant badland zones. One small basin in the stable area (Cal Parisa), and two macroplots nested in two small basins within the active area (Devinol creek,) are here presented. Instrumentation is based on multislot divisors for macroplots, and on gauging stations provided with samplers and electronical logging of data on discharge, temperature, electrical conductivity and turbidity (this last in one point only). Calcium bicarbonate is usually present near to saturation level, whereas water from badland areas shows concentrations of calcium sulphate up to 3 g l^{-1}. Sediment routing characteristics lead to very low sediment yields from stable areas, and to intricate temporal and spatial delays as badland areas are broad enough and well connected to the drainage net.

INTRODUCTION

Land conservation problems can be better managed if there is a sufficient description not only of sediment yield figures, but especially of the characteristics of sediment source areas and of the mechanisms of sediment routing from the sources to the outlet (Swanson et al., 1982; Bordas & Walling, 1988).

The Vallcebre basin was selected in early 1988 for research on land conservation and sediment yield because it was perceived as the chief sediment contributor of the high Llobregat basin (Clotet & Gallart, 1986). Monitoring of hydrology and sediment transport are the main aspect of several geoecological studies which are carried out in this basin (for a schedule, see Gallart, 1991).

The aim of the present paper is to introduce the instrumented network as a contribution to the discussion on the monitoring strategies capable to master the challenge of performing full sediment budgets in areas of high geomorphic activity.

THE STUDY AREAS

The Vallcebre drainage basin is located in the Pyrenees range at the headwaters of

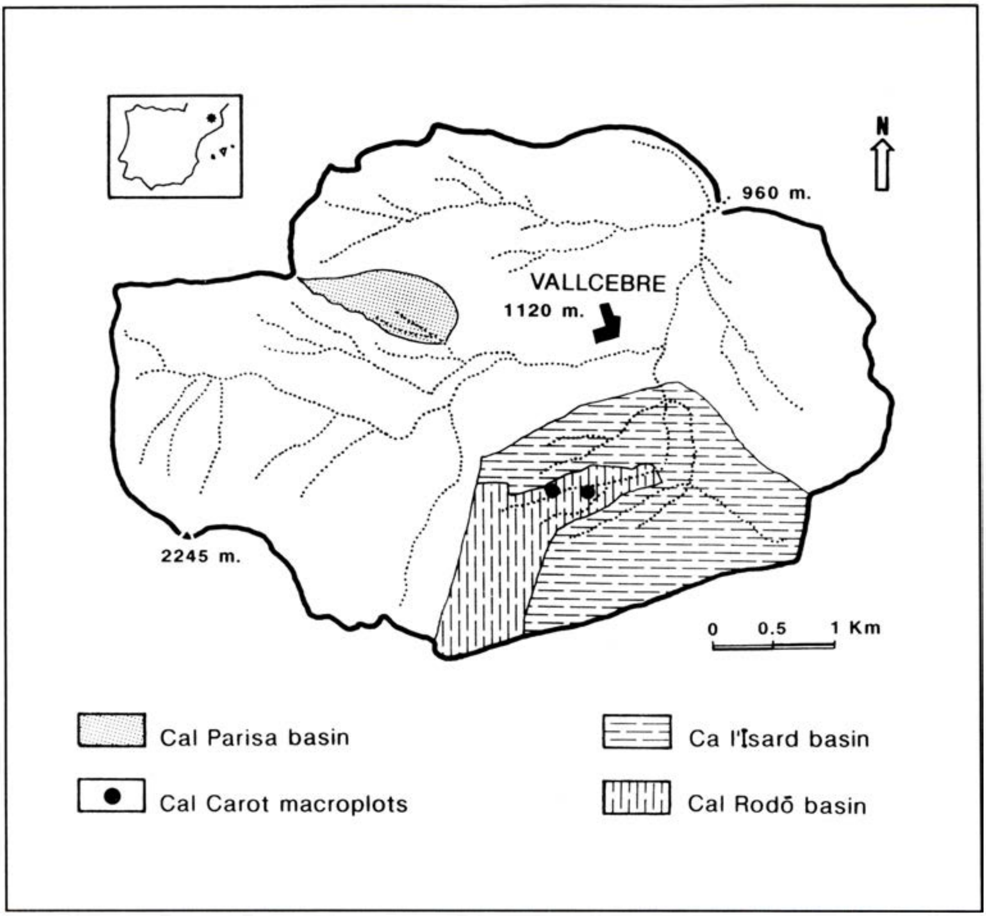

FIG. 1 Instrumented areas in the Vallcebre drainage basin (high Llobregat).

Llobregat river. This is a mountainous basin with heights between 900 and 2245 m a.s.l. and an area of 21 km^2. Outcropping materials are Mesozoic continental mudrocks and limestone beds. The climate is mountainous mediterranean with an annual precipitation of about 900 mm. There is a bimodal distribution with two rainfall peaks: in spring and in autumn. Because of convective rainstorms, another lower in amount but higher in intensity peak occurs in August. The mean annual temperature is about 9°C, with great annual and daily thermic amplitudes. Freezing occurs about 100 days per year, and snowfalls are frequent in winter, but this is the driest season and moreover snow melts in a few days.

As a result of lithology, relief and climate, geomorphic processes like gully erosion and mass movements are very active sediment sources. Relatively small badland areas strongly contribute to the sediment budget because erosion rates of about 9 mm $year^{-1}$ (Clotet et al., 1988). On the other hand, traditional land conservation practices preserved some small very stable areas, whose hydrological behaviour and sediment production contrasts with the whole.

The Cal Parisa small basin

The Cal Parisa small basin was selected as a representative of abandoned agricultural terraced areas (Llorens & Gallart, 1992). This basin is devoid of badlands, but has some small scattered gullied areas disconnected from the drainage net.

The basin is a south-east facing hillslope between 1400 and 1700 m a.s.l.; the more frequent hillslope gradients range between 10 and 30%, with some areas that reach up to 70% in gradient.

The more relevant characteristic of this small basin is the geoecological impact of old agricultural practices on vegetation cover, topography and water circulation.

The progressive abandonment of agricultural activity since the fifties allowed a differential recovering of vegetation, early abandoned areas are overgrown by Pinus sylvestris trees, whereas more recently abandoned terraces are covered by mesophile and xerophile grasslands with some patches of hygrophile vegetation.

Topographical modifications due to terracing provoked important changes in water circulation, forcing phreatic waters to outcrop at the inner part of terraces were the soils are thin or lacking. A net of shallow ditches was constructed to drain these areas, increasing 50% the total drainage density.

The Davinol creek area

Davinol creek is one of the most important sediment load contributors to the Vallcebre basin, because the occurrence of very active badland areas (5% of the surface), surrounded by pine forests and partly abandoned agricultural fields. It drains an area of about 4 km^2 called "Cal Rodó" drainage basin, formed by the confluence in the same point of three channels, the main one (Davinol creek itself), and two other minor streams. The basin drained by Davinol creek above the triple channel confluence is called "Ca l'Isard" drainage basin, and it has an area of about 1 km^2, with about 8% of badland area. Davinol creek headwaters consist of the confluence of several small drainage basins which are characterized by strong gully erosion, and therefore are an important supply of sediment. Two elementary drainage basins in this badland area have been selected for monitoring runoff and sediment production, in the form of macroplots with natural boundaries, named Carot 1 and Carot 2, with 1706 and 72 m^2 respectively.

The most important character of the two different order drainage basins is the fact that the small one contains the two macroplots, and it is itself nested into the larger. This allows a better comparison of processes as well as a better representativeness of numerical results. At the same time, temporal and spatial analysis of sediment delivery ratios resulting from sediment routing can be performed, with the help of field observations and sediment transport measurements (Swanson et al., 1982, Walling 1983).

MONITORING DESIGN

Before starting the network monitoring program it was essential to carry out a geomorphic mapping as well as observation and description of processes. A first step comprised both hillslope and channel survey, in order to estimate a preliminary sediment budget (Balasch, 1986) in the sense of a quantitative description of sediment sources, stores and exportation (Dietrich & Dunne, 1978, Swanson et al., 1982).

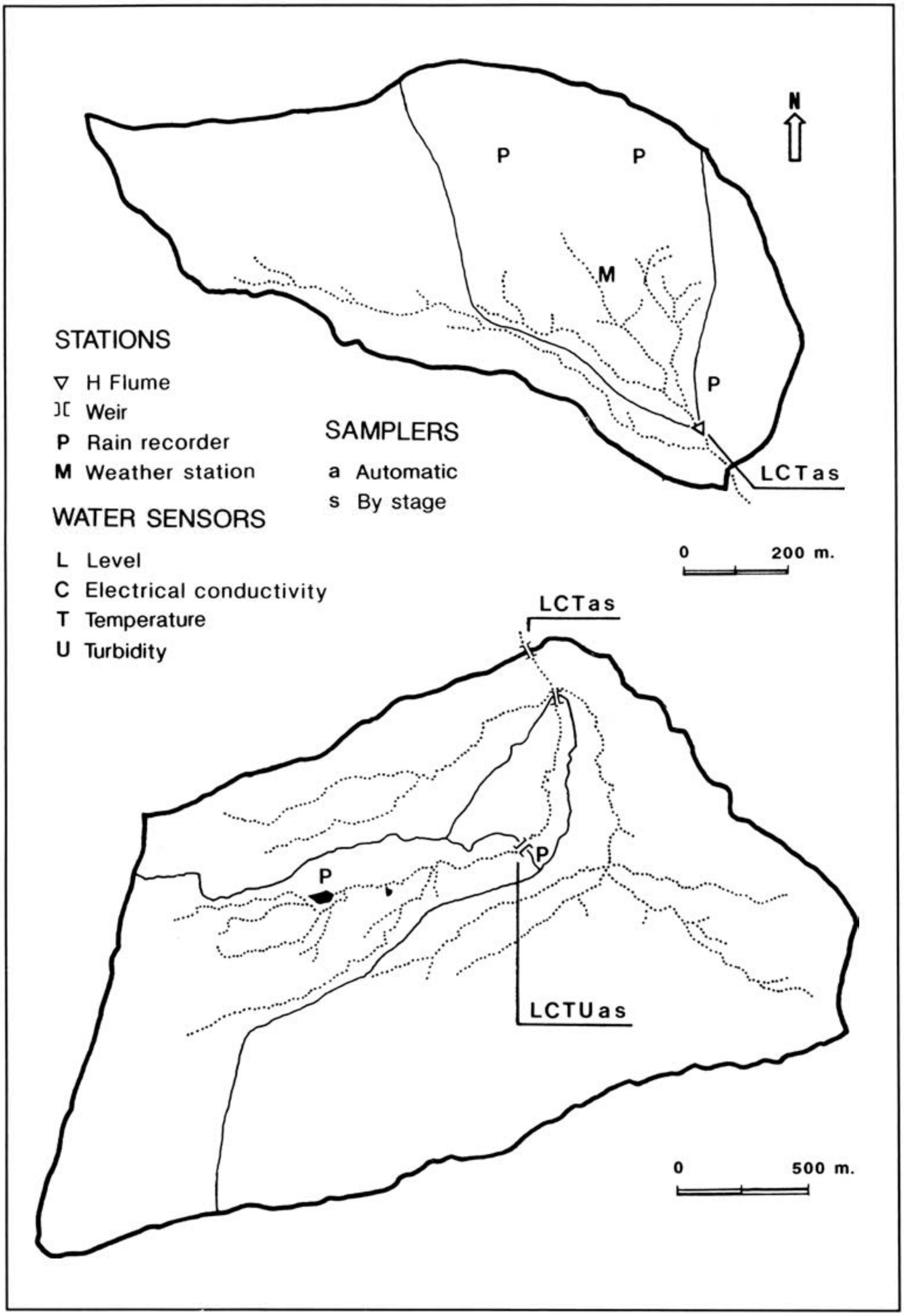

FIG. 2 Instrumentation design of the research areas.

Channel mapping involved bank and bed sediment sources and different kinds of channel sediment stores, focusing on their volumes, in order to assess storing channel capacity and probable residence times. It also included a survey of neighbouring non-stream sediment sources, such as adjacent footslopes, and a variety of mass movements. There are five monitored units in the research area of Vallcebre, selected as representative of the main geoecological units on this basin and at different scales of integration. These are (figs 1 and 2):

STATION NAME	SURFACE (Ha)	GEOECOLOGICAL UNIT
Cal Parisa	16.70	Abandoned terraces-pastures
Carot (1)	0.17	Badland
Carot (2)	0.007	Badland
Ca L'Isard	114.00	Forest-Badlands
Cal Rodó	400.00	Forest-Badlands-pastures

The two Carot stations are included in the Ca L'Isard basin, which is itself nested within the Cal Rodó basin.

The instruments used are:

Meteorological station

One weather station, located at the Cal Parisa basin, records every five minutes data on: global radiation, air temperature, air relative humidity, wind velocity and wind direction. This station, UNIDATA 6504D, is an assembly of the following sensors: a flat Si cell for the global radiation, an AD590 solid state temperature sensor, a gold grid absorbtion relatively humidity sensor, a cup anemometer and a wind direction device. All these instruments are connected to a UNIDATA Starlog 6003A data logger, with scans the instruments every 10 seconds and logs mean values every 5 minutes.

Rainfall measurements

Precipitation is measured with 6 tipping bucket rainfall recorders, 4 of them are located at the Cal Parisa basin and the others at the Ca l'Isard basin. The logging of pluviometric data is made in two different ways: the 2 instruments close to standard data loggers send the signal to them, which log the total rainfall amount collected every log interval; the 4 remote ones are connected to single channel data loggers provided with a 6K removable memory pack (AW-RP Institut Analític), which record the time at each movement of the bucket.

Macro-plot stations

The two Carot macro-plot stations are based on a set of tanks connected by multislot divisor devices (Brakensiek et al., 1979). These systems are able to collect respectively 29.275 and 258 m^3 of water and sediment.

Hydrological and sampling basin stations

The Cal Parisa station consists of a H steel Flume (76 cm) able to measure a peak discharge of 450 l s^{-1} (Brakensiek et al., 1979), provided by an UNIDATA 6521B capacitive water level sensor, an UNIDATA 6515A solid state water temperature sensor and a CRISON-523 water electrical conductivity device. All these instruments are scanned every 15 seconds by a UNIDATA Starlog 6003A data logger that records mean values every 5 minutes. The station is also provided with an ISCO-2700 automatic sampler, which is triggered when water reaches a preselected level and sends an electrical signal to the data logger when it takes a sample. Finally, a 12 bottles siphon stage sampler is coupled with the Flume and takes samples every discharge increment of 45 ls^{-1} during the rising of the water level.

The Ca l'Isard gauging station consists of a rectangular concrete weir one meter wide and high, four meter long, able to measure a peak discharge of 1.8 m^3 s^{-1}. It is provided with a MONTEDORO WDM-1 water level pressure sensor, a MARTEK MARK XVII water temperature and conductivity instrument and a OD&A OBS-IP nephelometric turbidity meter, able to measure continuously sediment concentrations up to 4 g l^{-1}. All these instruments are connected to a GEONICA HIDRODATA data logger which scans the instruments every 2 seconds and logs mean values every 10 minutes. This station is also provided with an ISCO-2700 automatic sampler, which is triggered by the data logger when both water level and turbidity reach a preselected threshold. A siphon-based stage sampler, a plastic net bedload trap, and a reed-switch tipping bucket rainfall gauge complete the instrumentation.

The Cal Rodó gauging station consists of a rectangular convergent wall concrete weir which has two different levels for reaching a wide range of water discharges, up to eight cubic meters, the lower step is 1.8 m. wide and 0.8 m high, whereas the upper one is 3.6 m wide and 0.9 m high. The whole weir is 8 m long and is provided with a MONTEDORO WDM-1 water level pressure sensor and a MARTEK MARK XVII water temperature and conductivity device, both connected to a GEONICA HIDRODATA data logger which operates like the formerly described. The station is also completed by an ISCO-2700 automatic sampler triggered by the data logger when water level reaches a selected threshold.

Soil water monitoring

Because of the importance of antecedent water conditions in modifying basin response, a piezometric network has been established. It supplies information about underground water level, which is related to the amplitude of partial contributing area and to baseflow. One well is weekly surveyed at Cal Parisa basin and five wells are watched in "Ca l'Isard" drainage basin, like other three wells more and two springs in "Cal Rodó" drainage basin.

Soil moisture is also weekly measured in two points at the Cal Parisa basin.

SOME RESULTS AND THEIR DISCUSSION

Cal Parisa basin

The hydrological and sediment response of this basin has been studied for the period July

1989-December 1990 (Llorens, 1991); the following data summarize the main results (see also Llorens & Gallart, 1991).

During the study period, the hydrological response of this small basin was characterized by a high variability of runoff production. At a monthly scale, 90% of the runoff was produced in only 6 months, but 98% of the total runoff was afforded by 6 events.

This high runoff variability is partially due to rainfall variability (50% of the 18 months total rainfall fell in only 5 months), but also to the important role of antecedent conditions of the basin in runoff generation.

The analysis of rainfall-runoff relationships evidence that runoff is generated by contribution of saturated areas, whereas significant summer rainstorms (up to 50 mm) are completely absorbed by the basin, because Horton overland flow produced in small bare areas do not reach the basin outlet. The 6 main runoff events show great variability in rainfall volume and response time before starting of runoff, due to different antecedent conditions, but once runoff is produced, the basin shows a relatively homogeneous response for all the events, with a mean sharp peak which represents about 50% of the total runoff of the event.

During the same study period, the sediment response of the basin is characterized by a high and constant (mean 250 mg l^{-1}, variation coefficient 2%) dissolved solids concentration, and a low and very variable (mean 25 mg l^{-1}, variation coefficient 123%) suspended sediment one.

Dissolved solids concentrations demonstrate clear dilution effects with clockwise hysteresis loops when present. The analysis of dissolved solids show a concentration of calcium carbonate close to saturation level, a noticeable concentration of sulphates (about 20 mg l^{-1}), and low concentrations of chloride and nitrate.

Suspended solids concentrations show strong exhaustion effects and depend on the hydrological behaviour during every event. Mineralogical analysis of suspended sediments show the omnipresence of calcite, partly because of precipitation after sampling, and some opposition between quartz and smectite, probably because a grainsize selection. X-ray fluorescence chemical analysis show a P and Mn content higher than from soil samples, associable to a organic matter enrichment (Peart & Walling, 1986).

During the studied period, solid discharge was strongly dominated by dissolved transport (4000 kg), about 4 times higher than suspended sediments (925 kg), and more than 100 times greater than bedload transport (>20 kg).

This low particulate sediment yield (about 4.7 t km^2 $year^{-1}$) strongly contrasts with the sediment dynamics within the basin (estimated on about 60 t km^2 $year^{-1}$). This is the result of the present environmental conditions created by the old land conservation practices and the change from agriculture to grazing but that are out of equilibrium because of the lack of maintenance of terraces and ditches (Llorens & Gallart, 1991).

Devinol creek

Monitoring of the Devinol creek area started by late 1990. There are data on about 10 significant events, but the elaboration of these data is partial by now, and only a general review can be presented here.

The hydrological response of this area is clearly influenced by badland areas. Summer rainstorms which are completely absorbed in the Cal Parisa basin produce some runoff in badland macroplots, which loses importance as drainage area increases. High loads of

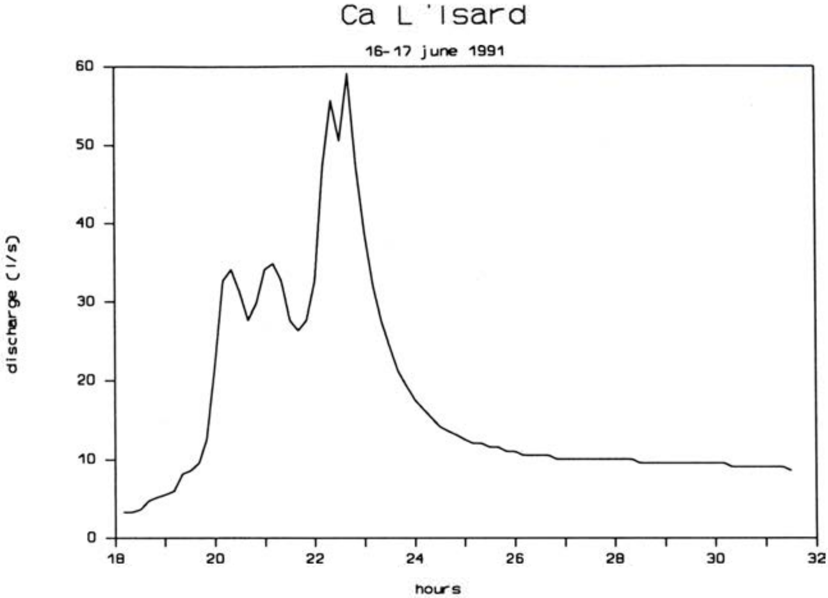

FIG. 3 Hydrograph at the Ca l'Isard gauging station for the event on 16-17 June, 1991 Precipitation was 46 mm in 4 h.

water discharge at the gauging stations depend indeed on antecedent conditions, demonstrating the main role of the saturation mechanism in runoff production.

Dissolved solids concentrations show typical values as high as 3 g l^{-1} because the abundance of calcium sulphates dissolved from gypsum veins in badland hillslopes. Calcium bicarbonate is present also at saturation level. Electrical conductivity of water during flood events demonstrates dilution effects but not distinct hysteresis loops.

Suspended sediment concentrations show very high variations, with values up to 25 g l^{-1} at Ca l'Isard, and 75 g l^{-1} at Cal Rodó. At the event scale, sediment concentration increases with discharge, but some anti-clockwise hysteresis loops occur.

The balance between dissolved and suspended sediment transport seems to be difficult to assess. The high suspended transport rate during flood events can be counteracted by a lower but longer dissolved transport rate by baseflow (see figs. 3 and 4).

Field observations suggest an important role of gypsum dissolution in badland processes.

The analysis of sediment routing is somewhat consistent with previous non instrumental observations (Clotet et al., 1988). Summer rainstorms produce the higher erosive work on badland areas, but low discharges at the drainage net are unable to convey the high amounts of sediments received, and channels become filled up by sediments. Autumn wet periods produce much lower sediment volumes from badland hillslopes, probably by both sediment exhaustion and lower rainfall energy, but higher water discharges are able to convey sediments to a much longer distance. Grainsize analysis demonstrate that suspended sediment is transported in form of coarse silt aggregates, because of the role of high Ca^{2+} concentrations. This fact enhances redeposition of significative amounts of sediment, contributing to spatial and temporal discontinuities of sediment transfer (see Walling, 1983).

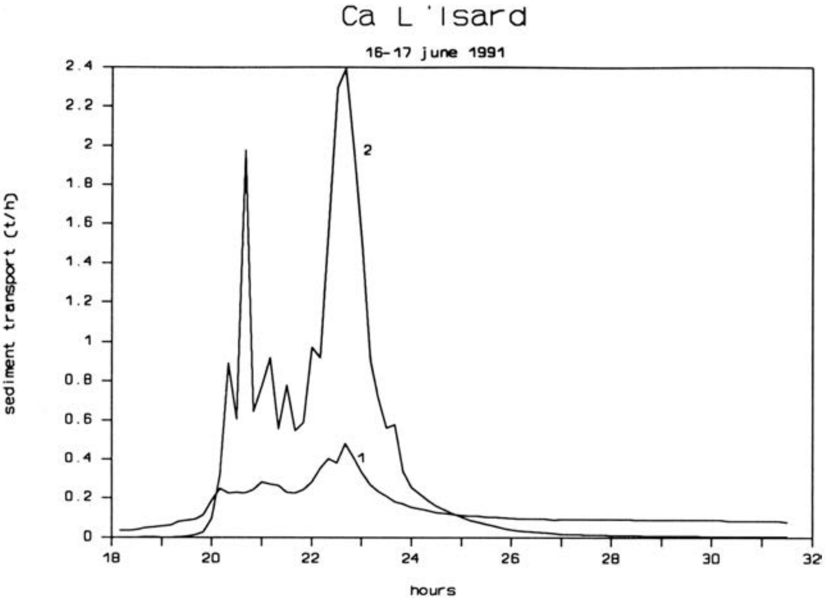

FIG. 4 Dissolved sediment transport (1) and suspended sediment transport (2) for the same event on Fig. 3.

ACKNOWLEDGEMENTS We are indebted to N. Clotet-Perarnau who lead the research work in the Carot, Ca l'Isard and Cal Rodó areas until September 1990, when she died in a traffic accident. Funding for the instruments and field work was obtained by an agreement between ICONA and CSIC (LUCDEME Research Program), and by the Research Project NAT89-1072-C06-01 financed by the Plan Nacional de Investigación y Desarrollo. The contribution of the third author was supported by a research fellowship from the Departament d'Ensenyament, Generalitat de Catalunya.

REFERENCES

Balasch, J.C. (1986) La conca de Vallcebre (alt Llobregat): anàlisi de la dinàmica geomorfològica contemporània i balanç previ de sediments. Unpublished Master Tesis, Universitat de Barcelona.

Bordas, M. & Walling (1988) Preface. In: Sediment Budgets (Ed. by Bordas, M. & Walling, D.E.) IAHS Pub. no. 174, v-vi.

Brakensiek, D.L.; Osborn, H.B. & Rawls, W.J. (Coord.) (1979) Field manual for research in agricultural hydrology. Agriculture Handbook no 224, USDA.

Clotet, N. & Gallart (1986) Sediment yield in a mountainous basin under high Mediterranean climate. Z. Geomorphol. supp. Bd. 60, 205-216.

Clotet, N., Gallart, F. & Balasch, J.C. (1988) Medium-term erosion rates in a small scarcely vegetated catchment in the Pyrenees. Catena sup. 13, 37-47.

Dietrich, W. & Dunne, T. (1978) Sediment budget for a small catchment in mountainous terrain. Z. Geomorphol. sup. Bd. 29, 191-206.

Gallart, F. (1991) Hydrological and land conservation studies in the High Llobregat Basin (Barcelona). In: Soil erosion studies in Spain (Ed. by Sala, M., Rubio, J.L. & García-Ruíz, J.M.) Geoforma, Logroño, 91-96.

Llorens, P. (1991) Resposta hidrologica i dinàmica de sediments en una petita conca pertorbada de muntanya mediterrània. Ph. D. Tesis, Univ. of Barcelona.

Llorens, P. & Gallart, F. (1991) Short-term sediment budget for a small drainage basin in a mountainous abandoned farming area. In: Sediment and stream water quality in a changing environment: trends and explanations (Ed. by Peters, N.E. & Walling, D.E.), I.A.H.S. Pub. No. 203, 63-71.

Llorens, P. & Gallart, F. (1992) Small basin response in a mediterranean mountainous abandoned farming area. Research design and preliminary results. Catena 19.

Peart, M.R. & Walling, D.E. (1986) Fingerprinting sediment sources. The example of a drainage basin in Devon, U.K. In: Drainage basin sediment delivery (Ed. by Hadley, R.F.), IAHS Pub. No. 159, 41-55.

Swanson, F.J., Janda, R.J., Dunne, T. (1982) Summary: Sediment budget and routing studies. in: Swanson,F.J., Janda, R.J., Dunne, T. and Swanston, D.N. (Editors) Workshop on Sediment Budgets and Routing in Forested Drainage Basins. Pacific Northwest Forest and Range Experiment Station, General Technical Report PNW-141, 157-165.

Walling, D.E. (1983) The sediment delivery problem. J. Hydrol. 65, 209-237.