# Flood and sediment transport response to hydrometeorological events of diverse magnitude in the Vallcebre basin, Eastern Pyrenees

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**Abstract** Precipitation, discharge and suspended sediment concentrations were continuously measured for ten hydrological years (1995–2004), in the Ca l'Isard sub-basin (1.32 km$^2$) of the Vallcebre experimental catchments, Spain. The daily precipitation record is 22 years long. When all the events were analysed, the diverse variables considered (precipitation depth, peak discharge, runoff depth, and sediment load) showed significant Spearman rank correlation coefficients among them. Nevertheless, when the major events, corresponding to the upper 10%, were selected, several of these variables were poorly correlated, and the Spearman coefficients strongly dependant on the variable used for selecting the events. The results confirm the complexity of the sediment processes in these catchments, and demonstrate that the ranking of events according to precipitation characteristics may be adequate for sediment transport purposes only for the main events.

**Key words** badlands; magnitude-frequency; Mediterranean climate; recurrence interval; sediment transport

## INTRODUCTION

The study of extreme events is almost always associated with the study of precipitation and maximum discharges, but there are few studies that describe the periods of recurrence of suspended sediment transport. Nevertheless, the estimation of the relative role of sediment transport produced by infrequent events is necessary for the calculation of long-term sediment yields from catchments, as one single event may represent the transport of several "normal" years (Wolman & Miller, 1960; Wolman & Gerson, 1978). Although there is much evidence on the great role of infrequent rainstorms in the evolution of mountainous relief, it is very difficult to know the relative effect of these events in comparison with the role played by more frequent events of moderate magnitude. Two main problems contribute to this uncertainty: the differences between the processes triggered by common and rare climatic episodes, and the lack of knowledge of the frequency of rare events. (Gallart, 1995).

In Mediterranean areas both the marked seasonality of hydrological processes and the strong interannual variation in precipitation rates enhance the role of large relatively infrequent events. It is relevant to note that in Vallcebre (our study area), the amount of sediment transported during a single event was exceeded only by the annual sediment transport in 1 year from a record of 12, if the year of occurrence of this event is excluded (Gallart *et al.*, 2005).

The objective of this work is to estimate the magnitude–frequency relationships of the events observed during 10 years of record at the Ca l'Isard basin using several measures of event magnitude (precipitation, runoff, peak discharge, sediment load), to assess the long-term validity of the sediment yield rates obtained during this period, and to analyse whether the magnitude–frequency relationships obtained for precipitation may be transferred to sediment transport.

## STUDY AREA AND METHODS

The Ca l'Isard basin (1.3 km$^2$) is located within the Vallcebre basin (19.6 km$^2$) in the headwaters of the Llobregat River, in the southeastern Pre-Pyrenees at 1100 m a.s.l. (1º49'E, 42º12'N).

The bedrock comprises continental sediments of Garumnian facies (Palaeocene), in which smectite clays dominate, alternating with massive limestone beds. Clays are especially prone to landsliding and also favour concentrated erosion, generating locally developed badlands with high levels of geomorphic activity. Soils on clayey materials are of loamy texture.

The climate is Mediterranean humid and highly seasonal, with an annual average precipitation of 890 mm and an annual average temperature of 9ºC. The wet seasons are spring and autumn with a generally homogenous precipitation. The dry seasons are winter (little precipitation occasionally falling as snow), and summer (during which a water deficit usually develops). The summer deficit owes its origin more to relatively high temperatures than the lack of precipitation. Land covers in the Ca l'Isard basin are forest (70%), abandoned agricultural terraces (10%), sparse vegetation (8%), limestone outcrop (7%), and badland areas (4.5%) (Latron, 2003). Since 1990 the basin has been equipped with a gauging station using a hydrostatic pressure probe to measure water depth and temperature. The station is also equipped with an automatic water sampler, an infra-red backscattering turbidity sensor that measures suspended sediment concentrations up to 6 g L$^{-1}$, and an ultra-sonic beam attenuation sensor that measures sediment concentrations up to 240 g L$^{-1}$. All the readings of the instruments are stored in data loggers.

During the last five years, the mean annual runoff from the Ca l'Isard sub-basin was 81.5 mm, the mean runoff coefficient was 0.096, the suspended sediment yield was 4.8 Mg ha$^{-1}$ year$^{-1}$, and the dissolved sediment yield about 1 Mg ha$^{-1}$ year$^{-1}$. The maximum suspended sediment concentration, observed in July 2002, was 175 g L$^{-1}$. (Soler & Gallart, 2004).

The study period extended from October 1994 to September 2004. The hydrological year has been chosen for analysis instead of the calendar year, because it better reflects the seasonal variability of climate.

The variables considered in the analysis were storm and daily precipitation, maximum discharge, runoff and suspended sediment transport at the event scale. After a preliminary analysis of the annual maxima, following Cunnane (1973), Madsen *et al.* (1997) and Beguería (2005), partial duration series were used for assessing the magnitude–frequency relationships of the records. These are more efficient for parameter estimation than annual maxima series when the average number of annual occurrences is above 1.6 and exceedences are modelled by an exponential distribution. The annual flood series was derived from the assumed distributions of the annual number of occurrences and the magnitudes of the peaks over a selected threshold (Önöz & Bayazit, 2001). The partial duration series were obtained taking all events that exceeded the 90th percentile, obtaining a threshold of 36 mm for precipitation, 405 L $s^{-1}$ for maximum discharge, 11.8 mm for runoff, and 64 Mg for suspended sediment transport.

## RESULTS AND DISCUSSION

During the study period a total of 420 floods were measured. The highest monthly number of floods was registered in May (64), whereas February was the month with the least floods (5). The 22-year series of rainfall data from the Vallcebre basin showed that the rainiest month was May, with an average of 101 mm, and the driest month was February, with an average of 24 mm. The month with most days with precipitation higher than the 90 percentile was November (Fig. 1).

When the ranks of all the events (420) using the different variables were compared, the Spearman coefficients were significant (Table 1(a)). Nevertheless, when just the events exceeding the 90 percentile were compared, only some of the variables were significantly correlated, and these depended on the variable used for selecting the events in the analysis (Table 1(b)). When the ranks of the highest four events selected using the precipitation and sediment load criteria were compared (Fig. 2), the agreement among the different variables was very good for the chief event, but decayed for subsequent events. The annual numbers of events over the threshold for the different variables provided contrasting results (Table 2). Some years showed several events with high transport volumes against few or no runoff events over the threshold

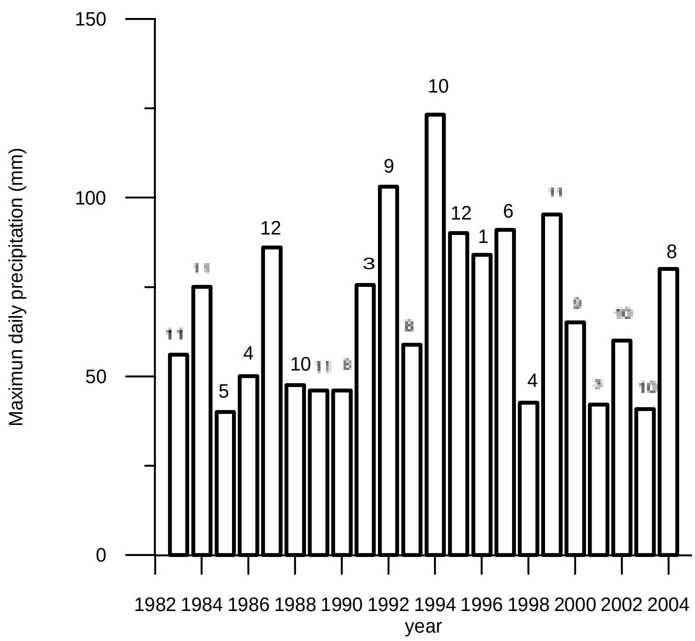


**Fig. 1** Annual maxima of daily precipitation observed during the 22-year record. Numbers over columns show the months when the maxima occurred.

**Table 1** Spearman's rank correlation coefficients among the ranks of the events obtained with different variables. (a) All events (420). (b) Events over the 90 percentile (42), selected using the variable of the row (every row represents a different sub-sample of events). Bold figures show that correlation is significant at the 0.01 confidence level.

| (a) All events | Precipitation | Peak discharge | Runoff | Sediment tr. |
|---|---|---|---|---|
| Precipitation | **1.00** | **0.50** | **0.50** | **0.66** |
| Peak discharge | **0.50** | **1.00** | **0.59** | **0.81** |
| Runoff | **0.50** | **0.59** | **1.00** | **0.73** |
| Sediment tr. | **0.66** | **0.81** | **0.73** | **1.00** |
| (b) Events >90 percentile | Precipitation | Peak discharge | Runoff | Sediment tr. |
| Precipitation | **1.00** | **0.45** | **0.54** | **0.52** |
| Peak discharge | 0.25 | **1.00** | **0.44** | **0.51** |
| Runoff | **0.63** | **0.62** | **1.00** | **0.69** |
| Sediment tr. | 0.19 | **0.65** | 0.07 | **1.00** |

**Table 2** Number of event as a function of each variable and each hydrological year.

| Year | 94–95 | 95–96 | 96–97 | 97–98 | 98–99 | 99–00 | 00–01 | 01–02 | 02–03 | 03–04 |
|---|---|---|---|---|---|---|---|---|---|---|
| Precipitation | 5 | 4 | 6 | 2 | 3 | 3 | 3 | 3 | 4 | 7 |
| Runoff | 3 | 3 | 5 | 1 | 2 | 3 | 1 | 16 | 6 | 2 |
| Peak discharge | 7 | 9 | 8 | 1 | 3 | 10 | 1 | 0 | 1 | 2 |
| Transport | 4 | 7 | 1 | 2 | 7 | 10 | 0 | 6 | 2 | 3 |

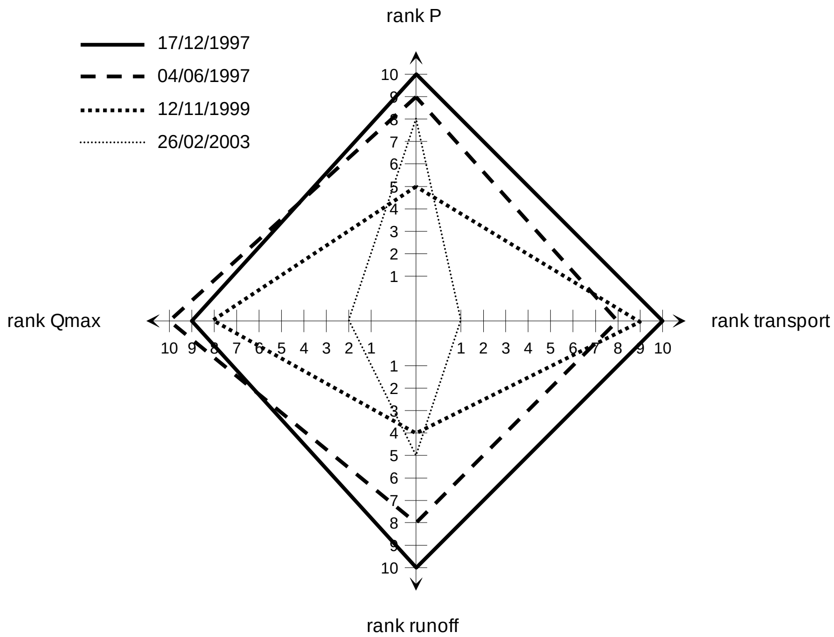


**Fig. 2** Four-axis diagram, showing the ranks on the diverse variables of the three events with the highest precipitation and sediment transport (the greater the scale values, the larger are event magnitudes).

(1999–2000), whereas the opposite occurred in other years (1996–97). Other years showed a good agreement among the number of events with high transport and runoff volumes (1994–95).

**Table 3** Result of magnitude–frequency analysis for annual maximum data.

| Function | Magnitude of the 50-year recurrence event | Max event recurrence interval (years) | Series |
|---|---|---|---|
| Gumbel | 136 mm | 33 | Precipitation (22 years) |
| Log-normal | 131 mm | 27 | |
| Gumbel | 139 mm | 21 | Precipitation (10 years) |
| Log-normal | 140 mm | 20 | |
| Gumbel | 4100 L $s^{-1}$ | 8 | Peak discharge (10 years) |
| Log-normal | 5130 L $s^{-1}$ | 6 | |
| Gumbel | 117 mm | 21 | Runoff volume (10 years) |
| Log-normal | 153 mm | 13 | |
| Gumbel | 5370 Mg | 27 | Sediment transport (10 years) |
| Log-normal | 10790 Mg | 14 | |

The recurrence interval estimated for the highest event in the record using the annual maxima (Table 3) was much longer than 10 years for all the criteria except for the peak discharge criterion, in spite of the 10-year length of most of the series. In this table, the discrepancy between the results obtained with the Gumbel and log-normal distributions was striking (2:1) for the sediment transport criterion.

## Precipitation and peak discharge

The maximum precipitation for a single event during the 10 years of study was 118 mm in October 1994. The goodness-of-fit of such events to a log-normal distribution was poor especially for the largest values in the series (Fig. 3(a)). Such large events tend to have a longer duration and this may explain this poor fit, as events during dry periods had an average duration of 16.6 h, whilst in wet periods this increased to 32 h (Soler & Gallart, 2004). Indeed, daily precipitation showed a much better fit to the log-normal distribution (Fig. 3(b)). According to the log-normal distribution, the maximum daily precipitation that has been collected in the period of study would have a recurrence interval of 20 years.

A maximum peak discharge of 2900 L $s^{-1}$ was reached in October 1994. It is worth stating that the flow during this and another three large events exceeded the calibrated gauging control, and therefore these measurements have a large error range. The fit of peak flows to a log-normal distribution was acceptable (Fig. 3(c)). According to this distribution, the maximum peak discharge would have a recurrence interval of 7 years, a period much smaller than those obtained for the other variables. We do not know if this difference is caused by the characteristics of the events and catchment response, or if it must be attributed to the error in the high discharge measurements.

## Runoff and suspended sediment transport

The maximum runoff for a single event was 96 mm in December 1997. The fit of the runoff series to a log-normal distribution was not satisfactory for the few highest runoff events (Fig. 4(a)). According to this distribution, the maximum runoff would

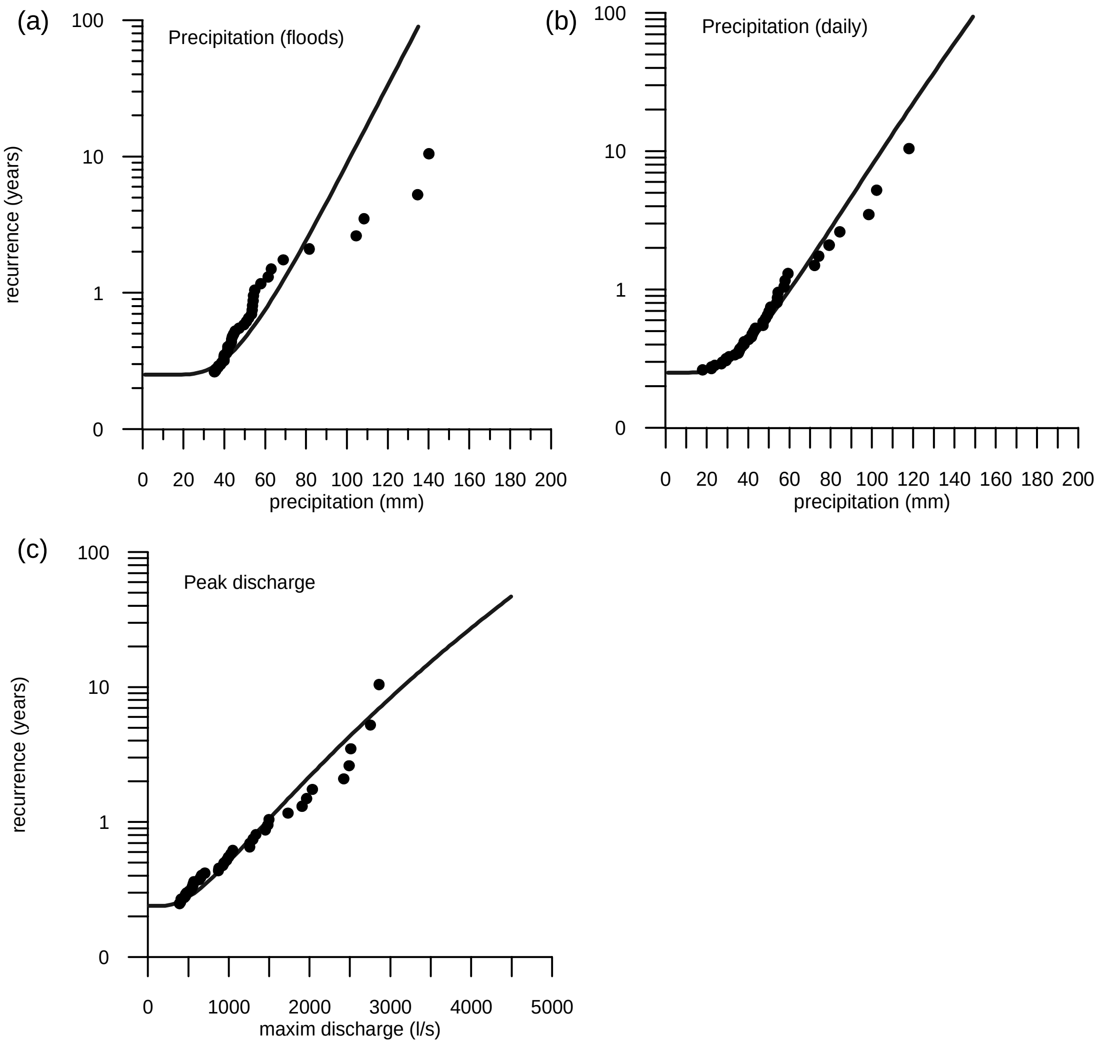


**Fig. 3** Magnitude-recurrence interval plots for the partial duration series and the fitted log-normal distribution. (a) Total precipitation during an event; (b) daily precipitation; (c) peak discharge.

have a recurrence interval of 96 years, which is not coherent with the results obtained with the other variables. Alternatively, a bi-modal log-normal distribution had a much better fit although the values increase considerably with higher recurrence intervals (Fig. 4(a)). The maximum event in these series would have a recurrence interval of 9 years according to the bimodal log-normal distribution. It is worth recalling that the recurrence intervals estimated for the main event using annual maxima series showed diverging results when the Gumbel (21 years) and log-normal (13 years) distributions were applied.

At Ca l'Isard, the 10 main suspended-sediment transporting floods only represent 2% of the total record but transported 68% of the material in suspension during the 10 years of study. Three events exceeded 1500 Mg: December 1997 (4600 Mg), November 1999 (3400 Mg) and June 1997 (1800 Mg).

The fit of the sediment transport events to a log-normal distribution was very poor, especially for the largest events that clearly overestimated their respective recurrence

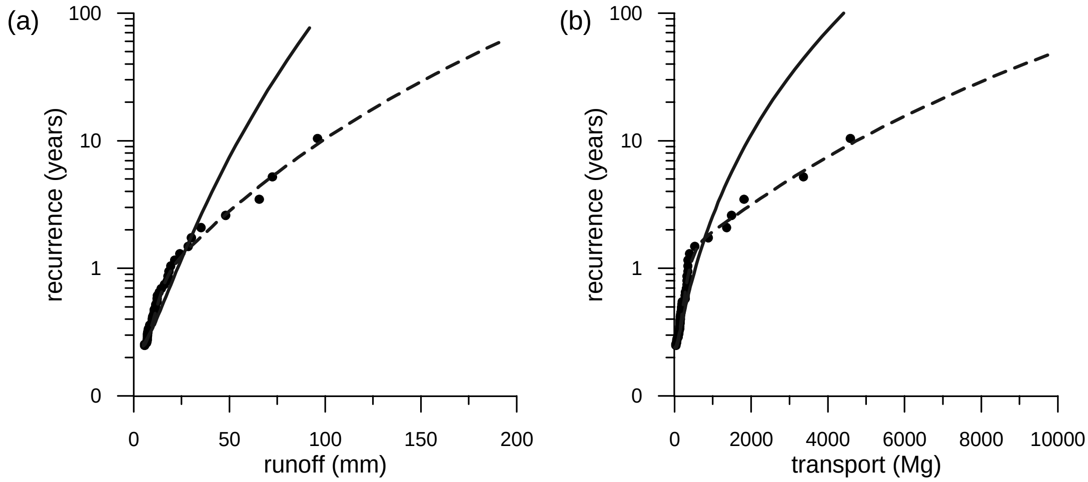


**Fig. 4** Magnitude-recurrence interval plots for the partial duration series and the fitted log-normal distribution (solid curve) and bi-modal log-normal distribution (discontinuous curve). (a) Runoff volume; (b) sediment transport.

intervals (Fig. 4(b)). As described earlier for the event runoff, a bi-modal log-normal distribution was adjusted to this series, reaching a good fit (Fig. 4(b)). The maximum event in the series would have a recurrence interval of 115 years according to the log-normal distribution but 8 years according to the bimodal log-normal distribution. It is worth recalling that the recurrence intervals estimated for the main event using annual maxima series showed diverging results when the Gumbel (27 years) and log-normal (14 years) distributions were applied. Nevertheless, the divergences were much smaller for the annual maxima than for the partial duration series, and the recurrence intervals obtained from the first were more reasonable than those obtained from the second.

## CONCLUSIONS

Partial duration series for daily precipitation and peak discharge showed good fits with log-normal distributions. On the other hand, event precipitation, runoff volumes and sediment transport had poorer fits. The poor fits of the second variables may be attributed to the increase of event duration with event magnitude. Runoff volume and sediment transport series had good adjustments to bi-modal distributions.

The 10-year record contained the two largest precipitation events that occurred during the 22-year precipitation record. This means that the actual recurrence intervals for these events are expected to be higher than 10 years. Indeed, using most of the five variables and methods (but excluding the peak discharge and some of the analyses made with transport amounts), the maximum event in the record had a recurrence interval exceeding 20 years. Instrumental errors may provide an explanation for the divergence of the peak discharge series from the modelled distribution, whereas a bi-modal distribution of transport events may provide an explanation for its divergence from the standard log-normal distribution.

For the two largest events, there was a good consistency between their rank (using different measures of magnitude: precipitation, peak flow, runoff volume and sediment load), but this consistency was somewhat lost for the intermediate events. Precipitation may therefore be helpful in identifying large magnitude events, and may be used as a surrogate for the main sediment transport events, but not for those of intermediate magnitude. The daily precipitation series was much better modelled with a log-normal distribution than the event precipitation series, presumably because of the progressive increase in event duration when larger events were included

One of the main purposes of this work (i.e. the determination of recurrence intervals of observed sediment transport events) was only partly achieved. Indeed, the annual maxima series provided diverging results depending on the distribution function used, and the partial duration series showed a distribution that suggested a bi-modal character. The results obtained with the annual maxima sediment transport series are more consistent than the results obtained with the other variables. Nevertheless, the problems encountered confirm the complexity of transport phenomena in this catchment and deserve further attention regarding the role of antecedent conditions (soil moisture, sediment stores) and event characteristics (rainfall intensity) in transport dynamics.

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