Temporal variability in the relationships between precipitation, discharge and suspended sediment concentration in a small Mediterranean mountain catchment

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Abstract Relationships between discharge and suspended sediment are very complex in most Mediterranean catchments. In the case of the Arnás catchment (Central Spanish Pyrenees), with a long history of human activity, the main factors that explain the variability of suspended sediment concentration (SCC) during floods are the peak flow and the intensity of precipitation. A cluster analysis distinguishes four types of floods according to different characteristics of precipitation, discharge, suspended sediment transport and antecedent moisture conditions. G1 and G2 floods occur under dry conditions (which prevail most of the year), with moderate rainfall and low precipitation intensity; the discharge and suspended sediment response are very fast but limited in intensity. This suggests that the origin of water and sediment is restricted to areas located very close to the channel. G3 floods also occur under dry conditions, although during intense rainfall events; then the response in both discharge and suspended sediment is very high, showing an enlargement of the contributing areas. Under very wet conditions (G4 floods) relatively moderate precipitation produces a very high response in discharge, but suspended sediment concentration records moderate values due to the effect of dilution when the entire catchment is contributing.

Keywords Antecedent humidity; Central Spanish Pyrenees; experimental catchment; floods; sediment sources; suspended sediment

Introduction

Mediterranean water resources mainly depend on the hydromorphological functioning of the watersheds in mountainous areas (Thornes 1999). The strategic importance of the latter has spurred the development of research projects which try to understand runoff generation and sediment yield, along with the temporal variability of runoff and sediment contributing areas in a changing scenario. Mediterranean areas are subject to large-scale land-use changes like farmland abandonment of steep cultivated slopes (Lasanta-Martínez *et al.* 2005), plant colonisation of the old fields (Molinillo *et al.* 1997), reforestation (Ortigosa *et al.* 1990), and enlargement of ski resorts. How these complex processes affect the quality and quantity of water resources, reservoir siltation and the dynamics of fluvial channels is a key question for understanding the characteristics and temporal trends of water resources in Mediterranean basins.

The research made at different temporal and spatial scales points in the same direction: streamflow is progressively decreasing regardless of climate oscillations (Beguería *et al.* 2003), and sediment sources undergo a clear spatial shrinkage partially compensated by erosion in fluvial channels (García-Ruiz and Valero-Garcés 1998). Studies carried out in different

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experimental catchments confirm the hydrological and sedimentological contrasts resulting from different plant covers and land uses (Llorens and Gallart 1992; Cosandey *et al.* 2005).

In Mediterranean areas sediment budget is mainly dominated by suspended sediment (Webb *et al.* 1995). Several papers illustrate the complexity of hydrological response and sediment transport due not only to the seasonal variability of rainfall events but also to the state of the catchment before the rainstorm (antecedent rainfall, soil moisture content, water table level) and the dynamics of runoff and sediment contributing areas (Klein 1984; Gallart *et al.* 2002; Seeger *et al.* 2004; García-Ruiz *et al.* 2005). This variability is enhanced in Mediterranean environments, where the precipitation regime is very irregular and soils are remarkably degraded due to the strong human pressure. As a consequence, on a scale of events, the relationships between precipitation, discharge and suspended sediment transport show an extremely high variability (Dunne and Black 1970; Williams and Baird 1970), thus making the implementation of predictive hydrological and sedimentological models difficult. The understanding of this variability is one of the keys to improving hydrological modelling in order to forecast the consequent effects of land use or plant cover change.

The main purposes of this paper are: (i) to order the relationships between precipitation, discharge and suspended sediment transport in a middle mountain Mediterranean catchment; (ii) to identify the factors that explain the temporal variability of suspended sediment concentration; and (iii) to distinguish different types of floods according to precipitation, discharge, suspended sediment transport and antecedent moisture conditions.

Study area

The Arnás catchment (284 ha) is located in the central part of the Spanish Pyrenees, in the basin of the upper Aragón River, a northern tributary of the Ebro River (Figure 1). The highest peak is at 1340 m a.s.l. and the outlet at 900 m a.s.l. The climate is sub-Mediterranean with Atlantic influences and is defined as a Cfc climate according to Köppen classification (De la Riva 1997). The average annual rainfall is about 1000 mm in the lower part of the catchment, mostly concentrated in autumn and spring.

The bedrock is Eocene Flysh with alternating sandstone and marl layers sloping northward. The NNW–SSE orientation of the stream results in a strong contrast between the

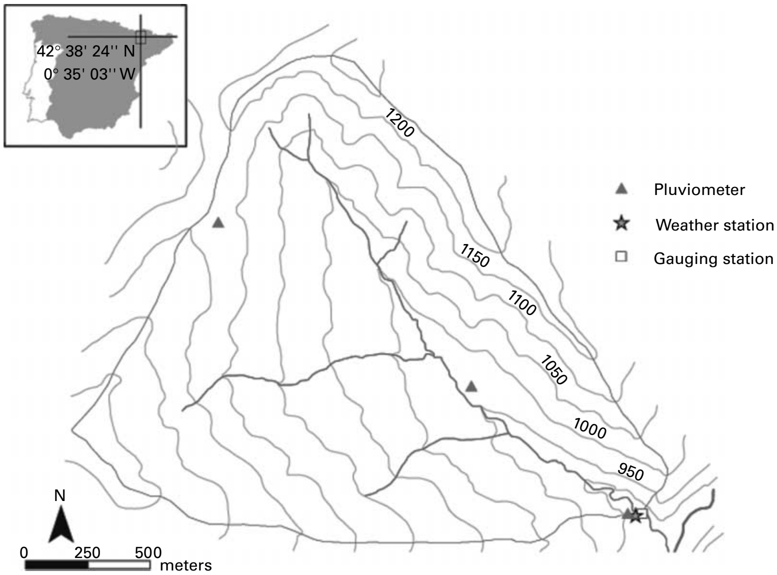

Figure 1 The Arnás catchment

south- and north-facing slopes. In the former there are some old debris flows disconnected from the drainage network. Stoniness and low field capacity Calcaric Regosol and Rendsic Leptosol soils suggest that this area has been affected by water erosion. The gentler, north-facing slope is characterised by old scars and tongues belonging to deep mass movements, nowadays inactive. Deep and well developed Haplic Kastanozems and Haplic Phaeozems soils predominate. Calcaric fluvisols occupy the valley bottom.

A field survey along the main channel showed that the principal sources of sediment are the bare sections of the slopes flanking the stream. These areas cover a surface of approximately 2200 m^2 and represent less than 1% of the catchment. The lack of vegetation and the occurrence of small slumps indicate that they are permanently eroded (González *et al.* 1997).

The catchment was totally cultivated until the middle of the 20th century with cereal crops in non-terraced fields, though some stone walls reduce the gradient at the lower end of the plots. Steeper and convex slopes of the sunny side were cultivated under shifting agriculture systems. Since then, the catchment has been abandoned and affected by a process of natural plant colonisation with *Genista scorpius*, *Buxus sempervirens*, *Rosa* gr.*canina*, *Juniperus communis* and *Echinospartum horridum*. The highest areas have been partially colonised by *Pinus sylvestris* and *Quercus faginea*. At present, the catchment is grazed by cows and sheep.

Equipment and methods

At the outlet of the Arnás stream a weather station and a gauging station have been installed. The latter is equipped with an ultrasound sensor (Lundahl DCU-7110) to measure the water level; a turbidity meter (LYX 800 PT1) to measure suspended sediment load; and a conductivity meter (Dr Lange) to estimate water conductivity. The turbidity meter was calibrated in the laboratory using fine sediment from the catchment. The calibration has been performed successfully three times since its installation in order to test its robustness through time. All these sensors, along with a pluviometer, are connected to data loggers that record average data every 5 min. Information is downloaded every 15 d into a portable computer. After data treatment, continuous series of discharge, sediment and rainfall are obtained. Floods are identified as an increase in discharge greater than 1.5 times the base flow discharge prior to the beginning of the rainfall event. The beginning and the end of the flood are determined visually.

The catchment has been monitored since 1996 so that 91 floods presenting reliable information have been selected between 1997 and 2003 (a six year period, considering that during 1998 there was a significant lack of data). For each flood a data base has been generated with variables related to (Table 1):

- The rainfall causing the event: total amount of rainfall (PTOT, mm), maximum rainfall intensity in 30 min (IPMAX, mm h^{-1}) and rainfall 1, 3 and 7 d before (AP1, AP3 and AP7, respectively, mm).
- Discharge: total runoff (QVOL, m^3), mean discharge (QMEAN, l s^{-1}), peak flow (QMAX, l s^{-1}), runoff coefficient (RC) and base flow at the beginning of the flood (BF0, l s^{-1}).
- Suspended sediment: suspended sediment transport (SSVOL, Mg) and maximum suspended sediment concentration (SSCMAX, g l^{-1}).

After evaluating the descriptive statistics, relationships between suspended sediment transport and maximum suspended sediment concentration, and the variables considered, have been explored through a linear correlation matrix. A stepwise regression was carried out in order to determine and rank the variables that explain the variability of suspended sediment concentration. A cluster analysis using Ward's method and introducing all the variables distinguished four types of floods according to different characteristics of

Table 1 Characteristics of the analysed events

	Min.	Max.	Mean.	S.D.
PTOT mm	2.4	57.0	16.0	11.0
IPMAX mm h^{-1}	2.4	57.6	19.0	8.4
QVOL m^3	27.3	54597.6	7410.6	9247.9
QMEAN l s^{-1}	3.3	1332.0	216.6	217.2
QMAX l s^{-1}	7.0	4152.4	551.2	687.4
RC	0.00	0.69		
BF0 l s^{-1}	0.0	631.5	74.2	106.8
SSVOL Mg	0.0	78.9	9.4	17.5
SSCMAX g l^{-1}	0.0	9.9	2.0	2.0
AP1D mm	0.0	77.0	10.8	13.3
AP3D mm	0.0	77.4	20.3	17.1
AP7D mm	0.0	109.6	36.0	27.7

$n = 91$; PTOT mm, Total amount of rainfall; IPMAX mm h^{-1}, Maximum rainfall intensity in 30 minutes; QVOL m^3, Total runoff; QMEAN l s^{-1}, Mean discharge; QMAX l s^{-1}, Peak flow; RC, Runoff coefficient; BF0 l s^{-1}, Base flow at the beginning of the event; SSVOL Mg, Sediment transport; SSCMAX g l^{-1}, Maximum suspended sediment concentration; AP1D mm, Rainfall 1 day before the event; AP3D mm, Rainfall 3 days before the event; AP7D mm, Rainfall 7 days before the event; S.D., standard deviation

precipitation, discharge and suspended sediment transport. An ANOVA with Bernoulli *post hoc* test was performed to test the differences between the groups and set their main features.

Results

Table 1 summarises the main characteristics of the 91 floods selected from between 1997 and 2003. Although the maximum value of rainstorm (PTOT) was 57 mm (16/12/1997) and the maximum intensity (IPMAX) was 57.6 mm h^{-1} (07/09/2003), most of the events were of small magnitude: more than 60% were related to rainfalls of less than 15 mm and peak flows below 500 l s^{-1}. Only 5 floods had peaks greater than 2000 l s^{-1}. The runoff coefficient varied between 0 and 0.6. Suspended sediment was always transported during floods; in 50% of the cases it was less than 1 Mg and only during 23 floods (25%) was it more than 10 Mg. The maximum suspended sediment concentration was almost 10 g l^{-1} (07/09/2003). The values of antecedent rainfall were quite diverse and varied between no rain during the 7 d before the storm flow and 77, 77.4 and 109 mm 1, 3 and 7 d, respectively, prior to the event.

Figure 2 shows that the relationship between peak flow and maximum suspended sediment concentration is statistically significant ($r^2 = 0.55$). Although a significant and positive trend, the scattering of the points is notable. For instance, for a 1000 l s^{-1} peak flow, the resulting maximum suspended sediment concentration is between 1.5 and 5.5 g l^{-1}. Thus, at event scale, suspended sediment concentrations do not depend exclusively on discharge.

Table 2 presents the linear correlation coefficients of suspended sediment transport (SSVOL) and maximum suspended sediment concentration (SSCMAX) with the variables describing the characteristics of the rainfall (PTOT, IPMAX), the flood event (QVOL, QMEAN, QMAX, RC, BF0) and the antecedent moist conditions of the catchment (AP1, AP3, AP7), considering all the floods and distinguishing between the two seasons defined in García-Ruiz *et al.* (2005); wet season (November–May) and dry season (June–October):

- Total rainfall (PTOT) always shows significant correlation with both SSVOL and SSCMAX.
- Rainfall intensity (IPMAX) correlates particularly with SSCMAX. During the wet season it also correlates with SSVOL.

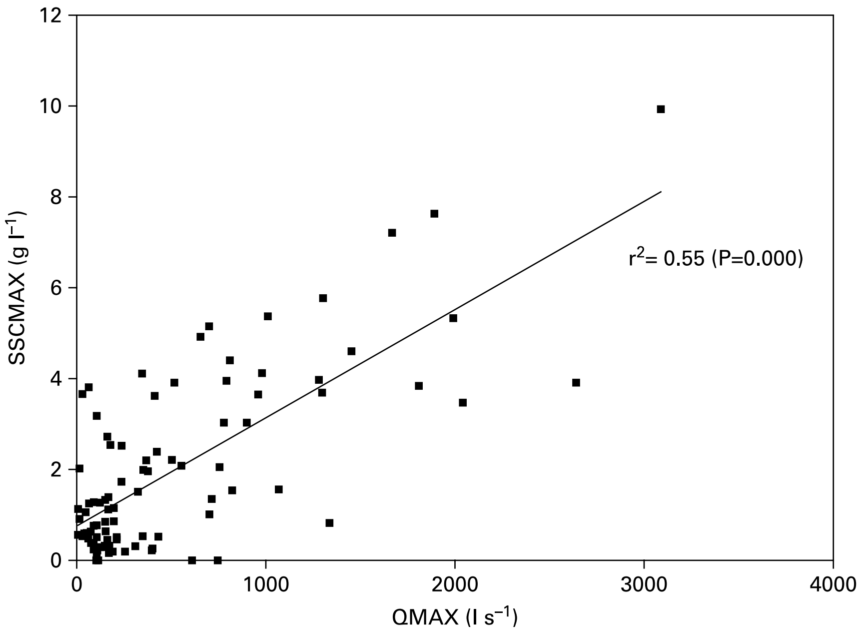

Figure 2 Relationships between peak flow (QMAX) and maximum suspended sediment (SSCMAX) at event scale

- SSVOL shows better correlations with QVOL, QMEAN, QMAX, RC and BF0 than SSCMAX does.
- The best correlations are found between SSVOL and QVOL, and between SSVOL and QMAX, during the dry season.
- The correlation between SSCMAX and QMAX improves considerably during the dry season.

Table 2 Linear correlation coefficients between suspended sediment transport (SSVOL) and maximum suspended sediment concentration (SSCMAX), and variables describing the characteristics of the events. A distinction between wet season (November–May) and dry season (June–October) has been considered

	All floods (n = 91)		**Wet season (n = 68)**		**Dry season (n = 23)**	
	SSVOL	**SSCMAX**	**SSVOL**	**SSCMAX**	**SSVOL**	**SSCMAX**
PTOT	**0.559**	**0.582**	**0.548**	**0.569**	**0.620**	**0.611**
IPMAX	0.188	**0.464**	**0.276**	**0.530**	0.346	**0.539**
QVOL	**0.836**	**0.509**	**0.856**	**0.586**	**0.850**	**0.576**
QMEAN	**0.719**	**0.496**	**0.733**	**0.567**	**0.669**	**0.437**
QMAX	**0.822**	**0.741**	**0.843**	**0.697**	**0.863**	**0.810**
RC	**0.414**	**0.174**	**0.417**	0.232	**0.464**	0.203
BF0	**0.234**	0.061	**0.268**	0.105	0.124	− 0.002
SSVOL	1.000	**0.764**	1.000	**0.772**	1.000	**0.840**
SSCMAX	**0.764**	1.000	**0.772**	1.000	**0.840**	1.000
AP1D	0.016	− 0.027	0.092	0.036	− 0.173	− 0.176
AP3D	0.033	0.022	0.069	0.047	− 0.083	− 0.039
AP7D	− 0.038	− 0.077	− 0.010	− 0.051	− 0.134	− 0.170

Correlation is significant at the 0.01 level
Correlation is significant at the 0.05 level

- Suspended sediment does not show any significant relationship with the antecedent moisture of the catchment (AP1, AP3, AP7).

A stepwise regression analysis (Table 3) indicates that two variables explain 65% of the variability of maximum suspended sediment concentration (SSCMAX). The peak flow (QMAX) is positively related to SSCMAX, while the base flow at the beginning of the flood (BF0) is inversely related to it. During the wet season, 70% of the peak of suspended sediment variability is explained by QMAX, QMEAN, IPMAX and PTOT. During the dry season, the explained variability is similar ($r^2 = 0.71$) with QMAX and BF0 as controlling factors.

A cluster analysis of all the variables divides the floods into four groups (G1, G2, G3 and G4). Table 4 shows the main characteristics (mean values) of each group.

Group 1 includes 36 floods (40%). These floods occur during moderate and low intensity rainfalls (PTOT = 17.8 mm; IPMAX = 9.4 mm h^{-1}). Antecedent rainfall is low and the catchment is in a very dry condition, as the base flow at the beginning of the flood demonstrates (BF0 = 29.7 l s^{-1}). As a consequence, floods show a low response, with a maximum peak flow of 376.3 l s^{-1}. Runoff coefficients are also low (RC median = 0.04), thus suggesting that most of the precipitation goes to restore the moisture status of the catchment. Suspended sediment transport and suspended sediment concentrations record low values (SSVOL = 2.8 Mg; SSCMAX = 1.4 g l^{-1}).

Group 2, with 38 floods (42%), is characterised by low values of both rainfall (PTOT = 10.6 mm) and rainfall intensity (IPMAX = 7.2 mm h^{-1}). The moisture status of the catchment is medium since the antecedent rainfall is relatively high (AP1 = 14.3 mm; AP3 = 29 mm; AP7 = 56.7 mm) and the base flow, even if still low, is slightly above the base flow of Group 1. Thus, with Group 2 rainfall values below those of Group 1, the hydrological responses in both groups are similar, except for peak flow values that are lower in Group 2 (QMAX = 271.1 l s^{-1}). The sedimentological response is also of the same magnitude as it is in Group 1 (SSVOL = 2.6 Mg; SSCMAX = 1.3 g l^{-1}), in accordance with the low rainfall intensity. This group corresponds, in part, to floods triggered a few days later than the Group 1 floods.

Group 3 includes 13 floods (14%) with the highest and most intense rainfalls (PTOT = 27.3 mm; IPMAX = 17 mm h^{-1}). The antecedent moisture condition of the catchment can be considered as low, with limited antecedent rainfall (AP1 = 5.8 mm; AP3 = 14.5 mm; AP7 = 26.1 mm). Because of the high values of the rainfall, peak flow is relatively high (QMAX = 1478.5 l s^{-1}) even though the runoff coefficients are moderate (RC median = 0.16). Both suspended sediment transport and suspended sediment concentrations show the greatest values (SSVOL = 43 Mg; SSCMAX = 5.4 g l^{-1}), thus indicating the influence of the peak flow and the intense rainfall. These floods occur when the catchment is relatively dry but reacts rapidly due to the high values of rainfall and rainfall intensity, triggering intense processes of erosion and suspended sediment transport.

Only four floods are included in Group 4. They are related to moderate rainfall and low intensity rainfall (PTOT = 14.3 mm; IPMAX = 7 mm h^{-1}). However, these floods occur when the catchment is very wet, after significant antecedent rainfalls during the previous week, especially one day prior to the event (AP1 = 49.3 mm). The high moisture condition of the catchment is reflected in the base flow that reaches 496.2 l s^{-1}, a value which is greater than the peak flow of Groups 1 and 2. This suggests that these floods occurred a few days/hours later than another flood, when the catchment is able to react very fast against any precipitation. Consequently, peak flows (QMAX), total discharge (QVOL), mean discharge (QMEAN) and runoff coefficients are the highest among the four groups. In this case, maximum suspended sediment concentration is moderate (SSCMAX = 2.4 g l^{-1}), clearly

Table 3 Stepwise regressions: standarize *B* coefficients and significance level (*p*)

Dependent variable: SSCMAX								
All floods (n = 91)			**Wet season (n = 68)**			**Dry season (n = 23)**		
	B	**P**		**B**	**P**		**B**	**P**
QMAX	0.910	0.000	QMAX	1.634	0.000	QMAX	0.913	0.000
BF0	− 0.363	0.000	QMEAN	− 1.159	0.000	BF0	− 0.307	0.019
			IPMAX	0.265	0.000			
			PTOT	0.178	0.027			
	r^2			r^2			r^2	
Model summary	0.65	0.000	Model summary	0.70	0.027	Model summary	0.71	0.019

Table 4 Average values and ANOVAS for variables of different groups of floods

Variables	G1	G2	G3	G4
PTOT mm	17.8	10.6	27.3	14.3
IPMAX mm h^{-1}	9.4	7.2	17.0	7.0
QVOL m^3	4153.1	4730.1	19419.3	23165.0
QMEAN l s^{-1}	122.6	149.4	469.5	878.3
QMAX l s^{-1}	376.3	271.1	1478.5	1771.9
RC median	0.04	0.07	0.16	0.36
BF0 l s^{-1}	29.7	68.0	86.1	496.2
SSVOL Mg	2.8	2.6	43.0	24.3
SSCMAX g l^{-1}	1.4	1.3	5.4	2.4
AP1D mm	4.7	14.3	5.8	49.3
AP3D mm	8.7	29.0	14.5	61.0
AP7D mm	13.5	56.7	26.1	73.9
No. of cases	36	38	13	4

n = 91; Significance level: 0.01

lower than in Group 3. Due to the volume of water, suspended sediment transport is high (SSVOL = 24.3 Mg), almost ten times greater than in Groups 1 and 2, thus suggesting that the bare ground areas still provide sediment to the channel. However, its importance is diluted within the high discharge. That is to say, there is presumable still hill-slope erosion but the relative contribution of eroded areas decreases because of the enlargement of the runoff contributing areas.

Figure 3 presents four examples of flood hydrographs with their corresponding sedigraphs and hyetographs for each group. All of them show (i) a rapid hydrological and sedimentological response (the time lag between the beginning of the rainfall and both the beginning of the

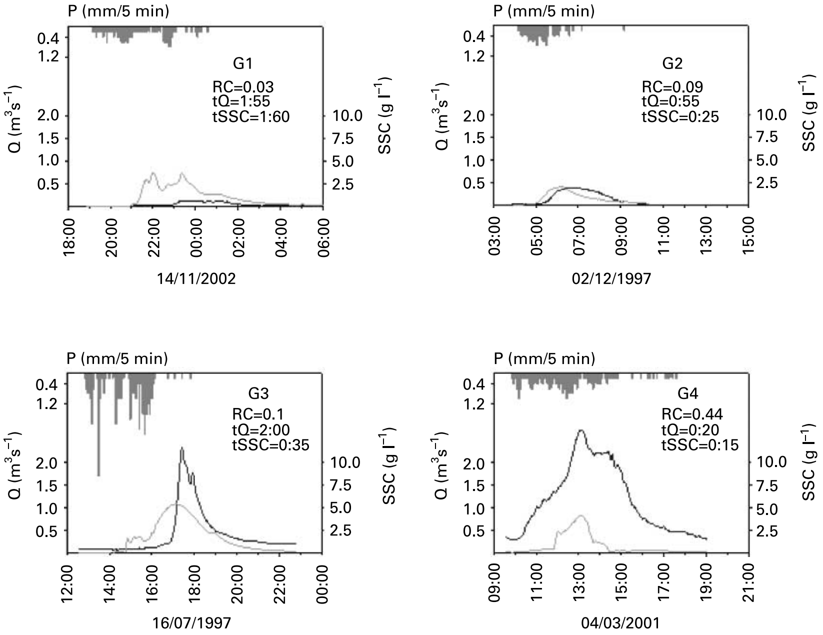

Figure 3 Hydrographs, sedigraphs and hyetographs for each group G1, G2, G3 and G4 (tQ: time lag between the beginning of the rainfall and the beginning of the hydrological response; tSSC: time lag between the beginning of the rainfall and the beginning of sedimentological response)

hydrological response and the beginning of the sedimentological response is below two hours), indicating that the contributing areas are either close to the channel or well connected to it and (ii) a good fitting between the shape of the hydrograph and the hyetograph, reflecting overland flow or fast throughflow processes (García-Ruiz *et al.* 2005). Diverse time lags between the peak flow and maximum suspended sediment concentration are observed, as Seeger *et al.* (2004) demonstrated in exploring Q-SSC hysteretic loops. The *clockwise hysteretic* floods (Figure 4) are the most common, characterised by a peak of sediment prior to the peak flow that indicates a rapid displacement of the sediment near the channel (the bulldozer effect, Regüés *et al.* 2000). From the floods depicted in Figure 3 it can be observed that, after a first peak, suspended sediment concentration hardly reacts to further increases in discharge. This is due either to a depletion of suspended sediment sources, which is quite unlikely, or the arrival of clean water as a consequence of the enlargement of the contributing areas.

The few floods in Group 4 do not permit an exhaustive analysis of seasonality. Nevertheless, these floods dominated within the wet season, characterised by long periods of rainfall that favour high runoff coefficients. The floods in Group 1 and 3, on the other hand, correspond to periods with low antecedent rainfall. While Group 3 floods are proportionately more related to the dry season, Group 1 floods occur throughout the year, as is also the case for Group 2 floods. However, the latter show wetter conditions, thus confirming that most of them are a continuation of floods in Group 1.

All the floods considered in this study are plotted in Figure 5, according to peak flows (QMAX) and maximum suspended sediment concentrations (SSCMAX), distinguishing between the four groups. Centroids for each group are also represented. There is a confusion between Groups 1 and 2 as all the floods appear in the bottom-left part of the graph, thus showing that these are floods with similar hydrological and sedimentological responses even though the rainfall characteristics and the antecedent moisture conditions are relatively different. Floods in Group 3 have high values of discharge and suspended sediment concentration so that they appear in the upper-right part of the graph. A greater weight of suspended sediment concentration can be observed in relation to the peak flow. Finally, Group 4 floods are plotted below floods in Group 3, reflecting the effect of dilution processes under high base flow conditions.

Discussion and conclusions

This paper confirms the complex and heterogeneous character of the responses of suspended sediment during floods in Mediterranean catchments, strongly influenced by the discharge but also by the rainfall characteristics and the antecedent moisture condition of the catchment (Ceballos and Schnabel 1998; Gallart *et al.* 2002).

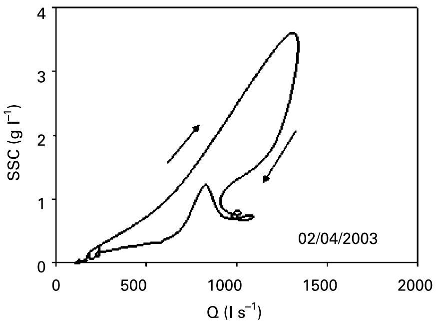

Figure 4 Example of a clockwise hysteretic loop, corresponding to the event of 02/04/2003

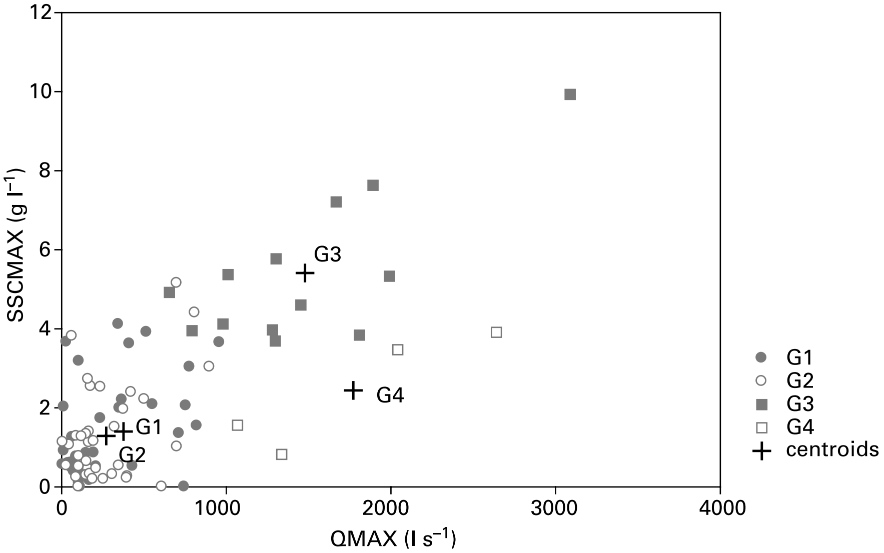

Figure 5 Relationships between peak flow (QMAX) and maximum suspended sediment (SSCMAX) distinguishing the 4 groups of floods

The analysis of a long series of data (91 floods over a 6 year period) indicates that the main factor in explaining the suspended sediment concentration variability is the peak flow. The influence of the rainfall intensity, greater than that of the total rainfall, enhances the effect of the kinetic energy of the rainfall on bare ground areas (Torri *et al.* 1999), suggesting that a relatively important part of the sediment is mobilised by *splash*. In this study, suspended sediment concentration increases with intense rainfall as in the case of Group 3. On the other hand, with less intense rainfall, the peak of sediment is lower, even with high discharges (Group 4). It is very likely that such a mobilisation takes place in unvegetated areas close to the channel. However, rainfall intensity only influences the sediment response during the wet season since during the dry period the latter is mainly controlled by the peak flow. This suggests that, when the soil is very dry, the determinant factor is not rainfall intensity, which can be absorbed by the soil, but hydrological response. This behaviour is also found in the Vallcebre catchment, where a rainstorm of 50 mm can have no hydrological response during the summer in catchments without badlands (Gallart *et al.* 1997).

The identification of four groups of floods reflects the high degree of variability of hydrological and sedimentological responses in the Arnás catchment as well as the influence of its antecedent moisture status and the rainfall characteristics. If the catchment is relatively dry, rainfall is moderate and rainfall intensity is low, then the hydrological and sediment response is also low. This is the case for Groups 1 and 2, whose peak flows and suspended sediment concentrations are very similar. Nevertheless, the antecedent rainfall conditions and, hence, the base flow at the beginning of the flood are higher in Group 2, whilst the intensity of rainfall is slightly higher in Group 1. These are the main features of most of the 91 floods analysed. With heavy, intense rainstorms, discharge and sediment concentration increase considerably (Group 3). The typical similarity between the hydrograph, the hyetograph and the sedigraph, as well as the rapid response of most of the floods, suggests that runoff and sediment are most probably generated over areas located near the channel (Seeger *et al.* 2004; García-Ruiz *et al.* 2005). Under wet conditions, moderate rainfall, even with low intensities, triggers a high hydrological response (Group 4): in this case, floods contribute with the greater discharge and the highest peak flows are recorded. Sediment transport and sediment concentrations are also high, though twice less than those of Group 3, indicating the occurrence of dilution effects. This suggests that water comes from all over the catchment, especially from vegetated areas that generate clean water, while sediment comes from the eroded places, especially from the channel itself; thus the enlargement of the contributing areas always implies a decrease of suspended sediment concentration.

Navas *et al.* (2005) found the highest erosion rates in the south-facing slope of the Arnás catchment by studying the ^{137}Cs distributions (up to 29.5 Mg ha^{-1} yr^{-1} for the upslope part and 14.3 Mg ha^{-1} yr^{-1} for the downslope part). Very low values were found in the north-facing slopes, with gentler gradients, deeper soils and denser plant cover. This study cannot confirm the exact origin of the sediment transported by the Arnás stream. Nevertheless, the relationships between discharge, rainfall and sediment transport suggest that the main sediment sources are (i) the bare sections of the slopes flanking the stream (in most of the floods the SSC peak precedes the peak flow: clockwise hysteretic loops), and (ii) the poorly vegetated areas in the lower parts of the south-facing slopes, reacting quickly during the most intense rainstorms.

Supposing that the material is constantly available, under dry conditions the hydrogeomorphological response in the Arnas catchment would be limited to the channel and neighbouring areas. Under wet conditions, runoff generation implies the contribution of clean water to the channel and an effect of dilution of the suspended sediment concentration.

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