Factors controlling suspended sediment yield during runoff events in small headwater catchments of the Basque Country

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Abstract

Turbidity (NTU), discharge (l/s) and precipitation (mm) are being continuously monitored in the gauging stations located at the outlet of Aixola, Barrendiola and Añarbe catchments (Basque Country) since October 2003. In this study, several data sets derived from flood events were used to develop turbidity and suspended sediment relationships for the three catchments separately, and so estimate continuous suspended sediment concentration (SSC). Linear relationships are found in Barrendiola and Añarbe, and two curvilinear relationships for Aixola owing to changing sediment sources in the catchment. On the other hand, several event (discharge, precipitation and suspended sediment concentration) and pre-event (discharge and precipitation) factors are calculated for all the events registered. With them correlation matrixes were developed for each catchment. Differences among catchments in the factors that control suspended sediment concentration and suspended sediment yield during the events were found, related to catchment size and land use predominantly. SSC-discharge evolutions through the events were also analysed. For Aixola four different types of hysteresis loops were observed: single lined, clockwise, counter-clockwise and eight-shaped and for Barrendiola and Añarbe just clockwise loops were observed.

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1. Introduction

Lots of authors have observed that a high variability in suspended sediment yield exists in one catchment from event to event (Regües et al., 2000; Lenzi and Marchi, 2000; Sun et al., 2001; Seeger et al., 2004). This variability is the consequence of differences in the way or the proportion in which interact in each event the physical and anthropogenic factors that control sediment production and delivery. Several studies have been published analysing the relationship between catchment characteristics, factors acting in runoff events and the quantity of suspended sediments in rivers.

One of the essential factors for sediment delivery is sediment availability. In this sense Smith et al. (2003) have examined the influence of antecedent sediment storage in event sediment yield; others (Regües et al., 2000) have analysed temporal patterns of sediment transport linked to badlands dynamics. Availability is strongly related to different land uses (forest, pasture, and so on) present in the catchment (Erskine et al., 2002; Sala and Farguell, 2002), but many of the times land use and suspended sediment availability is altered by human activities as industry (Siakeu et al., 2004) or forestry (Olarieta et al., 1999).

Besides, analysis of sediment yield relationship with event precipitation and discharge characteristics can help in the understanding of processes acting in the sediment transporting events. Thus, sediment yield rates may be expected to change in response to changes in rainfall (Nearing et al., 2005, Old et al., 2003), to the total precipitation, as well as to the intensity of it. Relationships between sediment yield and discharge (Picouet et al., 2001; Crawford, 1991; Asselman, 2000) have also been widely analysed. Some authors (Seeger et al., 2004) have also established that the antecedent conditions of the catchment, as soil moisture or antecedent rainfall, have an important influence on suspended sediment delivery.

As well as the relationship between hydrological and sediment transport parameters of the event can be studied, relationship of discharge and suspended sediment concentration along the event can also be analysed. Most of the times this relationship is not homogeneous during the events, producing hysteretic loops (Williams, 1989; Llorens et al., 1997; Sichingabula, 1998; Lenzi and Marchi, 2000; Picouet et al., 2001; Alexandrov et al., 2003; Seeger et al., 2004). Williams (1989) determined that five common classes of hysteretic loops can be distinguished: single valued, clockwise, counter-clockwise, single valued plus a loop and eight shaped. Hysteresis offers a useful insight into the suspended sediment sources and mechanics of sediment delivery (Jansson, 2002).

The aims of this work are: to determinate the factors that have a major influence in the event suspended sediment delivery of each catchment and to identify the different hysteresis types of single flood events and the relationship of those with runoff generation parameters.

2. Study catchments

The studied catchments are located in the central part of the Basque Country, in the province of Gipuzkoa, at average latitude of 43º and average longitude of 1º (Fig. 1). This region is characterized by steep slopes, higher than 25% in most of the territory, and a humid and temperate climate.

Aixola River is located in the west of the Gipuzkoa province and drains a headwater catchment of 4.8 km^2 into the Aixola water reservoir. The main bedrock in the basin is Upper Cretaceous Calcareous Flysch with alternating marl and sandy limestone layers. Average annual precipitation for this area is about 1200 mm that are well distributed along the whole year. The highest peak is at 750 m a.s.l., the outlet at about 340 m a.s.l. and mean elevation is 511 m a.s.l. The river runs from south to north, building up a valley with moderate slopes facing to the east and the west. This basin is mostly (90%) reforested for industrial use with *Pinus radiata* trees.

Añarbe River, located in the east part of the province, drains a 48 km^2 headwater catchment into the Añarbe water reservoir. Main bedrock is Devonian-Carboniferous alternating layers of shale and grauvacke, granitic materials from the Aiako Harria Stock and metamorphic materials. Average annual precipitation is around 2250 mm, being the area with highest precipitation in the Basque Country. Mean elevation is 532 m a.s.l., with the highest peak at 1035 m a.s.l. and the gauging station in the outlet at 200 m a.s.l. This high elevation range explains the very steep slopes of the basin. Most part of the catchment is covered of reforested and mature *Pinus nigra* (also for industrial use) in the lower half of the basin and autochthonous vegetation as *Quercus robur* and *Fagus sylvatica* in the upper half.

Barrendiola River, located in the south of the territory, drains a headwater catchment of 3 km^2 into the Barrendiola water reservoir. Main bedrock in the north part of the catchment is Supraurgonian terrigenous materials as clays and sandstones. To the south, appear Urgonian fine grain sandstones and calcareous silts first, and after, an alternation of Urgonian massif limestones with impure limestones and marls. Mean annual precipitation is about 1300 mm. Mean elevation is 840 m a.s.l., and catchment goes from the 550 m a.s.l. of the gauging station to the 1350 m a.s.l. of the highest peak. This is an area with steep slopes, where autochthonous vegetation as *Fagus sylvatica*, *Quercus robur* or *Quercus petraea* and reforested vegetation as *Pinus radiata*, *Pinus nigra* or *Larix decidua* can be found.

3. Types and source of data used

Turbidity (NTU), discharge (l/s) and precipitation (mm) are being continuously monitored in the gauging stations located at the outlet of each of the catchments since October 2003 up to date. The three parameters mentioned are measured every 10 minutes. Turbidity is measured using Solitax infrared backscattering turbidimeters (Dr. Lange devices) with an expected range of 0 – 1000 NTU. Turbidimeters are commonly used to estimate continuous suspended sediment flux (Gippel, 1989; Brasington and Richards, 2000), because if relation of turbidity to suspended sediment concentration (SSC) is frequently calibrated, continuous time series of SSC can be efficiently derived from continuous turbidity series (Lewis, 1996). In these sense, automatic water samplers are installed in these stations and programmed to take water samples of about 600 ml when discharge (in Aixola and Barrendiola) or turbidity (in Añarbe) rise. Samples taken are carried to the laboratory for sediment concentration and water turbidity measurements. SSC is measured in laboratory by means of filtration of the samples through 0.45µm filters. In addition to field data, turbidity is also measured in samples carried to laboratory with a WTW Turb 555 IR turbidimeter that has an expected range of 0 – 10000 NTU. Relationship between field and laboratory turbidity data is linear and it can be used to fill field data lacks or extrapolate the occasional field data higher than 1000 NTU.

3.1. Deriving continuous records of SSC

Continuous turbidity (NTU) data were calibrated to SSC (mg/l) using relationships found in laboratory. But these relationships are usually site and maybe also time specific, so a relationship is normally unique for a particular catchment and within a particular period of time (Gippel, 1989). For that reason, in this study a specific turbidity / SSC relationship was established for each study catchment and as much events as possible were taken into account. It is known that turbidity and SSC are linearly related when physical properties of the suspended particles remain constant (Foster et al., 1992; Gippel, 1995). But, physical properties of the suspended sediments (size, shape) rarely stay constant and this can have different effects on turbidity-SSC relationships. On one hand, if the sediment size changes with increasing streamflow, a curvilinear relation between turbidity and SSC should be expected (Lewis, 2003). However nonlinearity should not be a problem when using turbidity to derive SSC. On the other hand, source of materials can also change in drainage basins with spatially heterogeneous soils or because of land use effects. In this second case, a scatter will be introduced in the turbidity – SSC relationship (Foster el al., 1992; Gippel, 1995). But as Gippel (1995) stated, despite these complications, an adequate relationships between field turbidity and SSC can be determined in most environments.

For the three catchments studied in this work SSC was regressed against corresponding turbidity values forcing relationships to the origin (Wass and Leeks, 1999). Turbidity – SSC calibrations with their 95% confidence interval are presented in Fig. 2. For Añarbe and Barrendiola (Fig. 2b) a linear model can adequately describe turbidity-SSC relationships which means that the physical properties (size, mainly) of the suspended particles are constant. But, for Aixola (Fig. 2a) this relationship is more complicated and the turbidity – SSC graph shows a high dispersion of the samples. Lewis (1996) suggested analysing this kind of scattered relationships producing calibrations for individual events. With this approach two data sets can be distinguished in the graph. The first one, from October 2003 to the 15th of March of 2004 and from the 26th of December of 2004 to the end of October of 2005. The turbidity – SSC relationship is curvilinear for this group of time intervals and a second order positive polynomial can adequately describe it. This type of relationship has been linked, at least in part, to particle size variations of the suspended particles (Old et al., 2003) and more precisely by sediment load coarsening with increasing water discharge (Frostick et al., 1983; Lewis, 2003).

The second data set, from the 15th of March of 2004 to the 26th of December of 2004, shows also a curvilinear turbidity – SSC relationship but in this case the second order polynomial that describes it, is negative, suggesting, as Colby and Hembree (1955) observed, that the proportion of fine sediments increases with discharge. This second set of samples appears at the same time that a filling of land is made in an area near the river in the upper part of the catchment, so that new and different material is provided to the river to be transported.

3.2. Selection of event factors

Not all the events were analysed in this paper but just the ones that showed a response in suspended sediment concentration. For that reason there is a high difference in the number of events analysed for each catchment; from 119 events characterised, 76 are from Aixola, 25 from Barrendiola and 18 from Añarbe. These rainfall–runoff events have been characterised by four groups of parameters: antecedent conditions to the event, precipitation causing the event, discharge during the event and suspended sediment delivered during the event.

Antecedent conditions are described by accumulated precipitation of one hour before the event (aP1, mm), one (aP1d, mm), seven (aP7d, mm) and twenty-one days (aP21d, mm) before the event and average discharge of the day before the beginning of the event (aQ1d, l/s).

Precipitation that caused the event is characterised by total precipitation (Pt, mm), average intensity of the precipitation during the rainfall event (IP, mm/h) and maximum intensity of the precipitation (IPmax, mm/h).

Discharge during the event is expressed by the total specific water volume of the runoff event (Qt, mm), the average (Qav, l/s) and the maximum discharge (Qmax, l/s), and the relationship between this maximum discharge and the initial discharge prior to the event (Qmax/Qb).

Sediment delivery has been explained with the average (SSCav, mg/l) and the maximum suspended sediment concentration of the event (SSC max, mg/l) and the total suspended sediment yield of the event (SSt, Kg).

4. Results and discussion

During the monitoring time, 76 events were recorded in Aixola, 18 in Añarbe and 25 in Barrendiola. The precipitation (Pt) that caused the floods ranged between 2.5 and 56.6 mm in Aixola, between 5.4 and 61.2 mm in Barrendiola and between 16.8 and 147 mm in Añarbe. Maximum intensity of the rainfalls (IPmax) ranged between 1.8 and 111.6 mm/h in Aixola, 2.4 and 81.6 mm/h in Barrendiola and 4.8 and 43.2 mm/h in Añarbe, whereas the average precipitation intensity (IP) ranged between 0.5 and 21.8 mm/h in Aixola, 0.8 and 13.2 mm/h in Barrendiola and 1.3 and 5.3 mm/h in Añarbe.

Concerning to discharge characteristics of the events, the total water volume of the event (Qt) ranged between 0.2 and 25.2 mm in Aixola, 0.2 and 33.6 mm in Barrendiola and 0.2 and 131 mm in Añarbe, the maximum discharge (Qmax) ranged between 79 and 2109 l/s in Aixola, 11 and 1132 l/s in Barrendiola and 342 and 88278 l/s in Añarbe and the relation between maximum discharge and initial discharge (Qmax/Qb) ranged between 1.4 and 73 in Aixola, 1.5 and 23 in Barrendiola and 1.7 and 27 in Añarbe.

Delivered suspended sediment characteristics also ranged widely. Suspended sediment maximum concentration during the event (SSCmax) ranged between 11 and 8816 mg/l in Aixola, 35 and 1614 mg/l in Barrendiola and 17 and 1595 mg/l in Añarbe and total suspended sediment yield of the event (SSt) ranged between 18 and 46305 Kg in Aixola, 13 and 5322 Kg in Barrendiola and 215 and 2622220 Kg in Añarbe.

In relation to antecedent conditions to the event, accumulated precipitation of the seven days before the event (aP7d) ranged between 0.1 and 96 mm in Aixola, 0 and 92.8 mm in Barrendiola and 3.5 and 141.9 mm in Añarbe and average discharge of the day before the event (aQ1d) ranged between 26 and 494 l/s in Aixola, 7 and 490 l/s in Barrendiola and 144 and 4230 l/s in Añarbe.

In order to analyze the factors that control suspended sediment yield during events in each of these catchments a correlation matrix and a factorial analysis that include all the parameters mentioned above have been carried out for each of the catchments.

In Aixola, as table 1 shows, total precipitation during the event is well correlated with all discharge parameters, Qav, Qt and Qmax and also with Qmax/Qb. However this last parameter, Qmax/Qb, is better correlated with maximum intensity of the precipitation. Pt is also strongly related to total sediment yield of the event, while SSCav and SSCmax are much better correlated with maximum intensity of the precipitation. On the other hand, discharge parameters that have a higher control on suspended sediment yield and concentration are Qmax and the Qmax/Qb parameter. Taking into account all these data, a principal component analysis with Varimax rotation was performed with SPSS programme package. This analysis (Fig. 3a) grouped in the first factor, IP, IPmax, SSCav, SSCmax and Qmax/Qb parameters, explaining the 29% of the variance. In the second factor, Pt, Qt and Qav are grouped explaining the 23% of the variance. In a I-II factorial plane, total sediment yield of the event (SSt) shows a high relationship with these two factors, even if the correlation is better with factor I, and no relationship with antecedent conditions to the event.

Therefore, in Aixola there is a strong correlation between precipitation, discharge and suspended sediment parameters, but no significant correlation between those and antecedent conditions. These results suggest a very rapid response of the catchment to rainfall events, in the discharge as well as in the sediments, so that the kind of events that are being analysed are of the flash flood type.

In Barrendiola (Table 2), Pt is well correlated with total sediment yield of the event, while, as in the previous case, SSCav and SSCmax are well correlated with maximum intensity of the precipitation. In this case, although discharge parameters also have a high control on suspended sediment yield they don’t show any significant correlation with suspended sediment concentration parameters. However, aQ1d has a strong relation to the suspended sediment yield. The principal component analysis (Fig. 3b) grouped in the first factor, Qav, Qmax, Qt and SSt, explaining the 33% of the variance. In the second factor, IP and IPmax and SSCmax and SSCav, explaining the 28% of the variance. Consequently, in a I-II factorial plane, total sediment yield of the event shows a high relationship with the first factor.

In Barrendiola, precipitation and discharge are related to suspended sediment, but precipitation and discharge don’t show significant relationship between them as neither suspended sediment concentration and suspended sediment yield. Besides, antecedent discharge is strongly correlated to sediment yield and discharge during the event. So, in Barrendiola response to rainfall events is not so quick and there is a higher regulation of discharge and sediment in the catchment.

For Añarbe two correlation matrixes were developed. The first one (Table 3) takes into account all the events recorded (18), and in the second one (Table 4) are included just 17 events. The event of the 22/01/2004 was excluded from the second matrix, because it was an extraordinary event that delivered the 78% of the total sediment yield of the events monitored in the two years, with total precipitations of 147 mm and maximum water levels above the maximum that measures the gauging station. So, the results are very influenced by this event, and considering it in the analysis can create misinterpretations of the correlations between factors acting the most part of the time. On the other hand, not considering this extreme event would mean losing important and necessary information, because sediment delivering in the rest of the events is quite low. For that reason both matrixes are presented here. In the first matrix, suspended sediment yield is strongly correlated with Pt and Qav, Qmax and Qt, and also with the previous precipitation (aP1).

Looking to the second correlation matrix (n=17), the one that would reflect the usual dynamic of the catchment, a weaker relationship between discharge parameters, suspended sediment yield and precipitation can be observed. Pt appears positively correlated with discharge parameters and with total sediment yield and maximum sediment concentration. Discharge parameters show a much higher control on suspended sediment yield and maximum suspended sediment concentration. On the other hand, antecedent conditions, as aP1 and aP1d, are also very well correlated with suspended sediment yield. The principal component analysis for these 17 cases (Fig. 3c) shows that Qav, Qmax, Qt, aP1 and aP1d are grouped in factor one that explains the 47% of the variance. On the other hand, SSCav and SSCmax are grouped in factor two, that explains the 22% of the variance. Suspended sediment yield has a strong relationship with both factors but mainly with the first one.

Therefore, taking into account all the events of Añarbe, there is a very strong correlation between precipitation, discharge and suspended sediment that reflects the optimum situation to suspended sediment delivery in this catchment, with high precipitation, discharge and suspended sediment concentration records. But, looking to the most usual situation, taking out the exceptional event of 22/01/2004, there is still a good correlation between precipitation, discharge and suspended sediment and also to antecedent conditions, which makes us think again in the regulation capacity of the catchment.

Relation between discharge (Q) and suspended sediment concentration (SSC) was also analysed for all the individual events of each catchment. For Añarbe (Fig. 4a) and Barrendiola (Fig. 4b) one type of hysteresis was predominant; most of the events recorded show clockwise hysteresis, and few of them, the smallest ones, had a linear relationship between SSC and Q (Williams, 1989). But in Aixola different types of relationships between SSC and discharge were found. Twenty-two of the seventy-six events recorded in Aixola showed a linear relationship between SSC and Q (Fig. 5a), eighteen as clockwise hysteresis loops (Fig. 5b), twenty-six were classified as counter-clockwise hysteresis loops (Fig. 6a), and the remaining ten as eight shaped loops (Fig. 6b), where after a clockwise or a counter-clockwise loop, during the falling limb of the hydrograph, another peak appears in the sediment graph.

A factorial analysis was performed for these 76 events (Fig. 7), taking into account precipitation (Pt and IPmax), discharge (Qav), sediment yield (SSt) and antecedent 12 hour precipitation (aP12) parameters. The two principal components created explained the 71% of the variance, with total precipitation, average discharge and suspended sediment yield in the positive side of the first factor (explaining the 40% of the variance) and in factor two (explaining the 31% of the variance) maximum intensity of the precipitation in the negative side and antecedent 12 hour precipitation in the positive. Fig. 7 shows position of different event types in the factorial plane. Clockwise events are located in the positive side of factor one, so they can be described as events with high precipitation records and high average discharges, and also as the ones that show highest suspended sediment yields. Events with eight shaped hysteretic loops are related with low precipitation and average discharge, but high maximum precipitation intensity. All of them occurred in summer when antecedent conditions are predominantly dry. The ones with a linear relationship between SSC and Q are events with low precipitation and discharge records and low precipitation intensities. Counter-clockwise events can’t be discriminated with any of the parameters used in this work.

5. Conclusions

The correlation matrixes and factorial analysis performed with the events recorded in each study catchment, showed meaningful differences in the factors controlling sediment yield and suspended sediment concentration. In Aixola (4.8 km^2) and Barrendiola (3 km^2), while event suspended sediment yield is related to total precipitation, suspended sediment concentration is related to precipitation intensity. But in Añarbe (48 km^2), even if total precipitation is related to suspended sediment yield, the influence of precipitation intensity on suspended sediment concentration is not evident, because the larger area of the catchment attenuates the importance of intensity. Relationship between discharge and sediment yield is also positive for the three catchments. However, despite maximum suspended sediment concentration is related to maximum discharge in Aixola and Añarbe, there is no relationship between these parameters in Barrendiola. In the same way, suspended sediment average concentration and sediment yield are interrelated in Aixola and Añarbe, but not in Barrendiola. These differences are attributable to the different hydrologic behaviour of Barrendiola catchment surely owing to the higher regulation capacity of its soils and the undisturbed character of its forest.

As Seeger et al. (2004) attempted, other important factor that controls the deliver of suspended sediment in catchments are the antecedent conditions. In the case of Aixola, a very disturbed catchment, antecedent conditions are no correlated to suspended sediment parameters and the sediment response is very quick in any of the hydrological situations of the year. In Barrendiola the precipitation of one hour prior to the event and the average discharge of the day before are related just to the sediment yield, not to concentration, that in this catchment seems to be related only to maximum precipitation intensity. In Añarbe, antecedent precipitations of some hours before the event are related to suspended sediment average concentration and suspended sediment yield, in this case the suspended sediment response is much slower due to its larger area.

Different patterns of suspended sediment concentration (SSC)/discharge hysteresis loops have been observed for each catchment. In Añarbe and Barrendiola almost all of the events were clockwise. In Añarbe, due to the larger area, channel dynamics get a higher relevance than in the other catchments. The particular behaviour is the very quick depletion of sediment due to the scarcity of sediment available to be transported in the river bed and near the channel and the rapid displacement of it (Regües et al., 2000). In Barrendiola, owing to the undisturbed forest that covers the catchment, the low production of sediment from the catchment make that a very low quantity of sediment is available for transport and a quick exhaustion of all available sediment during early stages of the event occurs.

In Aixola, four different kinds of relationships between SSC and discharge have been observed, suggesting a significant spatial and temporal variability in sediment source areas. The single valued line relationships are related to events with low precipitation and discharge records and low precipitation intensities, where differences of suspended sediment concentration between the rising and the falling limb of the hydrograph are not meaningful. Clockwise hysteresis loops occur with high discharge and precipitation records, and they mostly appear from October to April. In these cases, as Williams (1989) described, a rapid depletion of the sediment available for transport occurs before the water discharge leads its maximum. This kind of hysteresis can be related with a fast-response contribution from sediment stored in the channel network (Lenzi and Marchi, 2000; Jansson, 2002). In some of the events analysed, the pattern of the precipitation intensity through the storm period is mirrored by suspended sediment concentration. For these cases, Brasington and Richards (2000) suggested that sediment is derived predominantly from the sheetwash over hillslopes rather than from riparian or channel erosion.

The next group of events, eight-shaped hysteresis, appears only on summer, when soil moisture of the catchment is lower, and associated to high intensity rainfall events. In these cases a latter loop appears in the falling limb of the hydrograph after a first clockwise or counter-clockwise loop, suggesting that suspended sediment is arriving from a farther source area. Seeger et al.

(2004) related this second loop with moments when contributing areas are extended all over the catchment, owing to a generalised hortonian flow that occurs as a consequence of the hydraulic conditions of the catchment. Counter-clockwise hysteresis loops, occur all over the year and in many different conditions. This kind of loop has been explained in terms of the presence of a significant sediment source distant from the zone of major runoff production, or a significant difference between flood wave celerity and the mean flow velocity that carries the bulk of the suspended sediment (Williams, 1989; Brasington and Richards, 2000; Seeger et al, 2004). Further work is being carried out from the authors of this paper in the understanding of the factors that determinate the different types of hysteresis in Aixola and its relationship with sediment sources into the catchment.

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References

Alexandrov, Y., Laronne, J.B., Reid, I., 2003. Suspended sediment concentration and its variation with water discharge in a dryland ephemeral channel, northern Negev, Israel. Journal of Arid Environments 53, 73-84.

Asselman, N.E.M., 2000. Fitting and interpretation of sediment rating curves. Journal of Hydrology 234, 228-248.

Brasington, J., Richards, K., 2000. Turbidity and suspended sediment dynamics in small catchments in the Nepal Middle Hills. Hydrological Processes 14, 2559-2574.

Colby, B.R., Hembree, C.H., 1955. Computations of total sediment discharge, Niobrara River, near Cody, Nebraska. US Geological Survey Water Supply Papers 1357.

Crawford, C.G., 1991. Estimation of suspended-sediment rating curves and mean suspended-sediment loads. Journal of Hydrology 129, 331-348.

Erskine, W.D., Mahmoudzadeh, A., Myers, C., 2002. Land use effects on sediment yields and soil loss rates in small basins of Triassic sandstone near Sydney, NSW, Australia. Catena 49, 271-287.

Foster, I.D.L., Millington, R., Grew, R.G., 1992. The impact of particle size controls on stream turbidity measurements; some implications for suspended sediment yield estimations. International Association of Hydrological Sciences 210, 51-62.

Frostick, L.E., Reid, I., Layman, J.T., 1983. Changing size distribution of suspended sediment in arid-zone flash floods. Special Publication of the International Association of Sedimentology 6, 97-106.

Gippel, C.J., 1989. The use of turbidimeters in suspended sediment research. Hydrobiologia 176/177, 465-480.

Gippel, C.J., 1995. Potential of turbidity monitoring for measuring the transport of suspended solids in streams. Hydrological Processes 9, 83-97.

Jansson, M.B., 2002. Determining sediment source areas in a tropical river basin, Costa Rica. Catena 47, 63-84.

Lenzi, M.A., Marchi, L., 2000. Suspended sediment load during floods in a small stream of the Dolomites (northeastern Italy). Catena 39, 267-282.

Lewis, J., 1996. Turbidity-controlled suspended sediment sampling for runoff-event load estimation. Water Resources Research 32 (7), 2299-2310.

Lewis, J., 2003. Turbidity-controlled sampling for suspended sediment load estimation. In: Erosion and Sediment Transport Measurement in Rivers: Technological and methodological advances (ed. by J. Bogen, T. Fergus & D.E. Walling) (Proc. Oslo Workshop, June 2002), 13-20. IAHS Publ. 283.

Llorens, P., Queralt, I., Plana, F., Gallart, F., 1997. Studying solute and particulate sediment transfer in a small mediterranean mountainous catchment subject to land abandonment. Earth Surface Processes and Landforms 22, 1027-1035.

Nearing, M.A., Jetten, V., Baffaut, C., Cerdana, O., Couturiera, A., Hernandez, M., Le Bissonnais, Y., Nichols, M.H., Nunes, J.P., Renschler, C.S., Souchère, V., van Oost, K., 2005. Modeling response of soil erosion and runoff to changes in precipitation and cover. Catena 61, 131-154.

Olarieta, J.R., Besga, G., Rodríguez, R., Usón, A., Pinto, M., Virgel, S., 1999. Sediment enrichment ratios after mechanical site preparation for *Pinus radiata* plantation in the Basque Country. Geoderma 93, 255-267.

Old, G.H., Leeks, G.J.L., Packman, J.C., Smith, B.P.G., Lewis, S., Hewitt, E.J., Holmes, M., Young, A., 2003. The impact of a convectional summer rainfall event on river flow and fine sediment transport in a highly urbanized catchment: Bradford, West Yorkshire. The Science of the Total Environment 314-316, 495-512.

Picouet, C., Hingray B., Olivry, J.C., 2001. Empirical and conceptual modelling of the suspended sediment dynamics in a large tropical African river: the Upper Niger river basin. Journal of Hydrology 250, 19-39.

Regües, D., Balasch, J.C., Castelltort, X., Soler, M., Gallart, F., 2000. Relación entre las tendencias temporales de producción y transporte de sedimentos y las condiciones climáticas en una pequeña cuenca de montaña mediterránea (Vallcebre, Pirineos Orientales). Cuadernos de Investigación Geográfica 26, 41-65.

Sala, M., Farguell, J., 2002. Exportación de agua y sedimento en dos pequeñas cuencas mediterraneas bajo diferentes usos del suelo. Sistema Costero Catalán. Rev. C. y G. 16 (1-4), 97-109.

Seeger, M., Errea, M.P., Beguería, S., Arnáez, J., Martí, C., García-Ruiz, J.M., 2004. Catchment soil moisture and rainfall characteristics as determinant factors for discharge/suspended sediment hysteretic loops in a small headwater catchment in the Spanish Pyrenees. Journal of Hydrology 288, 299-311.

Siakeu, J., Oguchi, T., Aoki, T., Esaki, Y., Jarvie, H.P., 2004. Change in riverine suspended sediment concentration in central Japan in response to late 20th century human activities. Catena 55, 231–254.

Sichingabula, H.M., 1998. Factors controlling variations in suspended sediment concentration for single-valued sediment rating curves, Fraser River, British Columbia, Canada. Hydrological Processes 12, 1869-1894.

Smith, B.P.G., Naden, P.S., Leeks, G.J.L., Wass, P.D., 2003. The influence of storm events on fine sediment transport, erosion and deposition within a reach of the River Swale, Yorkshire, UK. The Science of the Total Environment 314 –316, 451–474.

Sun, H., Cornish, P.S., Daniell, T.M., 2001 Turbidity-based erosion estimation in a catchment in South Australia. Journal of Hydrology 253, 227-238.

Wass, P.D., Leeks, G.J.L., 1999. Suspended sediment fluxes in the Humber catchment, UK. Hydrological Processes 13, 935-953.

Williams, G.P., 1989. Sediment concentration versus water discharge during single hydrologic events in rivers. Journal of Hydrology 111, 89-106.