Analysis of suspended sediment concentration and discharge relations to identify particle origins in small agricultural watersheds

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Abstract The relationship between suspended sediment concentration (SSC) and discharge often is highly variable in headwater streams, which highlights the temporal changes in particle origin and availability in small catchments. This paper analyses this variability to identify suspended sediment (SS) origins in two small agricultural catchments in northwestern France. Turbidity and discharge were monitored at high frequencies at the outlets. Annual and monthly SS fluxes were very different in the two streams. At the flood scale, various methods were tested to trace sediment origins and to quantify their specific fluxes: SSC-discharge pattern interpretation, SS flux modelling, temporal variations in specific turbidity (turbidity/ SSC ratio), or phosphorus content. The high SS fluxes in one stream mainly were due to the mobilisation of instream sediment or to bank erosion. SS fluxes in the other stream mainly were due to slope erosion caused by intensive farming; however, input to this stream was limited because of naturally-occurring tree-lined banks.

Key words suspended sediment; stream bank erosion; hysteresis; flood; turbidity; discharge; particle availability; modelling

INTRODUCTION

Suspended sediment (SS) transported in rivers generally is a mixture of particles from different origins. Identifying these origins and then instituting management options may reduce SSC. Indeed, high SSC causes depletion of biological diversity, decreases oxygenation of habitats (Turnpenny & Williams, 1980), and decreases light penetration. SS also affects water quality because it serves as a vector for different contaminants within river systems (Martin & Meybeck, 1979). The identification and quantification of particle origins can be made by directly measuring soil or bank erosion (Osterkamp & Hedman, 1977); however, erosion rates are difficult to measure and do not accurately predict SS loads in rivers (Lawler, 1993).

The investigation of variations in the SSC–discharge relationship can be useful for inferring the dominant origins and processes contributing to the SS load in a river (Asselman, 1999; Bronsdon & Naden, 2000). The power function, SSC = aQ^b, where Q is discharge, is the most commonly used empirical relation to determine the SS load in a river in the absence of actual samples/measurements, and implies that concentration or flux is controlled by variations in discharge (Walling, 1977). The relation between discharge and SSC typically is site specific and rarely can be applied to another location. Further, even at a single location, the relation can vary depending on the season of the year or changing hydrology (rising limb, peak, and falling limb for an event hydrograph; Walling, 1977). As such, plots of discharge *vs* SSC can display a high degree of scatter. Further, experience has shown that, at least in most rivers, SSC or flux is not discharge-limited but supply-limited, and sediment supply varies in time and space according to its source, such as hillslope soils, banks, and stream-channels.

Variability in the SSC–discharge relation has been studied at different time scales. For example, Bronsdon & Naden (2000) and Picouet *et al.* (2001) investigated annual and monthly changes in the SSC–discharge relation and found annual hysteresis due to production, mobilisation, and exhaustion of sediment. In other studies, individual events may display clockwise or anticlockwise hysteresis as a function of sediment origin (Williams, 1989; Goodwin *et al.*, 2003). Typological interpretation of hysteresis patterns is not unique, and can vary according to the study context. These diverse interpretations usually are not validated by other methods.

Sediment fingerprinting is designed to identify major catchment sources of suspended sediment. The method consists of identifying properties that characterise potential sources and comparing them with the same properties associated with actual SS using mixing models (Collins & Walling, 2002). Different properties have been used for distinguishing SS origins including mineralogical composition, chemical content, radionuclide content, colour, particle size, surface area, and magnetic susceptibility.

The objective of this study is to analyse the SSC–discharge relation to identify SS origins in two small agricultural catchments in northwestern France. After determining monthly and annual SS budgets for the two catchments, models were used to estimate how much of the SS flux was derived from deposited instream sediment, or bank erosion, at the flood-event time scale. This approach was merged with others, such as the interpretation of the SSC-discharge relation, phosphorus (P) concentration, or specific turbidity, to fingerprint the SS in both catchments.

MATERIAL AND METHODS

Study location

The study was performed on two Strahler second-order rivers in northwestern France (Fig. 1). The Moulinet catchment (1°11′20″W, 48°36′59″N) is a sub-basin of the Selune catchment, and the Kervidy-Naizin catchment (2°49′52″W, 48°00′20″N) is a sub-basin of the Blavet catchment. The bedrock of the two catchments is made up of a Brioverian schist covered by an aeolian silty loess of variable thickness. Soils are loamy and well-drained on the hillslopes, and hydromorphic in the valley bottoms. Surface area and geomorphology are similar in the two catchments (Table 1).

The climate is temperate maritime. Mean annual precipitation is 1028 mm (data Meteo France 1991–2001 at St Hilaire du Harcouët) in the Moulinet catchment, and 890 mm (data Meteo France 1994–2005 at Naizin) in the Kervidy catchment.

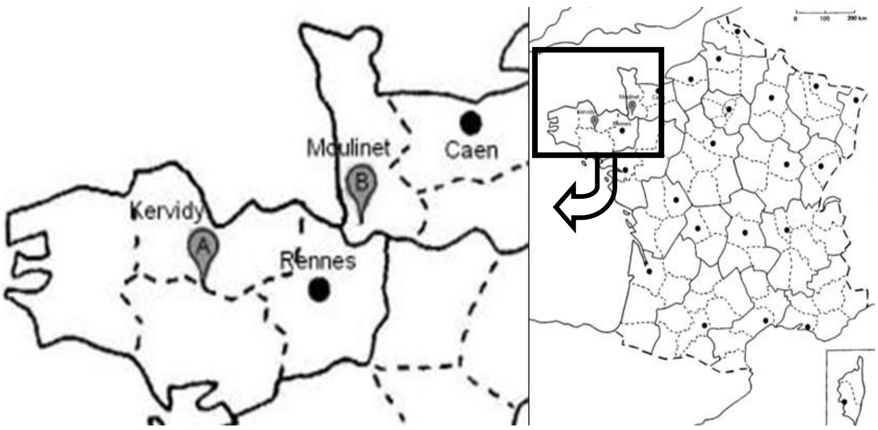

Fig. 1 Catchments in the study area: (a) Moulinet, and (b) Kervidy-Naizin.

Table 1 Catchment characteristics.

	Moulinet	Kervidy
Catchment area, km^2	4.5	5.0
Stream length, km	4.9	7.0
Mean longitudinal slope gradient, %	1.8	1.0
Minimal catchment altitude, m	55	93
Maximal catchment altitude, m	134	135

In the Moulinet catchment, agriculture is moderately intensive, with mostly dairy farming. Land use is dominated by pasture grassland (more than 50% of agricultural surface area), mostly in the riparian area, and the landscape contains dense hedgerows (7.8 km hedgerows per km^2). On the Kervidy catchment, agriculture is more intensive, consisting of dairy, cattle, and pig farming. The total surface area of the maize and cereal fields exceeds that of grassland areas, and hedgerows are few (2.7 km hedgerows per km^2).

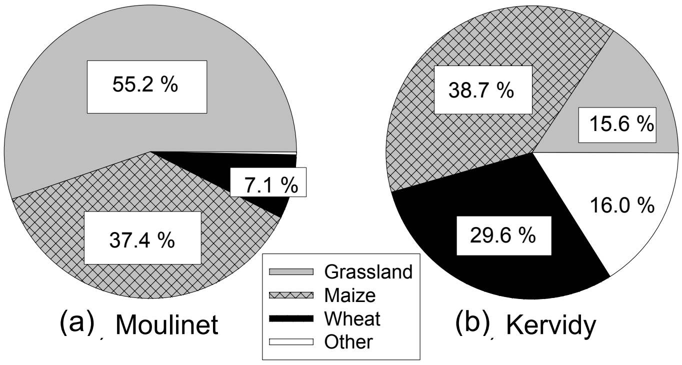

Fig. 2 Distribution of land use in 2008: (a) on Moulinet catchment (Macary *et al.*, unpublished data); (b) on Kervidy catchment (Akkal *et al.*, unpublished data).

Discharge and suspended sediment data.

Discharge and turbidity were recorded every 10 min at each catchment outlet. The turbidimeter (APC-TU, Ponselle) was calibrated in the laboratory with formazin solution (NF EN ISO 7027). The calibration was performed using stream samples (>300 per stream) collected during and between floods to establish the relation between turbidity and SSC. Irregularities in turbidity data due to high probe sensitivity were smoothed. Automatic cleaning is not sufficient to completely remove biofilms growing on optical sensors. Because biofilm disturbance on the sensor was assumed to increase linearly with time, a linear drift offset was applied to the data between two manual cleaning periods (Birgand *et al.*, 2004). SSCs used to calibrate the turbidimeter were measured from samples collected with an automatic sampler then filtered at 0.45-µm. SSCs estimated from turbidity data were used for quantifying the monthly and annual budgets. SSCs from direct measurements were used for analysing and modelling the SSC–discharge relation at the flood-event time scale. The study period covers October 2007 to February 2009.

SS origin and flux modelling

Modelling was used for analysing the SSC–discharge relations during flood events to identify and quantify the origin of suspended sediment in the two catchments. The model follows that described by Vansickle & Beschta (1983) and Picouet *et al.* (2009).

SS may come from various sources. For the two catchments studied, two principal origins were considered:

– Sediment deposited in the streambed (instream stock) combined with bank material dislodged by cattle; these stocks are rapidly mobilised at the beginning of flood events.
– Soil-surface erosion from agricultural fields inside the catchment: this source depends upon certain conditions (e.g. soil moisture, vegetative cover, rainfall intensity) and occurs later in a flood, when runoff with sediment enters the stream.

Total SS flux, $Q_S(t)$, at instantaneous time t is the sum of the fluxes from both sources. The flux for each source is the product of a transport function – the classical power function of discharge $Q(t)^b$ – and an availability function $\phi(t)$.

Only the flux Q_{S1} derived from instream and bank sources was modelled in this paper. The availability function $\phi(t)$ expresses the evolution of the sediment's initial stock, which exponentially decreases when the river exports the SS. The ϕ value ranges from 0 to 1.
The Q_{S1} expression is as follows:

$$Q_{s1}(t) = a \, . \left[Q(t)\right]^{b} . \, \phi(t) \tag{1}$$

in which
$$\phi(t) = 1 - \exp\left[-\left(\frac{m0 - m(t)}{mc}\right)^{\beta}\right] \tag{2}$$

where m_0 is the initial mass of instream and bank sediment and $m(t)$ is the total SS mass exported at time t after the beginning of the flood event. The value of m_0 must be greater than those of $m(t)$. Parameters m_c and β are empirical values.

Model calibration with experimental results was performed for the rising limb of the flood by least-squares minimisation between measured Q_S and predicted Q_{S1}. We admit that catchment erosion occurs after the rising limb. For this calibration we optimised 4 of 5 calibration parameters (a, b, m_c and β) and left a degree free for m_0.

The flux Q_{S2}, attributed to the second source, was calculated by subtracting Q_{S1} (attributed to the first source) from the total SS flux (equation (3)):

$$Q_{s2}(t) = Q_s(t) - a \, . \left[Q(t)\right]^{b} . \, \phi(t) \tag{3}$$

RESULTS AND DISCUSSION

Annual and monthly budgets

The two catchments received similar precipitation amounts, but their annual water volumes were different. They reached 476 10^3 and 299 10^3 m^3 km^{-2} for the Moulinet and Kervidy catchments respectively, for the hydrological year from October 2007 to September 2008. Also, seasonal variations in water volumes between winter and summer showed little contrast for the Moulinet catchment, whereas the Kervidy stream dried up in summer (Fig. 3).

Specific SS yields were markedly different between the two rivers for the same hydrological period. The specific SS yields were 64 10^3 kg km^{-2} in the Moulinet and 12 10^3 kg km^{-2} in the Kervidy stream. Monthly SS dynamics were marked by a high flux in May 2008 (62% and 54% of Moulinet and Kervidy annual budgets, respectively) due to heavy, but not exceptional, precipitation during the month.

In the Moulinet catchment, grassland and hedgerows have a buffer effect on surface runoff and erosion. The high SS budget is predominantly due to bank degradation and erosion caused by cattle (Lefrançois *et al.*, 2007). The bank degradation provides a large stock of sediment that is easily mobilised in response to relatively small increases in water discharge. In the Kervidy catchment, despite higher crop surface area and fewer grasslands and hedgerows, low SS flux is caused by the presence of many riparian trees alongside the stream.

Relation between suspended sediment concentration and discharge at the flood-event scale

For each stream, during flood events, different patterns between SSC and discharge were observed. A symmetric pattern (Fig. 4(a)) was interpreted as an unlimited sediment source during the flood event (Williams, 1989). A clockwise hysteresis pattern (Fig. 4(b)) was generally due to the mobilisation of particles from streambed stock whose availability is limited during the flood event (Seeger *et al.*, 2004). A complex pattern (Fig. 4(c)), predominately clockwise, but with an anticlockwise segment, was interpreted as the delayed arrival of particles, from hillslope soil erosion, upstream stock, or bank collapse (Lenzi & Marchi, 2000).

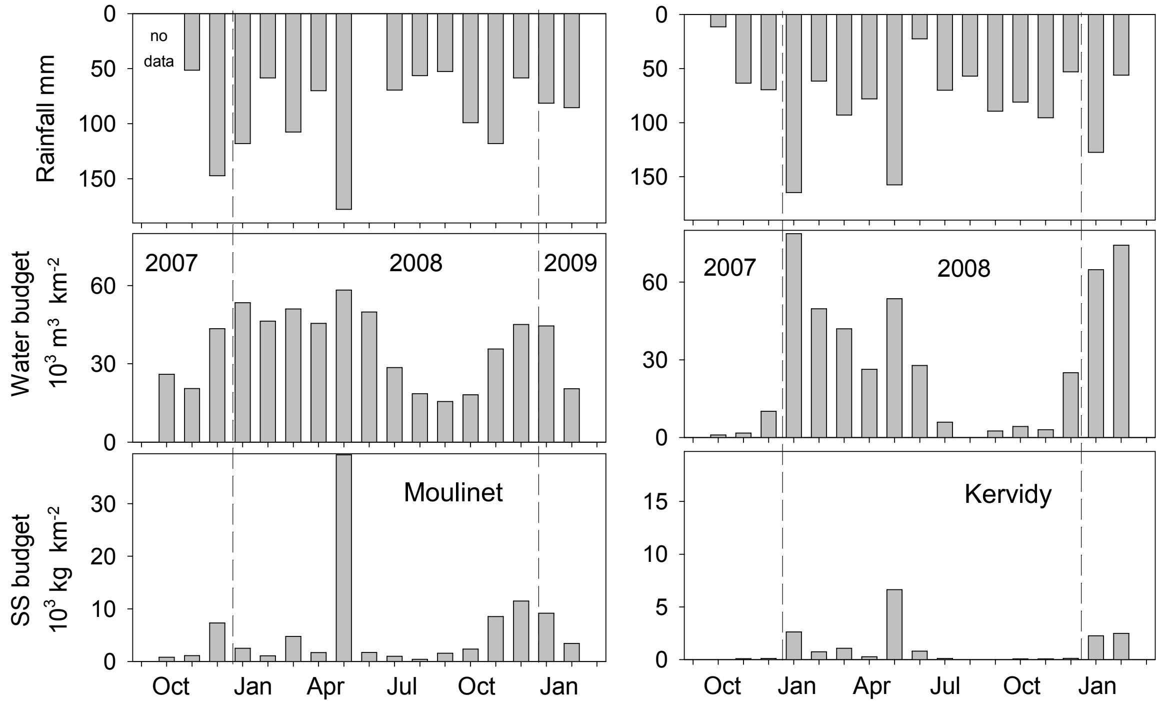

Fig. 3 Monthly rainfall, water and suspended sediment budgets for Moulinet and Kervidy-Naizin catchments from October 2007 to February 2009. NB: SS budget scale is different for both catchments.

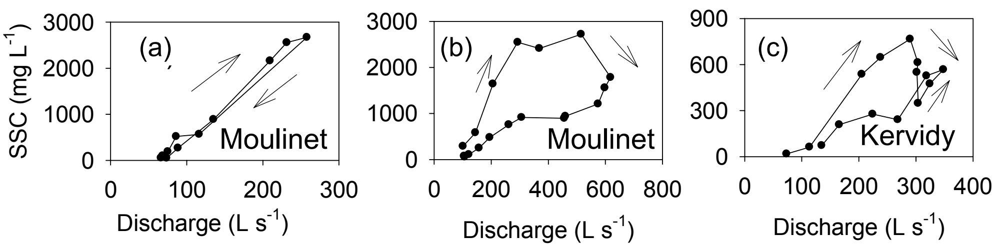

Fig. 4 Relations between SSC and discharge at flood-event scales.

Modelling SS origin during flood events

Modelling can help interpret SSC discharge patterns that seem strongly related to flood duration and discharge range.

For the Moulinet catchment, symmetric patterns corresponded to flood events that had initial sediment stock of unlimited availability. In this case, the modelling was unable to calculate m_0. Such floods were characterised, regardless of the discharge range, by extended antecedent dry conditions which lead to sediment accumulation. The availability of sediment stock became limited when discharge and flood duration increased. An estimate of m_0 provided high values (i.e. between 4×10^3 kg and 13×10^3 kg; Table 2) that confirm a large initial instream sediment stock or erosion from the banks. Catchment soil erosion occurred mainly during floods with high discharge and long duration (e.g. 10 March 2008 and 5 May 2008). In May, the floods resulted from high-intensity rainfall on recently sown maize plots (i.e. without significant plant cover). For these floods, the SSC-discharge pattern showed a large clockwise hysteresis related more to sediment stock depletion than to catchment erosion. The anticlockwise pattern on the 4 January 2008 flood event can be explained by a string of floods that occurred before this date. Hence, the initial sediment stock was low because previous floods had eliminated it, and slope runoff and erosion occur rapidly when rain falls on wet and bare soils.

Table 2 Sample of modelled flood events in the Moulinet stream.

Date (duration)	Discharge range (L s^{-1})	Measured Q_s (10^3 kg)	m_0 (10^3 kg)	Modelled Q_{s1} (10^3 kg)	Q_{s2} (10^3 kg)	SSC–Q pattern
10 Jan 08 (7:30 h)	150–300	2.7	unlimited	2.8	–	symmetric
26 Mar 08 (9:30 h)	100–150	0.3	unlimited	0.3	–	symmetric
24 Apr 08 (6:00 h)	80–140	0.6	unlimited	0.6	–	symmetric
7 Jul 08 (8:00 h)	70–260	4.1	unlimited	3.6	–	symmetric
3 Dec 08 (3:20 h)	70–220	0.5	unlimited	0.45	–	symmetric
18 Jan 09 (2:40 h)	100–170	1.6	unlimited	1.5	–	symmetric
10 Mar 08 (12:00 h)	100–620	12.7	13	8.0	4.7	clockwise
21 Apr 08 (7:30 h)	100–340	4.2	3.9	3.7	0.5	clockwise
5 May 08 (12:00 h)	90–720	19.1	9	7.3	11.8	clockwise
4 Jan 08 (8:00 h)	80–170	1.1	unlimited	0.6	0.5	anticlockwise

Table 3 Sample of modelled flood events in the Kervidy stream.

Date (duration)	Discharge range (L s^{-1})	Measured Q_s (10^3 kg)	m_0 (10^3 kg)	Modelled Q_{s1} (10^3 kg)	Q_{s2} (10^3 kg)	SSC–Q pattern
21 Nov 07 (3:30 h)	50–80	0.15	unlimited	0.15	–	symmetric
4 Jan 08 (11:00 h)	40–120	0.4	unlimited	0.4	–	symmetric
8 Dec 07 (9:00 h)	60–130	0.5	0.6	0.5	–	symmetric
29 Apr 08 (7:40 h)	50–130	0.18	0.17	0.11	0.07	clockwise
28 Nov 08 (9:00 h)	60–100	0.11	0.18	0.11	–	clockwise
23 Jan 09 (14:40 h)	250–500	1.5	0.9	0.8	0.7	clockwise
10 Nov 08 (12:40 h)	70–350	4.4	1.7	1.7	2.7	clockwise then anticlockwise

For the Kervidy catchment, instream sediment availability before floods was clearly lower (m_0 = 0.2 to 1.7 10^3 kg) than for the Moulinet catchment. There, soil erosion occurs frequently, but the flux is quite low (Table 3).

Use of fingerprinting to identify SS origins during flood events

Use of SS phosphorus concentration or water specific turbidity as fingerprints seems promising for identifying SS origins in the two catchments. Some examples are shown here for the Moulinet catchment, where the P concentration of instream and bank particles was lower than that of soil surface particles from crop fields (unpublished data) because they usually are fertilised with P. To limit the effect of particle size (because the adsorption area for P is larger for finer particles) the analysis was limited to the ≤50-μm fraction. During the floods of 4 January 2008 and 10 March 2008 the late arrival of particles from soil erosion increased SS concentration of P during the flood recession (Fig. 5). Note that the slope of this relation shows particle P content. For these floods, the model clearly identified a soil erosion source, as opposed to the flood of 10 January 2008, where the predicted SS source was only instream and bank particles (Table 2).

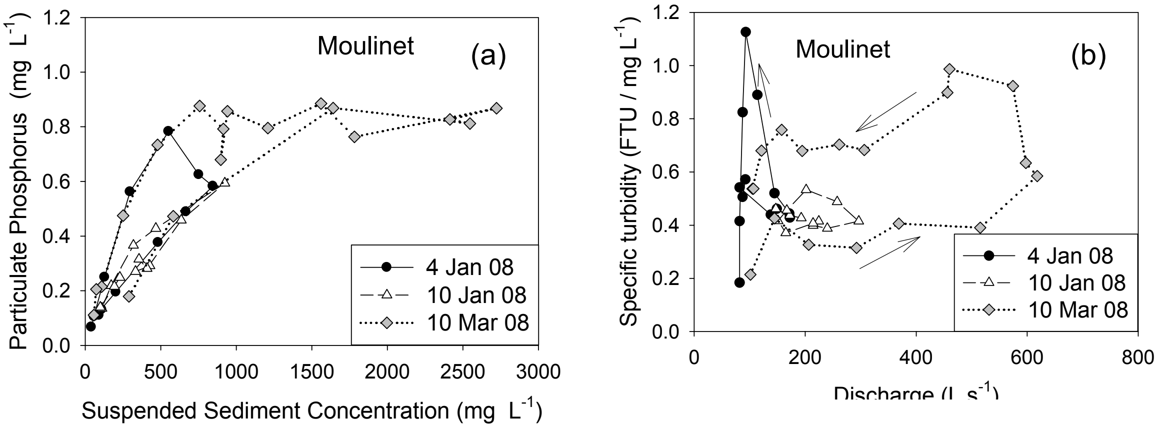

Fig. 5 (a) Particulate phosphorus content *versus* SSC, and (b) specific turbidity *versus* discharge in stream samples during three flood events on the Moulinet catchment.

The specific turbidity is the ratio between turbidity and SSC. This ratio depends on the colour and composition of the water, as well as the colour, and size of the particles (Gippel, 1995). It is likely that the arrival of finer particles from surface soil erosion increased specific turbidity during the falling limb of the 4 January 2008 and 10 March 2008 floods, whereas in-stream and bank-mobilised sediments were coarser during the rising limb of these floods or both limbs of the 10 January 2008 flood (Fig. 5).

CONCLUSION

Suspended sediment origins were different in the two watersheds studied: mainly bank erosion caused by cattle in the Moulinet catchment, and mainly slope erosion from crop fields in the Kervidy catchment. Lower SS fluxes in the latter catchment were explained by riparian trees lining the banks. In both catchments the high variability in SSC–discharge relations appears due to temporal variations in particle availability. We identified and quantified the origins of SS at the flood-event time scale using a modelling approach. By merging modelling results with the SSC–discharge relation patterns during the floods we showed that the interpretation of patterns is not easy because they depend on the relative importance of the various particle sources and on the gaps in their arrival times. Using either SS phosphorus concentrations or water specific turbidity as fingerprints seems promising for identifying the SS origins in the two catchments.

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