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EVENT SEQUENCE AND SEDIMENT EXHAUSTION IN A RURAL CATCHMENT, NORTHWEST SPAIN

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ABSTRACT

Suspended solids discharge during consecutive rain episodes was observed in a small rural catchment in northwest Spain during a study of the sources of production and transport of these sediments. At the catchment outlet, discharge was measured and suspended solid samples were taken in the later portion of the rainy season, using an automatic sampler. A multi-interval sampling program was carried out. The results show that in a sequence of discharge peaks, the suspended solid concentrations present an increase and a reduction with flow. The lowest suspended solid concentrations obtained at the last discharge peaks seem to reflect an exhaustion of the sediment source during the succession of events. Clockwise hysteresis loops are described, and the sediment peaks were found to occur either prior to or with the discharge peaks. This type of relation can be explained by the presence of nearby sources and/or sediment exhaustion. Erosion of riverbanks and roads has been observed as important sources of suspended solids in the catchment.
Keywords: hysteresis, northwest Spain, sediment delivery, sequence events.

1 INTRODUCTION

Suspended sediment concentration (SSC) is a key parameter to compute sediment load and yields in rivers and it is essential to understand its variability in time and space in order to assess dynamics of a river for a given period of time.

The transport of suspended solids from the soil to continental waters represents one of the main causes of water quality degradation. Increasing SSCs can be detrimental to aquatic ecosystems by, for example, reducing light penetration, clogging aquatic vegetation and spawning gravels. Suspended sediment is a non-point pollutant whose concentration in natural streams varies rapidly and unpredictably. Suspended sediment has been shown to be an important vector for the transport of nutrients, heavy metals and organic contaminants in rivers.

In recent years, there has been increasing recognition of the need to include sediment control strategies within catchment management plans. Information on the source of the sediment transported by a river is an important requirement for designing effective sediment control strategies.

Studies intended to highlight the pattern of sediment concentration during hydrologic events have been reported by several authors [1–3]. These studies show that the relation between instantaneous measurements of SSC and water discharge is generally too variable; in particular, a lag between the peak of suspended solids and water discharge is often reported.

The features of hysteresis loops have been attributed to the location of the sediment source in the catchment [4], the riverbed [5] or riverbanks [6], to the duration and intensity of rainfall [7], and to the progressive lag of sediment concentration with flood waves [8].

Clockwise loops have often been attributed to depletion of available sediment in the catchment or in the stream channel [9–11], or to the successive reduction of the erosive effect of rainfall [12]. Increased proportion of baseflow during the falling stage has also been considered [6, 9, 12]. Counterclockwise loops have been attributed to distant sediment source, minor precipitation event occurring after the major event, providing additional silt/clay from runoff-derived sources [13] or due to bank caving events that occur on the recessing limb of the hydrograph, providing a local source of fine-grained sediment.

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The purpose of this study was to examine sediment delivery in a small rural catchment of northwest Spain, where suspended sediment dynamics are still not totally understood because only a few studies have been conducted.

2 MATERIAL AND METHODS

2.1 Study area

An agroforestry catchment was selected in Galicia, northwest Spain (Fig. 1). Corbeira is a small stream of approximately 10 km in length that drains into the Mero River in the A Coruña province. The elevation from the top of the catchment to the confluence of Corbeira with the Mero River is 400 m. Mean slope is about 19%. The drainage catchment area is 16 km^2. Land cover in the catchment is mostly forested (65%). Agriculture, which is based on pasture, maize and winter cereal crops, occupies the remaining 35% of the catchment. The bedrock underlying the catchment is schist. The soils within the catchment are mainly Cambisol and Umbrisol [14] with acid pH, silty loam texture and variable organic matter content. The climate is humid with a mean annual precipitation for 1985–2005 estimated at 1022 mm, mostly concentrated in October to February. The average annual temperature is about 13°C.

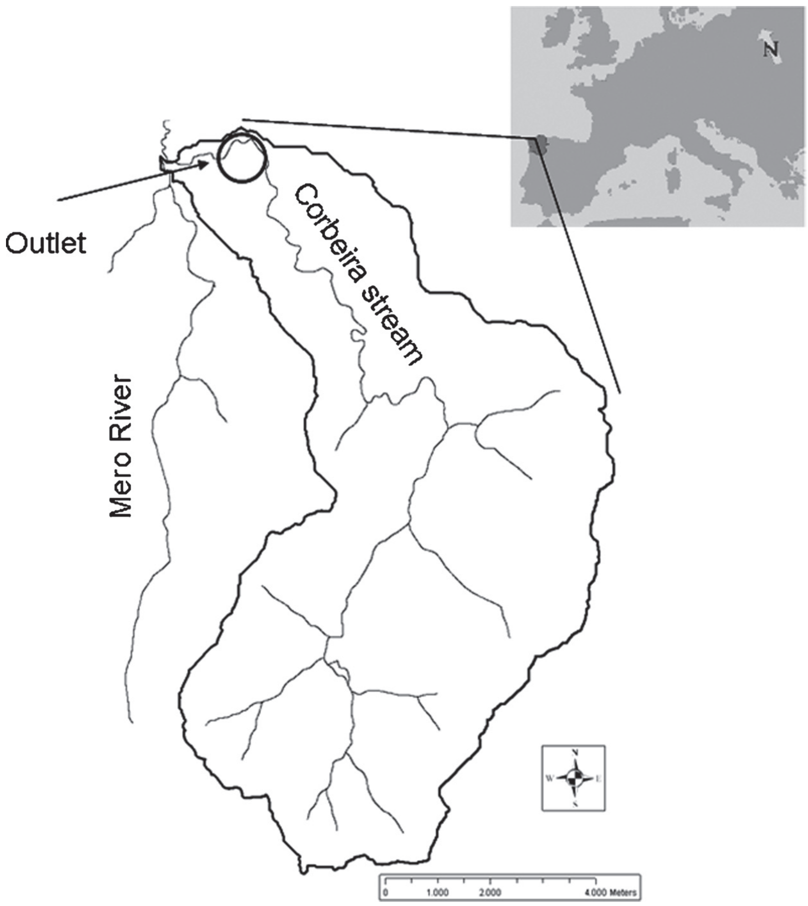

Figure 1: Location map of the study site.

2.2 Measurements of sediment output

Discharge (*Q*) was measured and suspended solid samples were taken at the catchment outlet. Samples were collected during the study period 16–26 February 2006, using an automatic sampler (ISCO 6712FS). The sampler could collect up to 24 samples of 1 L each. A multi-interval sampling program was carried out: samples were taken at 2-h intervals during the beginning and the main part of an event to record the rise and peak of suspended solid concentrations. During the recession, samples were taken every 6 and 8 h to record the recession rate of SSC. Within the catchment, rainfall characteristics were monitored.

The ISCO intake was installed 20 cm above the riverbed at the catchment outlet. Previous to sample collection, a rinse cycle was run in order to clean out the pipe so as to avoid sample contamination.

To determine SSC, 100 mL samples were filtered (0.45 μm pore diameter cellulose) using a Millipore vacuum-pump. The filters were dried in an oven at 105°C for 24 h and weighed on a precision scale to four decimal places.

Analysis of suspended sediment variability was structured in order to obtain the statistical relationship between SSC and discharge. In this study, the primary dataset was divided into data associated with each peak. Hysteretic relations between SSCs and discharge were analyzed by comparing *C*/*Q* ratios on the rising and falling limb of each peak for the same common value of *Q*.

3 RESULTS AND DISCUSSION

3.1 Response of water discharge to rainfall

The analyzed episode consisted of a peaks sequence that occurred between 16 and 26 February 2006. This was one of the wettest Februarys in the last 20 years; in fact, the 154.2 mm of precipitation recorded in the 10 days of the study period was much higher than the mean value (85 mm) observed for the period 1985–2005. Although the intensity (maximum intensity in 10 min was 2.6 mm) of the precipitations was not especially high, given its continuity and the prior saturation state of the soil, seven discharge peaks were found to have originated in the stream (Fig. 2).

Peak 1 was formed in response to a precipitation of 14.2 mm after nearly 15 days without rain. The maximum flow (0.26 m^3/s) was produced 6 h after maximum intensity rainfall. Subsequently, there was relatively continuous rainfall, giving rise to four peaks (peaks 2–5), with accumulated precipitation values of 41.8, 76.4, 92.6 and 122.6 mm. In the episode studied, peak 3 showed the greatest discharge (1.06 m^3/s, representing a specific discharge of 0.07 m^3/s/ km^2). This peak was formed with the same order of precipitation as that of peak 2. However, maximum discharge at peak 3 was threefold higher, demonstrating the importance of soil moisture for runoff to occur. Peaks 6 and 7 were generated with a precipitation of 15.6 and 12.2 mm, respectively.

The separation of flows in the hydrograph was complicated due to the characteristics of the rainfalls; however, there was a predominance of basal and subsurface flow over that of surface flow. There was a gentle increase in the peaks and prolonged decrease except in peak 3, which increased and decreased rapidly, which could be indicative of a strong influence of surface runoff.

3.2 Response of suspended solid concentration

Suspended solid concentrations ranged from 7 to 565 mg/L and the associated discharges were 0.54 and 1.06 m^3/s (Fig. 2). Mean SSC was 60 mg/L. The coefficient of variation was about 68%,

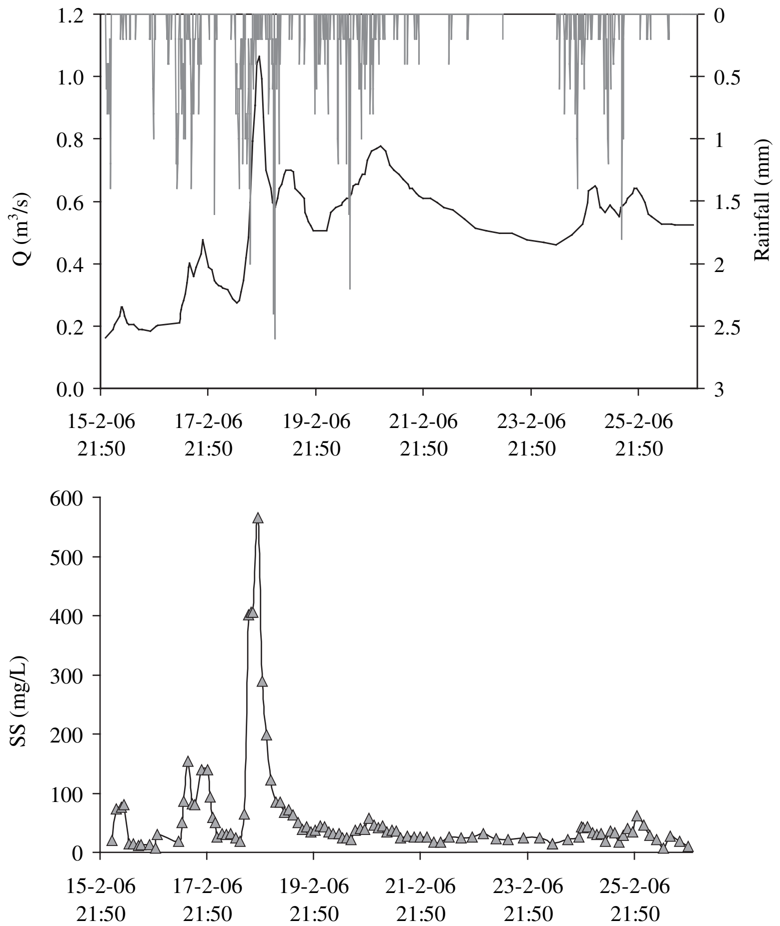

Figure 2: Stream hydrograph showing the precipitation and discharge (top) and suspended solid (SS) concentrations (bottom) at the catchment outlet.

with concentration equal or greater than 50 mg/L for 15.4% time. Huntley *et al.* [15] established a concentration of 50 mg/L as the limit above which the SSC can damage water quality. This value was surpassed in over 25% of the samples.

It is observed that, in this sequence of discharge peaks, the SSCs associated with later peaks are lower than those associated with the first ones (Fig. 1, Table 1). This suggests that after a period of relatively high sediment transport, sediment becomes less and less available and the sediment concentrations recorded during later peaks are consequently lower, i.e. the sediment availability exerts a primary control on the sediment load. Rovira and Batalla [16] and Hejduk *et al.* [17], among others, reported similar results. However, other authors observed that high sediment concentrations are exhibited in the later peaks. There are several explanations for these behaviors. For example, Walling and Webb [9], found that hill slope surface was able to recover and supply additional sediment whereas Hudson [3] indicates that inherent geomorphic thresholds between slope, soil and runoff are being exceeded, which would result in an additional flux of sediment.

Table 1: Basic characteristics of the sampled peaks.

	Date of peak	Peak discharge (m^3/s)	Maximum SSC (mg/L)
Peak 1	16/02/06 (7:20)	0.26	80
Peak 2	17/02/06 (19:20)	0.48	154
Peak 3	18/02/06 (20:40)	1.06	565
Peak 4	19/02/06 (10:40)	0.70	72
Peak 5	21/02/06 (2:50)	0.78	57
Peak 6	25/02/06 (2:30)	0.65	43
Peak 7	25/02/06 (21:00)	0.64	62

Table 2: Rating curve equations and regression coefficients. SS is suspended solids in mg/L and Q is discharge in m^3/s (r^2= correlation coefficient).

	Equation	r^2
All data	SS = 204.46Q – 45.99	0.17
Peak 1	SS = 954.04Q – 163.29	0.69
Peak 2	SS = 578.82Q – 127.12	0.66
Peak 3	SS = 657.61Q – 190.25	0.77
Peak 4	SS = 192.44Q – 59.63	0.51
Peak 5	SS = 61.67Q – 6.68	0.35
Peak 6	SS = 119.96Q – 36.78	0.41
Peak 7	SS = 213.66 Q – 92.78	0.39

Total suspended solid load was estimated. Load during the study episode was calculated using the mean values for discharge and concentration between two consecutive samples. The total suspended solid load for the episode studied was 27.2 tons, corresponding to an overall denudation rate of 2.5 tons/day.

When SSCs are plotted against Q, the slopes of the lines are assumed to be indicative of the suspended solid availability. Steep slopes are indicative of large quantities of suspended solid available for transport, whereas low slopes indicate a limited amount of suspended solid available for transport. Table 2 shows the relationship between Q and suspended solids for the data analyzed. Although there is a slight tendency for increase in suspended solids with Q, the considerable scatter, mostly associated with multi-peaks, suggests the complexity of factors influencing suspended solid transport. The scatter of the overall data, although a common feature in these kinds of relationships [18], is high as the correlation coefficient shows (Table 2). The r^2 value only explains 17 % of the variability of the scatter. The scatter has been reduced in each peak compared to all the data, and furthermore, the percentage of variance explained improves considerably. All peaks showed an increasing pattern of SSC with increasing discharge. However, the rate of increase was greater during the first three peaks than the later, which is represented by the exponents of the rating curve equations. In addition, the best relations between SSC and Q, with an r^2 of about 0.70, were obtained in the first three peaks.

Thus, suspended solid availability was highest at the beginning of the rain episode and decreased during subsequent peaks. On the other hand, for the later peaks, the slopes of the lines are less steep and the scatter about the lines is larger (r^2 of about 0.40), indicating limited suspended solid supply. This suggests that supply rather than transport controlled suspended solid dynamic during the later peaks.

The scatter in concentrations is, among other things, attributed to the exhaustion of the suspended solids available in the channel or to the differences in sediment availability at the beginning and end of the event [3, 19]. Consequently, SSCs and discharge during events often show hysteretic behavior related to a lag time between peaks of water and suspended solids.

In the Corbeira stream clockwise (or positive) hysteresis loops with great differences in concentration between rising and falling stages were found when suspended solids was plotted against discharge (Fig. 3). This common hysteresis means that the suspended solid peak occurred prior to or with the discharge peak. Heidel [8] reported that the peak of sediment concentration usually occurs prior to that of water discharge in small catchments, a hypothesis that seems to apply in general to small catchments of humid regions in the world. Several interpretations have been proposed to explain

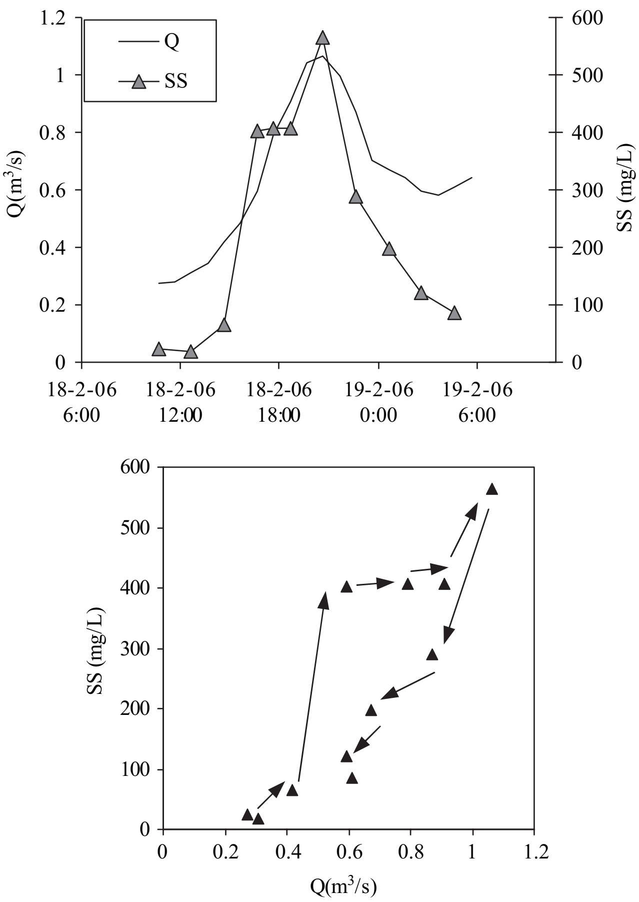

Figure 3: Plot of discharge and suspended solid (SS) concentration, and hysteresis loop for peak 3.

these clockwise hysteresis loops: (i) flushing and subsequent exhaustion of sediment from stream or nearby sources prior to discharge peak [11, 12]; (ii) an increased input from baseflow after the peak discharge [12, 20]; (iii) higher rainfall intensities at the beginning of the event [6]. In this study clockwise hysteresis in the SSC–Q relationship were attributed to sediment flushing and exhaustion from close sources to or in the stream. The rapid increase in SSC at the rising limb of the peak is explained by a rapid displacement of the suspended solids from sources near the sampling point. The decrease of SSC before the decrease of Q indicates that the suspended solids are limited. It was possible to observe how during the event the roads and riverbanks were significant sources of suspended solids. A decrease was also observed in SSCs during peak 4, as a result of the exhaustion of sediment to be transported, due to the intense activity of the preceding peak.

4 CONCLUSIONS

In a sequence of peak discharges, the suspended solid concentrations associated with the first water peaks were higher than those observed during the later peaks, although the magnitude of the peaks was similar. This can be related to the progressive exhaustion of available sediments to be transported during a sequence of events.

The relationships between suspended sediment and discharge show that the overall data set is not strongly dependent on the discharge, showing that other variables affect the concentration. However, the rating curves for each peak considerably improve the relationships, especially in the first peaks.

A clockwise hysteresis loop was found in the relationship between suspended solid concentration and water discharge. This type of relation can be explained by nearby sources and/or sediment exhaustion.

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