To link to this article : DOI : 10.1002/esp.3957
URL : http://dx.doi.org/10.1002/esp.3957

Suspended sediment delivery from small catchments to the Bay of Biscay. What are the controlling factors?

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ABSTRACT: The transport and yield of suspended sediment (SS) in catchments all over the world have long been topics of great interest. This paper addresses the scarcity of information on SS delivery and its environmental controls in small catchments, especially in the Atlantic region. Five steep catchments in Gipuzkoa (Basque Country) with areas between 56 and 796 km^2 that drain into the Bay of Biscay were continuously monitored for precipitation, discharge and suspended sediment concentration (SSC) in their outlets from 2006 to 2013. Environmental characteristics such as elevation, slope, land-use, soil depth and erodibility of the lithology were also calculated. The analysis included consideration of uncertainties in the SSC calibration models in the final suspended sediment yield (SSY) estimations. The total delivery of sediments from the catchments into the Bay of Biscay and its standard deviation was $272\,200 \pm 38\,107\, t\, yr.^{-1}$, or $151 \pm 21\, t\, km^{-2}\, yr.^{-1}$, and the SSYs ranged from 46 ± 0.48 to $217 \pm 106\, t\, km^{-2}\, yr.^{-1}$. Hydroclimatic variables and catchment areas do not explain the spatial variability found in SSY, whereas land-use (especially non-native plantations) and management (human impacts) appear to be the main factors that control this variability. Obtaining long-term measurements on sediment delivery would allow for the effects of environmental and human induced changes on SS fluxes to be better detected. However, the data provided in this paper offer valuable and quantitative information that will enable decision-makers to make more informed decisions on land management while considering the effects of the delivery of SS.

KEYWORDS: suspended sediment yield; continuous monitoring; propagation of uncertainty; environmental control; Atlantic environment

Introduction

Rivers constitute the main linkage between terrestrial and marine systems (Knighton, 1998; Walling, 2006). The transport and yield of suspended sediment (SS) in catchments all over the world have long been topics of great interest (Schumm, 1977; Milliman and Syvitski, 1992; Farnsworth and Milliman, 2003; Milliman and Farnsworth, 2013) due to their role in the global denudation cycle (Wold and Hay, 1990; Harrison, 1994), their importance to global geochemical cycling (Ludwig *et al.*, 1996) and their potential role as a pathway for the transport of nutrients (Walling *et al.*, 2001) and pollutants, including heavy metals (Ankers *et al.*, 2003) and micro-organisms (House *et al.*, 1997). SS is essential for rivers because its presence or absence determines the geomorphological and biological processes that occur in these environments (Wass and Leeks, 1999).

Attempts to quantify SS fluxes from terrestrial to marine systems face a number of important problems, including the availability and reliability of data on sediment loads for rivers (Walling, 2006). Despite these sources of uncertainty, some authors (Holeman, 1967; Milliman and Meade, 1983; Milliman and Syvitski, 1992; Ludwig and Probst, 1996, 1998, Milliman and Farnsworth, 2013) have been able to estimate that each year between 15 and 19×10^9 t of SS is delivered into the world's oceans by rivers. Recently, a global annual sediment yield of $190\, t\, km^{-2}\, yr.^{-1}$ was calculated by Milliman and Farnsworth (2013). Nevertheless, the global distribution of SS delivery rates is not homogeneous, and regional differences are considerable. In Europe, for instance, whereas an annual yield of less than $10\, t\, km^{-2}\, yr.^{-1}$ has been calculated for northern rivers, the rivers that drain into the Mediterranean Sea have annual sediment yields that are one or two orders of magnitude higher (Vanmaercke *et al.*, 2011; Milliman and Farnsworth, 2013). The same can be observed in Africa, where suspended sediment yields (SSYs) range from less than $10\, t\, km^{-2}\, yr.^{-1}$ for the Senegal River basin (Kattan *et al.*, 1987) in West Africa to more than $500\, t\, km^{-2}\, yr.^{-1}$ in the Maghreb area (Probst and Amiotte-Suchet, 1992). Vanmaercke *et al.*

(2014) explained that those differences found in SSYs in Africa are significantly correlated to tree cover and runoff.

A recent review by García-Ruiz *et al.* (2013) showed that soil erosion and sediment transport have been intensively studied in Spain during recent years, and a total of 380 studies have been published in SCI journals. However, most of these studies have focused on the Mediterranean region, and publications about this topic in the Cantabrian basin are scarce. This publication record reflects to the high density of SS data for the Mediterranean region of Spain, and the scarcity of data for the Atlantic region (including the Bay of Biscay) (Vanmaercke *et al.*, 2011). The first data on SS delivery to the Bay of Biscay were published by Uriarte (1998) and Maneux *et al.* (1999). Uriarte (1998) calculated that between 45 and 260 $t\,km^{-2}\,yr.^{-1}$ was transported to the coastal ocean from small catchments (drainage areas between 40 and 780 km^2) located in Gipuzkoa (Basque Country), whereas Maneux *et al.* (1999) estimated a SSY of 70 $t\,km^{-2}\,yr.^{-1}$ for the Nivelle River (238 km^2, French Basque Country). The latter highlighted the large contribution of small mountainous catchments, of basins smaller than 1000 km^2 in size, to the total SS that were delivered to the Bay of Biscay because they transport more than the 50% of the total sediments that reach the coast.

Indeed, the key role played by small mountainous catchments in the delivery of SS to the ocean has been widely discussed (Milliman and Syvitski, 1992; Leithold *et al.*, 2006; Syvitski and Milliman, 2007). Approximately 45% of the total global sediment is delivered to the ocean from small catchments. However, the database constructed by Vanmaercke *et al.* (2011) for European catchments revealed that relatively little data on SSY exists for small catchments. Furthermore, as Milliman and Farnsworth (2013) noted, there is a need to revise the estimates made for this type of catchment in global studies, considering that the number of small mountainous catchments that have been monitored for a relatively long period is rather small.

The Department of Land Planning and Environment of the Gipuzkoa Provincial Council established gauging stations during the 1980s to record discharge data in catchments throughout its territory. From the 2000s, SS was sampled, from 2006 for rivers draining into the Bay of Biscay. The objective of the present study was to estimate the SS delivery from coastal small catchments (with areas smaller than 1000 km^2) to the Bay of Biscay using existing high-resolution data. These data will enable the global SSY database to be extended in a barely studied area and will offer new regional data that may be of interest to the scientific community working on denudation rates and sediment loads to the ocean, especially from small coastal catchments. Additionally, the data provide insight into environmental controls on the spatial variability found in SS delivery in Atlantic coastal environments.

Study Area

The studied catchments are located in the province of Gipuzkoa, which is in the north-eastern part of the Basque Country (south-western Europe) and which has an average latitude of 43° and average longitude of 1° (Figure 1). Gipuzkoa is a small province covering an area of approximately 1980 km^2. The altitude ranges from sea level to a maximum elevation of

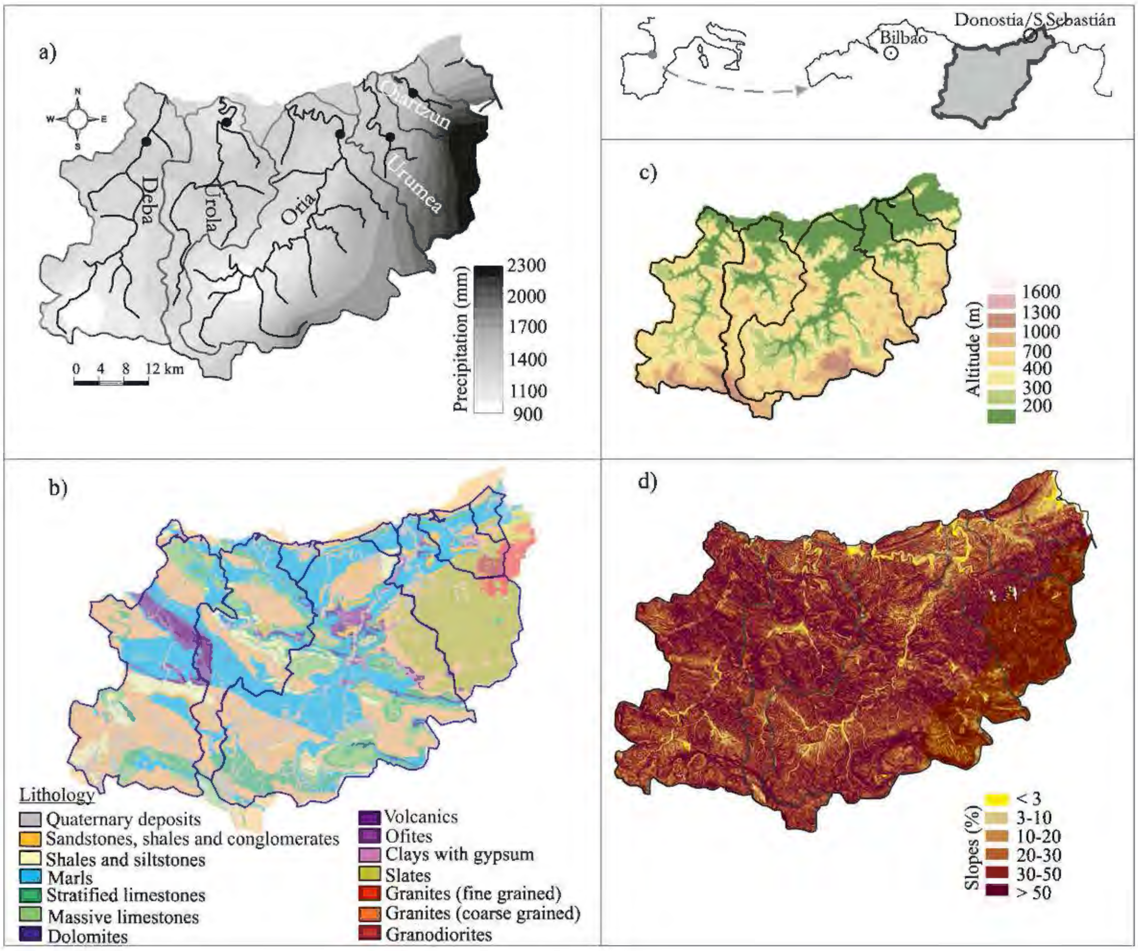

Figure 1. Location and environmental characteristics of the studied area. (a) Studied catchments and the locations of the gauging stations (black circles). The figure also shows the average annual precipitation map, (b) lithology, (c) altitude and (d) slopes.

1554 m, and although the mountains are not very high, their slopes are steep and exceed 25% throughout most of the territory, with average values between 40 and 50% for most of the catchments. The region is characterized by a humid and temperate Atlantic climate with 1500 mm of annual average precipitation (the precipitation is almost evenly distributed in all seasons) and a mean annual temperature of 13 °C that varies little between winter (8–10 °C, on average) and summer (18–20 °C, on average). A high spatial gradient is observed in annual precipitation; the maximums are registered in the eastern part and decrease towards the west and the south.

Geologically, Gipuzkoa is located at the western end of the Pyrenees; the region is structurally complex and lithologically very diverse, with materials from Palaeozoic plutonic rocks to Quaternary sediments (EVE, 1990). Nevertheless, most of the materials in this region are sandstones, shales, limestones and marls, except in the eastern part of the region, where slates are predominant (Figure 1b).

Forest is the predominant land-use in the area, and although autochthonous tree species have been promoted in recent years, pine tree plantations for timber production were introduced throughout the region in previous decades. With the government's promotion of afforestation policies in the second half of the twentieth century (Ruiz Urrestarazu, 1999), plantations with rapidly growing exotic species (primarily *Pinus radiata*) now cover 39–48% of potential native forestland on mountainsides and in areas with elevations below 700–750 m above sea level (a.s.l.), respectively (Garmendia *et al.*, 2012). *Pinus radiata* is very well adapted to the humid and temperate environment of Gipuzkoa, which allows large monoculture plantations to produce timber very efficiently (Michel, 2006). Forest management in these plantations involves clear-cutting on rotations of 30 to 40 years along with mechanical site preparation for reforestation (i.e. scalping and down-slope ripping). Exotic species do not always fit local ecosystems perfectly, which can generate uneven extents of forest cover with small areas of bare soil exposed to direct rainfall. In this respect, Porto *et al.* (2011) found that in southern Italy, the major contribution of soil erosion could be ascribed to those small areas not covered by vegetation. In contrast, *Pinus radiata* in Gipuzkoa are well adapted to the environment and have been considered rapid builders of forest communities (Carrascal, 1986; Ainz, 2008). Consequently, cutting and site preparation are the main drivers of land disturbance and sediment availability throughout the exotic tree plantations in Gipuzkoa. Additional human impacts on this region include civil engineering projects, for example, the construction of new highways and railways that can serve as important sources of river sediment. The effect of infrastructure construction on the generation and source variability of sediments has been assessed by several studies (Rijsdijk *et al.*, 2007; Wu *et al.*, 2012). A more recent publication (Martínez-Santos *et al.*, 2015) showed the effect of highway tunnel construction on sediments in one of the catchments analysed in the present paper (Deba catchment).

Catchment characteristics

From west to east, five rivers, the Deba, Urola, Oria, Urumea and Oiartzun, drain the catchments that were analysed (Table I). In this study, the outlet of each catchment was considered to be the location of the last gauging station before the river discharges into the Bay of Biscay. Considering those outlets, the catchments drain a total area of 1805 km^2. The annual precipitation (P, in mm yr.$^{-1}$) is spatially quite variable (Figure 1a and Table I) because more precipitation is recorded in the eastern part of the province (> 2000 mm in the Urumea and Oiartzun catchments) than in the middle and the west (< 1500 mm in the Deba, Urola and Oria catchments). The total runoff (R, in mm·yr.$^{-1}$), which was calculated from the data recorded at the gauging stations, and the runoff coefficient (Kr, in %), which was estimated as the ratio between the annual runoff and annual precipitation as a percentage, show the same spatial pattern as the precipitation. Differences in the drainage areas (A) for each of the catchments are also important; Oria has the largest drainage area (796 km^2), and Oiartzun has the smallest (56 km^2).

Table I. Names of the gauging stations where discharge and SSC data for this research work were recorded. Annual mean precipitation (P), runoff (R) and runoff coefficient (Kr) for the period 2006–2013 in the studied catchments. Area (A), maximum elevation (Elevmax), mean slope (S), land use (LW = exotic plantation, LF = native forest, LP = pasture, LU = others), mean soil depth (Z) and erodibility of lithology (LE = low erodibility, ME = medium erodibility, HE = high erodibility) for those catchments were also included. Source of data: (http://urhweb.gipuzkoa.net/)

Parameter		Catchment				
		Deba	Urola	Oria	Urumea	Oiartzun
Gauging station		Altzola	Aizarnazabal	Lasarte	Ereñozu	Oiartzun
P (mm)		1358	1453	1497	2071	1942
R (mm)		709	794	858	1251	1303
Kr (%)		52	55	57	60	67
A (km^2)		464.25	269.77	796.5	218.42	56.6
Elev$_{max}$ (m)		986	829	647	950	828
S (%)		44	47	44	56	42
	LW (%)	38.53	36.67	25.22	25.93	26.34
	LF (%)	26.1	31.48	34.46	50.46	37.05
	LP (%)	14.95	21.11	30.34	15.74	20.98
Land-use	LU (%)	10.1	10.74	5.74	0	15.62
Z (m)		1.5	1.2	1.1	0.9	0.9
	LE (%)	8	6	1	4	22
Erodibility	ME (%)	61	59	66	96	51
of lithology	HE (%)	31	35	33	0	27

The average slopes (S, %) calculated for the five catchments are very high and show, in general, slight differences; Urumea is the steepest catchment (Figure 1c and Table I). Regarding land-use and vegetation, the Deba and Urola catchments have higher percentages of exotic plantations (LW), which are primarily *Pinus radiata*. Urumea has more native forests (LF), which are primarily beech and oaks, and the Oria catchment has the highest percentage of pasture (LP) (Table I). Regarding land occupation, the catchments that are located in the middle and western part of the study area (Deba, Urola and Oria) suffer from the greatest human impact; they have larger population densities (maximums of more than 1000 inhabitants km^{-2} in contrast to the maximum of 150 inhabitants km^{-2} in the eastern part of Gipuzkoa) and infrastructure construction pressures (primarily new motorways and high-speed railways).

The Urumea and Oiartzun have the smallest average regolith thickness (Z, in metres), and Deba has the thickest regolith (Table I). The erodibility of the lithology was also considered a primary factor that may control the delivery of sediment. Following the classification proposed by Probst and Amiotte-Suchet (1992), which only considers rock hardness and sensitivity of lithology to mechanical erosion, on the basis of the data of Chorley *et al.* (1984), granites and volcanic rocks were considered to be lowly erodible (LE);

marls, quaternary deposits and lutites with gypsum were classified as highly erodible (HE); and other lithologies, including sandstones, shales, limestones, slates and conglomerates, were considered to be lithologies with medium erodibility (ME) (Figure 1b and Table I).

Materials and Methods

Data acquisition and processing

Since October 2006, precipitation (in millimetres), water depth (in metres) and suspended sediment concentration (SSC_F, in mg l^{-1}) have been measured in the field every 10 minutes at the gauging stations located at the outlets of each of the catchments. The gauging stations are included in the official hydro-meteorological network of the Basque Country. Discharge (in l s^{-1}) is estimated from water depth through an exhaustive calibration conducted by the local hydraulic authorities of a water pressure probe installed in crump-type gauging stations (http://www4.gipuzkoa.net/oohh/web/esp/index.asp). In the gauging station sections, direct discharge measurements are performed periodically and with higher frequency during extraordinary flood events. Three polynomial equations (for low, medium and high waters) relate pressure probe measurements of water depth and manual measurements of discharge for each station. The estimation error in discharge for those equations is between 0.1% and 0.8% (p=0.01) for low discharges, between 0.6% and 3.9% (p=0.1) for medium discharges and between 1.7% and 3.3% (p=0.1) for high discharges. SSC_F is measured optically using SOLITAX infrared backscattering probes (Dr Lange devices), with an expected range of 0 to 10 000 mg l^{-1}. Additionally, automatic water samplers were also installed at the stations. The samplers were programmed to start taking the first of 24 samples of 800 ml of water when an increase in SSC_F above 100 mg l^{-1} was detected. Time interval between samples varies depending on the type of event expected in order to ensure that samples are taken in the increasing and decreasing limbs of the hydrograph and the sedimentograph. The samples are carried to the laboratory for physical suspended sediment concentration (SSC_L) measurements to calibrate the SSC measured by the probes in the field (SSC_F). SSC_L is measured in the laboratory by filtration of the samples through previously weighted 0.45-µm filters and subsequent drying and weighting.

The calibration of SSC_F using physically measured SSC in the water samples is necessary in the catchments because the linear correlations (Pearson's r) between the instantaneous discharge and SSC_F in each of the five catchments have been found to be rather weak (r=0.58 in Deba; r=0.17 in Urola; r=0.59 in Oria; r=0.39 in Urumea; r=0.28 in Oiartzun) although statistically significant at the 1% due to the large amount of data involved in the analysis (more than 300 000 data for each river). Even in Deba and Oria, where the linear correlations are stronger, a high degree of scattering exists (Figure 2). The scattering may be related to the high variability in SSC with discharge (hysteresis effects) due to variations in sediment availability and/or in the sources of sediments during different flood events. Due to these effects, sediment rating curves that relate SSC_F to discharge are not suitable for use for sediment flux predictions in these catchments.

For that reason, to estimate SS delivery from the catchments, the relationship between SSC_F (measured continuously with the probe) and SSC_L (determined from the samples collected by the automatic water samplers) was used to derive calibrated continuous SSC (in mg l^{-1}) data. These relationships are site specific; therefore, the relationships are typically unique for a particular catchment and sometimes within a particular period of time (Gippel, 1989). Due to that specificity, in this study, a particular calibration was established for each catchment considering all of the events in which a threshold SSC_F value of 100 mg l^{-1} was exceeded. SSC values higher than 100 mg l^{-1} account for 5% of the values in Deba, 3% of those in Urola and Oria, 0.5% of those in Urumea and 2% of those in Oiartzun.

SSC calibration methodology

The relationship between SSC_F and SSC_L was investigated using generalized additive models (GAMs) (Hastie and Tibshirani, 1990; Wood, 2006). This type of method does not require any assumption of linearity between the predictor (SSC_F) and response variable (SSC_L), thus allowing the relationship between predictor and outcome to be modelled more appropriately. Smooth functions were estimated by means of P-spline smoothers (Eilers and Marx, 1996), which the literature suggests as the most convenient estimation technique (Rice and Wu, 2001). To fulfil the hypothesis of normality of the residuals, the response variable was log-transformed in those data sets in which it was required, such as Deba and Oria.

Suspended sediment load (SSL) and its temporal variability

Once the calibrations and 95% confidence intervals for SSC_F were established for each catchment (SSC_{L_inf}, for the lowest and SSC_{L_sup} for the highest boundary), annual suspended sediment loads (SSLs, in tonnes) were calculated using 10-minute SSC_F measurements. For each 10-minute measurement, estimation of the SSC_L was computed based on the estimated GAM and its confidence intervals. To allow full propagation of uncertainty associated with the SSC_F–SSC_L relationship, the SSLs were determined considering the 95% confidence interval of the estimated SSC_L. A SSC_L value was randomly selected in the 95% confidence interval of each prediction of SSC_L, transformed from logarithmic to real space (where necessary) and multiplied by the corresponding discharge. This process was undertaken for each 10-minute interval within the selected time period (event, month, hydrological year) and repeated 2000 times for each gauging station. To this end, the following equation was used (Equation 1),

$$SS_b = \Sigma_{i=1}^{n} \widehat{SSC}_{L_{ib}} * Q_i * \text{time} \quad (1)$$

where SSC_{Lib} is the instantaneous suspended sediment concentration randomly selected in the interval (SSC_{L_inf}, SSC_{L_sup}), Q_i is the instantaneous discharge, time is the 10-minute interval over which data were recorded at the gauging station, and SS_b is the estimated annual load in each b=1,…, 2000 replicates. This procedure permitted the derivation of basic statistical parameters [mean and standard deviation (SD)] for SSLs, based on the distribution of the 2000 replicates and the consideration of uncertainties inherent to the SSC calibration curves in the estimated SSLs.

The maximum SSC_F value (data recorded by the field probe) accompanied by an SSC_L value (data obtained in the laboratory by filtration and weighting of a water sample) is exceeded less than 0.07% of the time in Deba, 0.5% of the time in Urola and 0.02%, 0.007% and 0.05% of the time in Oria, Urumea and Oiartzun, respectively. The SSC_L for those SSC_F values above the maximum accompanied by physical data were estimated by extrapolating the trends of the GAMs, with standard errors set as identical to the running mean error calculated for the maximum observed SSC_F (Tarras-Wahlberg and Lane, 2003).

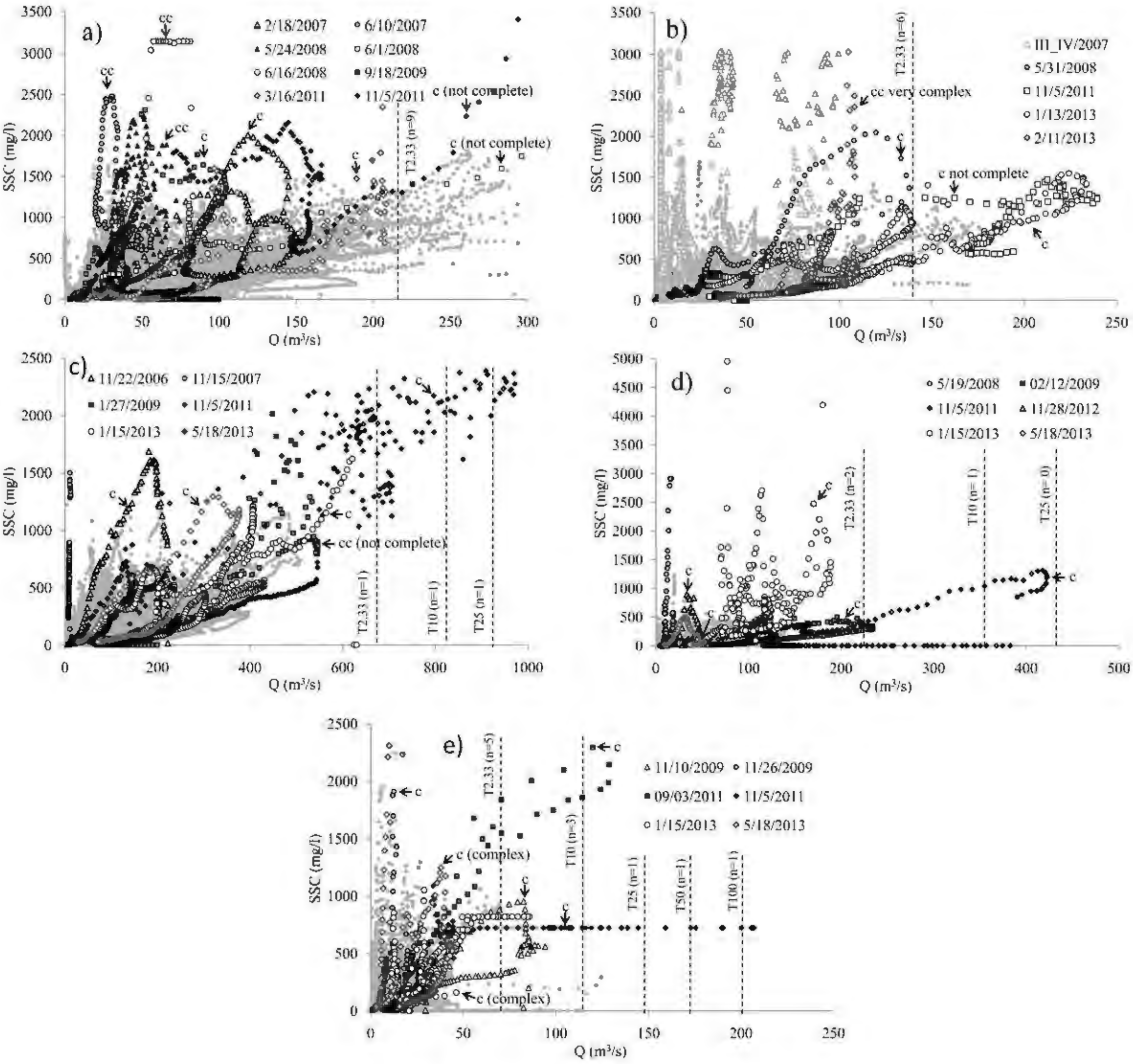

Figure 2. Suspended sediment concentration (SSC) versus discharge (*Q*) relationship for each catchment for the period 2006–2013. The major events in each catchment are indicated by different symbols. c: Clockwise hysteresis; cc: counter-clockwise hysteresis. (a) Deba; (b) Urola; (c) Oria; (d) Urumea; (e) Oiartzun. Return periods (T2.33, T10, T25) for discharge along with the number of events that exceed each of those periods were indicated for each catchment.

The reported data represent measurements taken 10–20 km upstream from the river mouth. Sediment is certainly deposited downstream of the gauging stations, and new sediment is possibly introduced such that the reported sediment load may not represent the actual amount of sediment transported towards the ocean; however, the reported sediment is an approximation of the actual amount of sediment. Considering the results obtained at each gauging station and the calculated area for each catchment, an approximation of the SS yield from Gipuzkoa to the Bay of Biscay was also made using a weighted mean.

Additionally, the temporal variability of SS was analysed using the $Ts_{50\%}$ indicator (Meybeck *et al.*, 2003), which corresponds to the percentage of time necessary to carry 50% of the SS flux to the ocean. The $Ts_{80\%}$ of the suspended sediment flux was also calculated as in Delmás *et al.* (2012). These indicators were calculated for the entire study period using the mean of the daily SSL data that had been previously obtained. The same indicators were calculated for the runoff ($Tw_{50\%}$ and $Tw_{80\%}$).

Environmental controls on suspended sediment yield (SSY)

Analyses of the effect of various hydroclimatic, geomorphological and lithological parameters related to the drainage basin of each of the studied catchments on the mean of the SSL were undertaken. The considered parameters were selected based on availability of data for the five studied catchments. Besides this, it was intended to include variables that are most widely reported to be related to soil erosion and sediment transport processes (Ludwig and Probst, 1998; de Vente *et al.*, 2011) and show some variations in the studied region. Variables related to channel morphology were not included because, considering the small size of catchments, there are not important morphological variations between catchments that would imply significant differences in the SSY at the multiannual timescale. Parameters that were considered and the corresponding data sets are listed in Table I.

The hydroclimatic parameters that were included in the analyses were the mean annual precipitation (*P*, in millimetres), mean annual runoff (*R*, in millimetres) and mean annual runoff coefficient (Kr, %) for the period 2006–2013. The precipitations were calculated for the entire catchment considering 48 meteorological stations for the 1805 km^2 of Gipuzkoa Province.

The other geomorphic parameters that were considered in the analyses were the area of the catchment (*A*, in km^2), maximum elevation ($Elev_{max}$, in metres), mean slope (*S*, %), the average soil depth (*Z*, in metres) and land-use as a percentage of exotic plantation (LW, %), native forest (LF, %), pasture, including cultivated land (LP, %), and other uses, including urban, artificial, water bodies, bare rock (LU, %) in the catchment. In this region, cultivated land is considered together with pasturelands because in Gipuzkoa the percentage of crop cultivated area is very low and it is distributed in small lands that do not have the environmental impact of wide agricultural areas. In fact, the main cultivated areas of Gipuzkoa are exotic plantations. The erodibility of rock was also considered as the percentage of the catchment with lithologies that had low (LE), medium (ME) or high (HE) erodibility. All the data were derived from geographic information system (GIS) data that are freely available at the Department of Land Planning and Environment of the Gipuzkoa Provincial Council (http://urhweb.gipuzkoa.net/, accessed 12 January 2015) and Basque Government (www.geoeuskadi.net, accessed 12 January 2015) websites.

The relationships between all of the variables and the means of the SSY and SSL were assessed. First, the relations between the hydroclimatic, geomorphic and lithologic parameters with SS were assessed using linear correlations (Spearman correlation coefficient and its significance level). Later, principal component analysis (PCA) was completed to assess the main factors that control the spatial variability of the SSY in the studied region and describe the relationship between all the variables. The PCA was performed with a Varimax rotation to better visualize the principal components (PCs). PCA was based on log-transformed data in order to normalize distributions.

Results

SSC versus discharge relationships

Figure 2 shows SSC and the discharge data that were recorded every 10 minute from 2006 to 2013 for each catchment. In the studied locations, the low percentage of missing values for discharge and SSC should be noted. There are no missing discharge values for any of the gauging stations, and the percentages of missing data for SSC are 0.11% in Deba, 0.47% in Urola, 0.25% in Oria, 0.01% in Urumea and 0.25% in Oiartzun. Most of these data are missing during high flow periods, which is when most instrument malfunctions happen. However, we consider the minimal number of gaps and the length of the series to provide sufficient confidence to the obtained results. In Figure 2, even if SSC seems to increase with increasing discharge, a large amount of scattering in the relationship between the instantaneous SSC and *Q* measurements can be clearly observed. Such scattering may be related to variations in sediment availability according to the season, hydrological characteristics and/or source of different events contributing sediment. As a consequence, such variations would induce hysteresis effects that could be observed in those relationships, particularly during flood events between rising discharge and recession periods (Williams, 1989; Lenzi and Marchi, 2000; Smith and Dragovich, 2009). Additionally, Figure 2 shows the major events (concerning discharge, SSC or both) registered for each site during the study period (between five and eight events) using different symbols. The lack of a global relationship between SSC and discharge for each river, along with different relationships between those parameters for different events in each of the analysed catchments, are also evident in Figure 2.

Most of the basins in Figure 2 follow a similar pattern – even if a general positive relationship exists between SSC and discharge, higher maximum concentrations of SS were detected in events with lower maximum discharges, and there was a decrease in the maximum SSC with an increase in maximum discharge. Therefore, during events with lower maximum discharges, which were usually related to drier conditions (lower initial discharges), more intense precipitation (between 2 and 8 mm in 10 minute of maximum precipitation intensity) and higher surface runoff contribution, sediments were more concentrated. However, during wetter periods when precipitation lasts longer (2–3 days) and maximum discharge is higher, sediments are more diluted in water, but the total sediment amounts are usually higher. Nadal-Romero *et al.* (2015) found that Atlantic storms approaching from the northwest are the most influential precipitation events in the study region in terms of runoff and sediment yield. In Oria, this pattern was not as clearly observed, and higher maximum discharges were apparently related to higher concentrations of SS. This trend may be related to higher surface runoff contribution combined with a higher capacity of water fluxes to transport more and/or coarser sediments.

For each of the events highlighted in Figure 2, the SSC registered in the rising limb of the hydrograph is different from that registered in the falling limb, which shows a clear hysteresis effect that has been widely observed in other catchments (Kattan *et al.*, 1987; Williams, 1989; Llorens *et al.*, 1997; Alexandrov *et al.*, 2003; Seeger *et al.*, 2004; Rodríguez-Blanco *et al.*, 2010). In all of the catchments, clockwise hysteresis loops can be observed between SSC and *Q* for most of the major events because the maximum concentration is registered before the maximum discharge and the SSC in the rising limb of the hydrograph is higher than in the falling limb. For such events, Probst (1986) and Etchanchu and Probst (1986) showed that the contribution of surface runoff to the total river discharge is higher during the rising period than during the falling limb of the hydrograph, and during the rising period, this contribution increases the mechanical erosion of the soils and the SSC in the river. Moreover, Kattan *et al.* (1987) proposed that the remobilization of bottom sediment deposited after a previous event could contribute to an increase in the SSC during the rising period. Williams (1989) suggested a rapid depletion of the available sediment coming from a river channel before the runoff peak was reached. There are some cases in which the maximum SSC is reached after the discharge peak and the concentration of sediments is higher in the falling limb of the hydrograph than in the rising one, which produces a counterclockwise hysteretic loop. In the studied catchments this type of loop is usually observed during intense precipitation events that occur under dry soil moisture conditions. This type of loop has been explained by the presence of significant sources of sediment that are distant from the major runoff generation area (Williams, 1989; Brasington and Richards, 2000; Seeger *et al.*, 2004).

Due to the high uncertainty related to the use of sediment rating curves in this case, to estimate the SSC in the river and SS delivery from the studied catchments, the relationship between SSC_F and SSC_L was used to derive calibrated continuous SSC (in mg l^{-1}) data for each catchment. Sixty-three events in Deba, 39 in Urola, 42 in Oria, 15 in Urumea and 21 in Oiartzun were analysed and included in the regressions. For the five catchments that were studied, SSC_L was regressed against the corresponding SSC_F values using a GAM. The calibrations and their 95% confidence intervals are presented in Figure 3.

Field-laboratory relationships (SSC_F versus SSC_L) can be adequately described for the Urola, Oria, Urumea and Oiartzun gauging stations (Figures 3b–3e) using unique models. The fact that regressions do not change throughout the studied period indicates that the physical properties of the suspended particles remain, on average, more or less constant for different events, even if there is a high diversity of lithologies in the catchments. However, changes in the physical characteristics (mainly size)

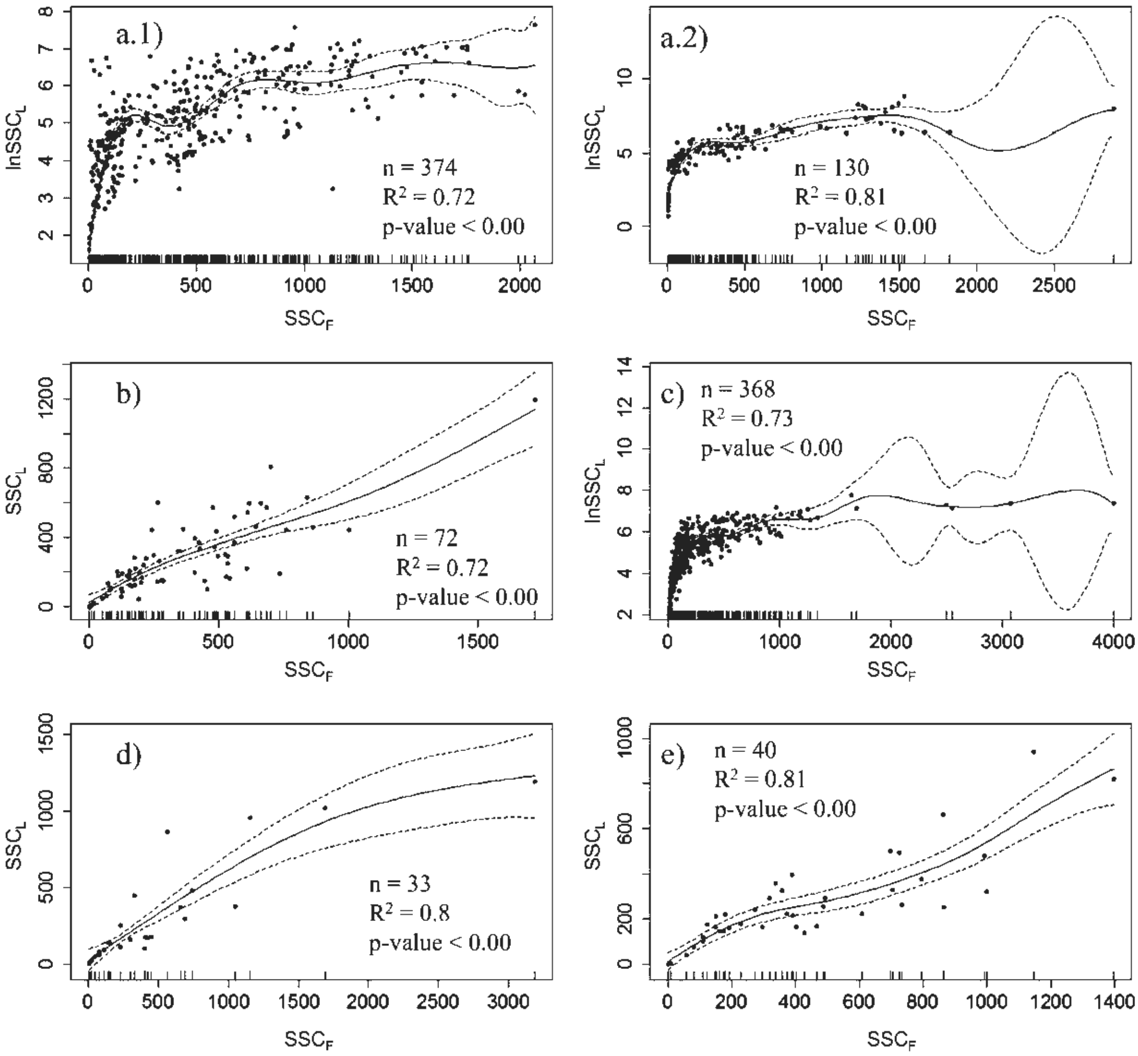

Figure 3. Generalized additive models (GAMs) for field suspended sediment concentration (SSC_F, in mg l^{-1}, optical) and laboratory suspended sediment concentration (SSC_L, in mg l^{-1}) regressions with their 95% confidence intervals for (a1) and (a2) Deba, (b) Urola, (c) Oria, (d) Urumea and (e) Oiartzun Rivers. Data from events registered from October 2006 to September 2013 are included in all of the regressions. In Deba two regressions are included: (a1) for most of the 2006–2013 period; (a2) for the period between November 2011 and February 2012. See explanation in the text.

of SSs from event to event cannot be discounted, considering that the adjusted models are not simple linear regressions but are rather more complex models. Those changes in transported sediment size influence the relationship between the visual SSC measured in the field (SSC_F) and the physical SSC measured in the laboratory (SSC_L) (Regüés *et al.*, 2002). Finally, for the Deba catchment (Figure 3a1 and 3a2), no unique relationship is observed throughout the study period. As suggested by Lewis (1996), calibrations for individual events were produced, and two data sets are distinguished in the graph. One of these uses most of the events that occurred in the Deba River and the other runs from November 2011 to February 2012. This second set of samples appeared as a consequence of the upstream remobilization of a large amount of previously accumulated organic matter during an extreme event in November 2011. Considering this change, a different GAM was applied for each of the studied periods in Deba.

Suspended sediment delivery to the ocean

Table II presents the annual data for precipitation (*P*, in millimetres), runoff (*R*, in millimetres) and suspended sediments SSs, along with the means and SDs (SSL, in tonnes; SSY, in t km^{-2}) for the studied catchments. Approximately 172 600 ±84 641 t·$yr.^{-1}$ (i.e. 63% of the SSs delivered to the Bay of Biscay from this region) was exported from the largest catchment, Oria (Figure 4a). The Deba River was second, with almost 53 500±9824 t $yr.^{-1}$, or 20% of total exported sediment. Together, the two largest rivers exported 83% of the SSs from 70% of the drained area. Urola exported approximately 31 700±84 t (12%) and Urumea and Oiartzun exported 10 100±106 and 4400±20 t $yr.^{-1}$, respectively. Therefore, the largest rivers exported more sediments than the smallest rivers. When drainage area was considered and the SSY was calculated, the Oria catchment had the highest mean SSY of 217±106 t km^{-2}, followed by Urola, Deba, Oiartzun and Urumea, with 117±0.31, 115±21, 78±0.35 and 46±0.48 t km^{-2}, respectively (Figure 4b). The differences observed in the SSY of the five catchments are explained later in this paper, when the environmental controls determining spatial variability of SS delivery are identified. Based on these calculations, the total delivery of sediments to the Bay of Biscay from Gipuzkoa was estimated to be approximately 272 200±38 106 t $yr.^{-1}$ (i.e. 151±21 t km^{-2} $yr.^{-1}$) for a total drainage basin area of 1805 km^2.

In general, uncertainty in SS delivery associated to SSC_F–SSC_L relationships in these five catchments is rather low (Table II). However, the Oria catchment shows a mean SD at 50% of the estimated SSY. This high mean uncertainty is due

Table II. Annual precipitation (*P*, mm), runoff (*R*, mm), runoff coefficient (Kr, %), suspended sediment load (SSL, t) with its standard deviation (± SD) and suspended sediment yield (SSY, $t \cdot km^{-2}$) with its standard deviation (± SD) for the Deba, Urola, Oria, Urumea and Oiartzun catchments between 2006 and 2013. In the last column, the calculated mean annual precipitation, runoff and suspended sediment load and yield for the studied period (2006–2013) are listed. P, R, Kr, SSL and SSY data for Gipuzkoa are also included. The precipitation presented in this table was estimated for the entire catchment, taking into account all of the rain gauges in the study area

		2006–2007	2007–2008	2008–2009	2009–2010	2010–2011	2012–2013	2006–2013
Deba	*P* (mm)	1501	1217	1693	1281	1207	1959	1476
	R (mm)	705	640	995	710	566	1287	817
	Kr (%)	47	53	59	55	47	66	55
	SSL (t), ± SD	49800 ± 912	75000 ± 6267	40300 ± 380	48900 ± 767	48900 ± 912	66000 ± 332	53500 ± 9824
	SSY ($t\,km^{-2}$) ± SD	107 ± 1.96	161 ± 13.5	87 ± 0.82	111 ± 0.64	107 ± 1.96	142 ± 0.71	115 ± 21.16
Urola	*P* (mm)	1526	1307	1768	1367	1312	2195	1579
	R (mm)	709	649	1119	739	678	1515	902
	Kr (%)	46	50	63	54	52	69	57
	SSL (t), ± SD	80600 ± 90	17200 ± 52	21300 ± 69	16700 ± 73	12700 ± 49	49200 ± 107	31700 ± 84
	SSY ($t\,km^{-2}$) ± SD	299 ± 0.33	64 ± 0.19	79 ± 0.26	62 ± 0.27	47 ± 0.18	182 ± 0.39	117 ± 0.31
Oria	*P* (mm)	1657	1348	1764	1381	1427	2265	1640
	R (mm)	833	754	1139	793	753	1602	979
	Kr (%)	50	56	65	57	53	71	60
	SSL (t), ± SD	38600 ± 2260	29400 ± 222	197600 ± 70328	94800 ± 2215	52900 ± 312	150200 ± 637	172600 ± 84641
	SSY ($t\,km^{-2}$) ± SD	48 ± 2.84	37 ± 0.28	248 ± 88	119 ± 2.78	66 ± 0.39	189 ± 0.8	217 ± 106
Urumea	*P* (mm)	2405	1844	2344	1805	2134	2991	2254
	R (mm)	1224	1232	1554	1058	1172	2030	1378
	Kr (%)	51	67	66	59	55	68	61
	SSL (t), ± SD	7100 ± 55	3200 ± 52	10900 ± 96	5300 ± 50	9600 ± 74	19000 ± 134	10100 ± 106
	SSY ($t\,km^{-2}$) ± SD	33 ± 0.25	15 ± 0.24	50 ± 0.44	24 ± 0.23	44 ± 0.34	87 ± 0.61	46 ± 0.48
Oiartzun	*P* (mm)	2037	1784	2210	1745	2059	2727	2094
	R (mm)	1297	1139	1578	1169	1255	2230	1445
	Kr (%)	64	64	71	67	61	82	69
	SSL (t), ± SD	1600 ± 11	1200 ± 9	5200 ± 14	5200 ± 24	5400 ± 26	7500 ± 23	4400 ± 20
	SSY ($t\,km^{-2}$) ± SD	28 ± 0.2	21 ± 0.15	92 ± 0.25	91 ± 0.42	96 ± 0.46	132 ± 0.4	78 ± 0.35
Gipuzkoa	*P* (mm)	1700	1382	1830	1416	1459	2278	1677
	R (mm)	843	779	1163	807	760	1579	989
	Kr (%)	50	56	64	57	52	69	59
	SSL (t), ± SD	177800 ± 1091	126000 ± 2804	275400 ± 31452	170900 ± 1049	130500 ± 433	291800 ± 330	272200 ± 38107
	SSY ($t\,km^{-2}$) ± SD	98 ± 0.6	70 ± 1.55	154 ± 17	95 ± 0.58	72 ± 0.24	162 ± 0.18	151 ± 21.1

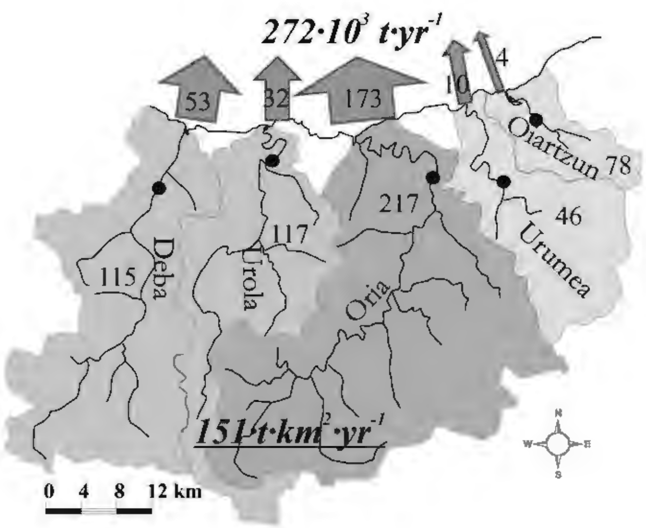

Figure 4. Annual discharge of suspended sediment (SS) from the studied catchments. The widths of the arrows correspond to the relative sediment loads. The colours of the catchments refer to the relative sediment yield. The numbers inside the arrows refer to the average annual sediment delivery in thousands of tonnes per year. The numbers inside each catchment refer to the suspended sediment yield in tonnes per square kilometre and year.

to the high range of values obtained in the 2000 replicates for the hydrological year 2011–2012. During November of 2011, an extraordinary event with high discharge and SSC_F data was registered in this catchment (Figure 2c), but as can be observed in Figure 3c, a high uncertainty exists in SSC_L for the upper range of SSC_F. Consequently, the SSY data obtained for that event and hydrological year 2011–2012 negatively influences the SD of the mean SSY for Oria.

The values obtained for Gipuzkoa are slightly higher than the average value modelled by Ludwig and Probst (1996) for Europe (88 $t\,km^{-2}\,yr.^{-1}$) using precipitation and slope as controlling factors, primarily due to the higher SSY values of catchments located in the middle and west of the study region (Oria, Urola and Deba). However, with the exception of the Oria catchment, these values are below the global annual sediment yield of 190 $t\,km^{-2}\,yr.^{-1}$ calculated by Milliman and Farnsworth (2013) and the 279 $t\,km^{-2}\,yr.^{-1}$ figure reported by Vanmaercke *et al.* (2011) as the mean value for European catchments based on data gathered from gauging stations. The values obtained in the present study are on the order of the mean SSY of 100 $t\,km^{-2}\,yr.^{-1}$ estimated for European catchments located in the Atlantic climatic zone by Vanmaercke *et al.* (2011). However, the results of this study are quite high compared with the sediment fluxes estimated by Delmás *et al.* (2012) for the French rivers that flow into the Bay of Biscay, except for the case of the Urumea River. Using the Improved rating curve approach (IRCA) method, the authors calculated SSYs between 8 and 36 $t\,km^{-2}\,yr.^{-1}$ for the Loire, Garonne, Aquitaine and Adour and Gaves zones, which have catchments that are larger (> 10 000 km^2) than those analysed in the present study. Uriarte (1998) derived SSYs between 20 and 260 $t\,km^{-2}\,yr.^{-1}$ for the Basque catchment areas using regressions of SS against river discharge for discrete or daily integrated water samples. These values are higher than those estimated in the present study, which are based on continuous optical measurements and a higher sampling frequency. However, Milliman (2001) identified wide variations in the SS regimes of European rivers, which are related to anthropogenic activity and other causes.

SSL and SSY estimations can be strongly influenced by the range of events within the measurement period (Regüés *et al.*, 2000; Lenzi and Marchi, 2000; Sun *et al.*, 2001; Ferro and Porto 2012). To assess the effect of events of different frequency and magnitude in each of the catchments, return periods for each of the sites were included in Figure 2, along with the number of events that exceeded a certain return period in each catchment. Return periods of 2.33, 10, 25, 50, 100 and 500 years (URA, 2012) are considered in Figure 2.

In Deba, each of the nine events that exceeded the 2.33-year return period (T2.33) accounted for between the 10% and 70% of the annual SS delivery of that catchment for the hydrological year of occurrence. In the Urola catchment, six events exceeded the 2.33-year return period, delivering between 25% and 55% of annual SSs. In Oria, only one exceptional event was responsible for 90% of the SS delivered to the ocean during the hydrological year 2011–2012. This was a 25-year return period event (T25). In Urumea, two events exceeded the established thresholds, with one T2.33 event accounting for almost 60% of SS delivery in one year and a T10 event that delivered the 80% of annual SS in another. Finally, in Oiartzun, five events exceeded the 2.33-year return period, two exceeded T10 and one exceeded T100. Approximately 50% of the annual SS was delivered during this last event. The other four events (2 T2.33 and 2 T10) were responsible for delivering between 20% and 35% of annual SS.

These data show the importance of low frequency events for SS delivery to the ocean, as they account for a high percentage of total SS delivery for a single year. However, the amount of sediment delivered during those extraordinary events show a wide range, especially in Deba and Urola catchments, where events of the same return period (T2.33) can deliver anywhere from a small percentage of annual SS to more than the half of it. Conversely, in Oiartzun, events with different return periods (T2.33 and T10) account for a similar percentage of the annual SS. Furthermore, catchments where events with higher return periods were recorded (Oiartzun, Urumea and Oria) are not necessarily those that show higher SS delivery rates. Therefore, other characteristics are also responsible for the amount of SS that an event can transport, which include antecedent conditions, precipitation amount and intensity, duration of the event or sediment availability, among others (Old *et al.*, 2003; Nearing *et al.*, 2005; Seeger *et al.*, 2004; Zabaleta *et al.*, 2007).

Table II also includes annual precipitation and runoff. A regional analysis of the hydrology in the Gipuzkoa territory (Zabaleta, 2008), in which 22 gauging and meteorological stations were analysed for more than 15 years, showed that a significant difference existed in the annual runoff coefficient between the catchments that are situated in the eastern part of the region and those in the western part. Therefore, a progressive decrease in precipitation and its productivity (in terms of runoff) from east to west was detected. Based on the corresponding analysis and the data presented in Table II, it can be observed that even if higher amounts of precipitation and runoff are registered for the catchments located in the east (Oiartzun and Urumea) than for the remaining catchments, the eastern catchments have the lowest calculated SSY. Based on these data, one could suspect that there must be other variables (that are not related to hydroclimatic variables) that are major controls of SSY on a regional scale in this area.

In the relationship between sediment delivery and erosion (sediment delivery ratio, SDR), sediment storage is a key factor for better understanding the physical processes and geomorphological evolution of the landscape. As demonstrated by Walling (1983), the SDR decreases when the drainage basin area increases. Porto *et al.* (2011) stated that the clear inverse trend between catchment area and SDR found in southern Italy largely reflected the increasing opportunity for sediment deposition and storage with larger catchment area. For the coterminous United States, Holeman (1980) calculated that only 10% of total eroded sediment reaches the ocean, and Wasson *et al.* (1996) estimated that in Australia only 3% of the soil eroded in the external drainage basins is delivered to the ocean. Nevertheless, in a semi-arid area such as southern Morocco, Haida *et al.* (1996) showed that SDR could reach 67% in the Oued Tensiff drainage basin (18 400 km^2). In our case study, the official erosion estimates (Basque Government, 2005) made using the RUSLE equations were compared with the SSYs calculated in the present paper to provide an order of magnitude estimate of the SDR (Table III), even if RUSLE is not perfectly adapted to our regional conditions. Erosion rates and, consequently, derived SDRs show important differences depending on the catchment. Considering the drainage basin area and relationships for different regions, the SDRs obtained for Deba, Urola, Lasarte, Urumea and Oiartzun, are in the range (16–59%) of those published by Walling (1983). However, they are higher than those calculated for catchments of more than 1000 km^2 in Australia by Wasson *et al.* (1996) or for catchments between 1.47 ha and 31.61 km^2 in southern Italy by Porto *et al.* (2011). The SDRs calculated for Deba and Oria are the highest in the studied area (37–59%). Small mountainous rivers generally have small floodplains and are more susceptible to floods and it is assumed that less sediment is deposited in smaller drainage basins than in larger ones. However, in Gipuzkoa, the drainage basin area does not appear to affect SDR because the highest SDR can be observed for the largest catchment and the lowest SDR for the smallest one. In this sense, Walling (1983) and de Vente *et al.* (2011) emphasized the uncertainties with respect to temporal and spatial aggregation of data on sediment transport, sediment yield and explanatory factors such as climate, land-use and lithology. We will return to this point when discussing the temporal variability indices for SS.

Table II shows the high variability of the SSLs from year-to-year, which is much higher than the variability in the precipitation or runoff. The largest amount of SS, with associated largest uncertainty, was exported from Gipuzkoa in the 2011–2012 hydrological year, a total of 733 500 ± 95 735 t. However, 2011–2012 was not the rainiest year (the precipitation was below the mean of the study period for each catchment) nor the year with the highest total runoff (even if the total runoff exceeded the mean of the study period for each catchment), but the runoff coefficients calculated for year 2011–2012 were quite high and exceeded 60% for most of the catchments, as a consequence of an extreme runoff event (Figure 2).

Table III. Erosion estimates made using the RUSLE equation (Basque Government, 2005), mean SSY (this paper) and sediment delivery ratio (SDR) calculated from those data. The area (A, km^2) of the studied catchments is also included in the table

	Erosion RUSLE (t km^{-2})	SSY (t km^{-2})	SDR (%)	*A* (km2)
Deba	415	90	22	464.25
Urola	320	117	37	269.77
Oria	370	217	59	796.5
Urumea	240	46	19	218.42
Oiartzun	490	78	16	56.6

Temporal variability of SS delivery

Figure 5 clearly shows that there were extraordinarily high deliveries of SS (compared with the rest of the data) during the spring of 2007 in the Urola catchment and during the autumn of 2011 in the Oria catchment. The high SSLs caused 2006–2007 and 2011–2012 to be the years with the highest levels of SS export in Urola and Oria, respectively. In Urola, this extremely high output of SS occurred when a factory located approximately 20 m upstream of the measurement station began excavation to expand its area. The excavated area had a volume of approximately 150 000 m^3, which would account for 142 500 t of material, assuming a soil density of 0.95 t m^{-3}. Therefore, the excavation generated a large amount of SS that was available for transport and delivery out of the catchment. The anomalous increase in SS delivery in 2006–2007 was approximated using the regression between runoff (in millimetres) and SS delivery (in t km^{-2}) using monthly values ($R^2 = 0.74$) for the period 2007–2013 (Figure 6a). The regression between these two parameters improved from the 10-minute to monthly scale because hysteresis effects did not affect their relationship on the longer timescale. The regression was then applied to the runoff data observed over the period 2006–2007 to obtain theoretical SS delivery values from Urola under non-modified conditions (Figure 6b). The difference between the observed and the theoretical SS delivery reached 235 t km^{-2}, 63 500 t or 60 300 m^3 (assuming a density of 0.95 t m^{-3}), representing 78% of the SS delivered to the coastal ocean from the Urola catchment over the period 2006–2007. This supplementary sediment was transported during March and April and can be attributed to higher availability of SS derived from human impact in the catchment, which was to a great extent due to the previously mentioned excavation works. Therefore, in this case, the increase in SS cannot be associated with uncertainties in the calibration of SSC data, and although the SD of SSY is very low in this catchment, it was clearly provoked by human activity.

However, in November 2011, the SSL in the Oria River was at least four times higher than that of any other month (Figure 5), with a high uncertainty associated to the SSC_F–SSC_L regression model. This high SSL was generated as a consequence of an extreme runoff event (the highest runoff registered, at least between 1999 and 2012). A lower-magnitude increase in discharge and SS delivery in November 2011 can also be identified for the other catchments because the strong rainfall event was regional (Figure 2).

Following the previously mentioned approach, a regression between the monthly means of SS delivery (in t km^{-2}) and runoff (in millimetres) was conducted for each of the five catchments to account for seasonal variations over the period

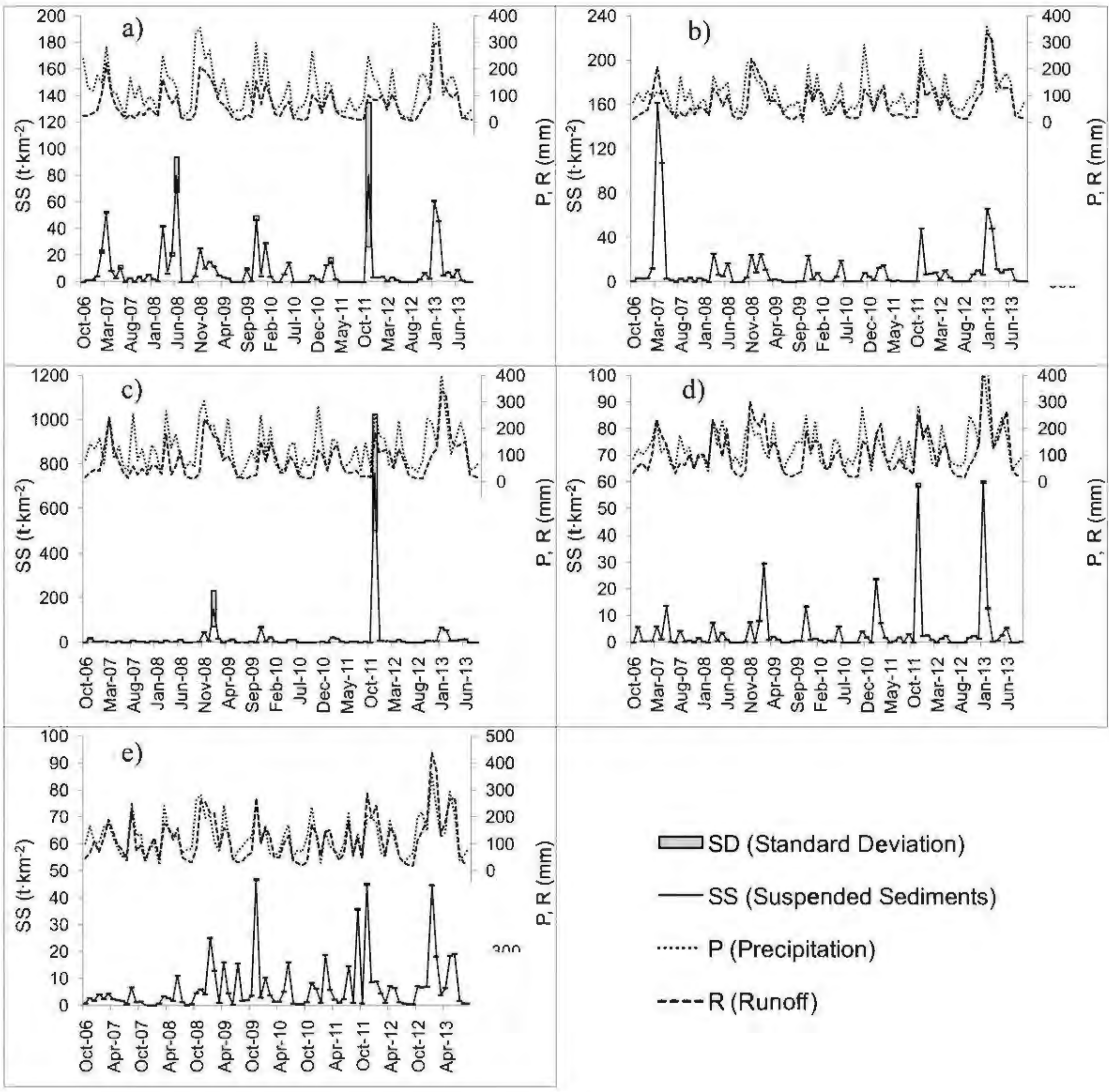

Figure 5. Monthly precipitation (*P*, in millimetres), runoff (*R*, in millimetres) and specific suspended sediment load (SSL) with its standard deviation (in t km^{-2}) for the (a) Deba, (b) Urola, (c) Oria, (d) Urumea and (e) Oiartzun catchments for the period 2006–2013.

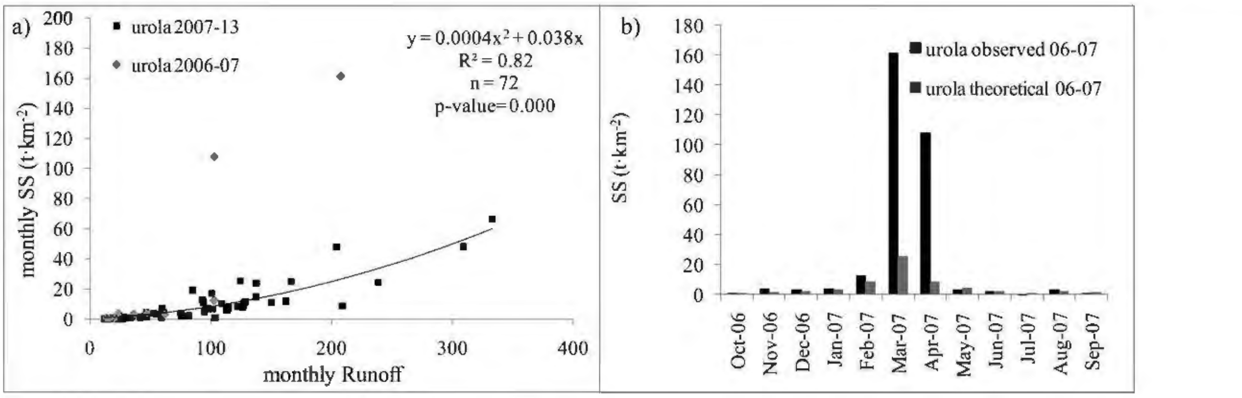

Figure 6. (a) Monthly mean suspended sediment (SS, in t km^{-2}) versus monthly runoff (in millimetres) for the Urola catchment over the periods 2006–2007 and 2007–2013. The regression for the period 2007–2013, with the number of data involved (*n*), the determination coefficient (R^2) and the significance level of the regression (*p*-value) also included. (b) Observed and theoretical SS delivery (in t km^{-2}) from the Urola catchment over the period 2006–2007. The theoretical SS delivery was calculated using the monthly relationship between runoff (in millimetres) and SS delivery (in t km^{-2}) from October 2007 to September 2013.

2006–2013 (Figure 7). For the regressions, a confidence interval of 95% was calculated. There was no significant hysteresis on the monthly timescale, and the regressions that are shown are statistically significant. The data located within the 95% confidence interval are considered to be related to erosion and sediment transport driven by environmental factors such

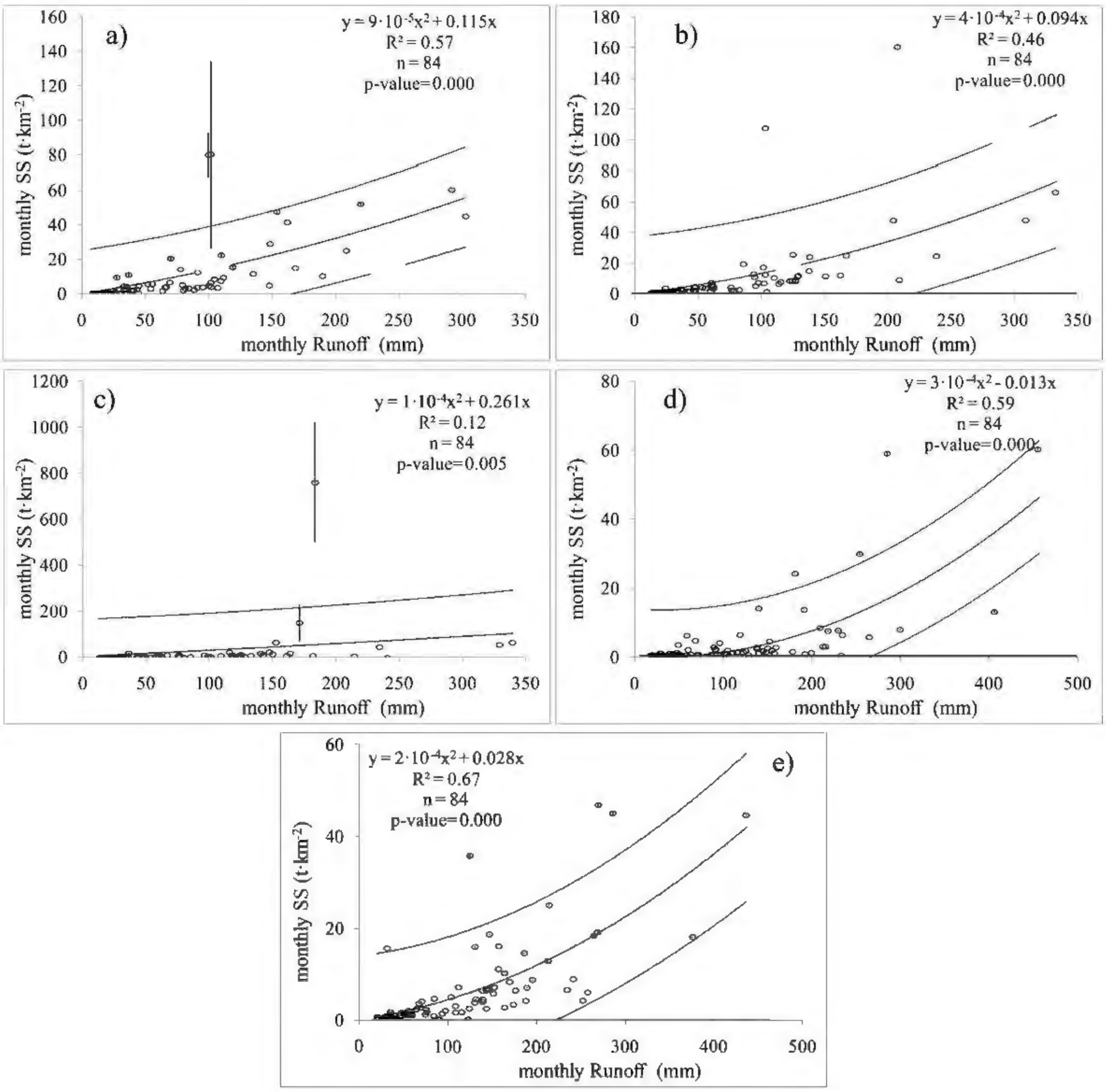

Figure 7. Regressions and 95% confidence intervals between the monthly specific mean suspended sediment loads (SSLs, in t km^{-2}) and monthly runoff (in millimetres) for the (a) Deba, (b) Urola, (c) Oria, (d) Urumea and (e) Oiartzun catchments for the period between 2006 and 2013. Standard deviation of the monthly SSL is represented by a vertical line. The regression equation, number of observations (*n*), determination coefficient (R^2) and significance level (*p*-value) are also shown.

as land-use and catchment geomorphology. In contrast, to detect possible effects on the SS delivery in the analysed catchments, the data outside of the 95% interval were considered to be affected by uncommon conditions such as civil engineering works or extraordinary runoff events for points above the confidence interval or sediment retention structures for points below the confidence interval. To estimate the amount of sediment that was delivered due to those conditions, the difference between the line drawn at the 95% confidence interval and the mean of the estimated data was calculated.

In Oria and Urumea (Figures 7c and 7d), the outlier data are related to the extraordinary runoff event that occurred in November 2011 (Figures 2c, 2d, 5c and 5d). During that month, 250 (±120)% more SS than that occurring under normal conditions was delivered in Oria and 89 (±3)% more was delivered in Urumea, and in Oiartzun, this event accounted for an extra 29 (±1)%. In Oiartzun, 80 (±2)% and 42 (±1)% more SS was transported in September 2011 and November 2009, respectively, likely due to the high discharge amounts observed there for the runoff events of 3 September 2011 and 10 November 2009 (Figure 2e). Finally, in Deba, the outliers accounted for 106 (±34)% and 105 (±138)% more sediment than normal conditions. In general, there are few points that are not located inside the 95% confidence interval, and most of them are related to runoff events in which high discharge amounts were observed. Therefore, it can be concluded that in the studied catchments, interannual SS delivery is not controlled by temporally and spatially isolated human impacts, but that more general characteristics of the catchment, such as geomorphology, land-use, general land management, are the drivers of SS availability and, consequently, of SSY.

The daily contribution of the runoff and SSL to the total were also calculated. Table IV lists indices of the temporal variability of the discharge and sediment for the five catchments. The results show that a large proportion of the total observed runoff and SS were transported within a short period. The temporal variability in the runoff was not significantly different between the catchments, with 50% of annual water volume exported over 10–16% (1–2 months) of the year ($Tw_{50\%}$) and 80% exported over 35–45% (4–5.5 months) of the year ($Tw_{80\%}$), depending on the catchment. These data demonstrate the high variability of water height in these catchments and how little the catchments are regulated because high values of $Tw_{50\%}$ (>30%) are typically observed in highly regulated or lake-influenced rivers (Meybeck *et al.*, 2003).

The duration for the SSL was much shorter than that for the water flow. Half of the SSL ($Ts_{50\%}$) was delivered between 0.3% (one day) and 1% (3–4 days) of the time, and 80% of the sediment was exported between 2.5% (nine days) and 8% (< 30 days) of the time. Similar data were obtained by Zabaleta and Antiguedad (2012) for three small headwater catchments

Table IV. Temporal variability indices for the runoff (mm) and SS load (t) for the five catchments studied. Tw50% and Tw80% are the percentages of time required to deliver 50% and 80% of the annual water volume, respectively. Ts50% and Ts80% are the percentages of time required to deliver 50% and 80% of the annual SS load, respectively

	Runoff $Tw_{50\%}$	$Tw_{80\%}$	SSL $Ts_{50\%}$	$Ts_{80\%}$
Deba	10.2	34.5	0.69	3.18
Urola	12.4	40.3	1.02	5.72
Oria	11.2	37.7	0.57	2.77
Urumea	16.3	45.6	0.29	2.44
Oiartzun	15.7	45.8	0.68	7.84

(3.8, 4.8 and 48 km^2) in the same area. This contradicts the findings of some authors who show that, sometimes, small events, over long periods, are more responsible than large events for sediment export (Ferro and Porto, 2012). Following the characterization of the duration patterns reported by Meybeck *et al.* (2003), these patterns suggest that the studied catchments show very short sediment flux durations due to small catchment size and scarcity of areas where sediment could be temporally retained (i.e. floodplains). These results are consistent with the relatively high SDR obtained (Table III). However, regarding their relationship with catchment area some contradictions can be found since a higher SDR (59%) was estimated for the largest catchments (Oria, 796.5 km^2) than for the smallest ones (16%, Oiartzun, 56.6 km^2), from which one could conclude that higher amounts of sediment are being deposited in smaller catchments. The contradiction found could be related to the relatively short period of time involved in SSY estimates (seven years). Nevertheless, the catchments with lower SDRs are those with higher RUSLE estimates as well as the steepest slopes and thinner soils. The steepness of those catchments could be related to an overestimation of erosion rates using RUSLE. In any case, the validity of the RUSLE equation in an environment such as that examined in this study can, at least, be discussed.

The duration pattern is also slightly different for SS transport (for some days) and water flow (for some months). Indeed, the Urumea catchment had a higher flow duration ($Tw_{50\%}$ = 16.3% of the time) but lower SSL duration ($Ts_{50\%}$ = 0.29% of the time). Conversely, Urola, with a similar catchment area, had a lower flow duration ($Tw_{50\%}$ = 12.4% of the time) but higher SSL duration ($Ts_{50\%}$ = 1.02% of the time). The differences may be related to sediment availability. In those catchments where SS transport is limited by its availability, the duration for SS would be lower than in those catchments where the availability of SS was not as limited.

These results support the idea that hydroclimatic variables are not the main factors that control the spatial variability of the delivery of SS in this area; there must be other, distinct environmental parameters that affect SS availability. Various studies have indicated that factors including topography/morphology (Pinet and Souriau, 1988; Milliman and Syvitski, 1992; Ludwig and Probst 1996; Montgomery and Brandon, 2002), lithology (Probst and Amiotte-Suchet, 1992; Ludwig and Probst, 1998; Nadal-Romero *et al.*, 2011), land-use (Walling, 2006; Lana-Renault *et al.*, 2010) and human activities (Olarieta *et al.*, 1999; Siakeu *et al.*, 2004; Evans *et al.*, 2006) may significantly affect SSY and its variability.

Environmental controls on SS delivery

To explore which factors control SS availability in the studied catchments and, consequently, SS delivery to the Bay of Biscay, Spearman correlation coefficients were calculated for all of the possible variable pairs shown in Table I (Table V). Many studies that have examined global SSYs have shown that hydroclimatic variables largely explain the amount of regional variations in SSY. However, contrary to what could be expected, in this area a negative relationship, although statistically not significant, exists between annual precipitation and SSY or SSL and between runoff and SSY or SSL. Taking into consideration the high variability in the hydroclimatic variables in the region, this fact mainly indicates that precipitation or runoff do not limit SS delivery, and other factors exert stronger control on SS delivery (Vanmaercke *et al.*, 2011). There should therefore be physical characteristics of the catchments that limit sediment availability and thus control SS delivery to the ocean. The amount of SS delivered by a river to the ocean is clearly related to the amount of the SS that is produced and to depositional processes that occur within the river's drainage basin. Usually, there is an increase in the relative importance of depositional processes with an increase in catchment area (Walling, 1983; Hovius, 1998), which is reflected in the inverse relationship between SSY and catchment area shown in several regional and global studies (Milliman and Meade, 1983; Probst and Amiotte-Suchet, 1992; Milliman and Farnsworth, 2013). However, in contrast to those results, there is a positive relationship between SSY and catchment area ($r = 0.8$) in the studied area (Table V). In fact, below a certain catchment area threshold (which is determined by local conditions), an increase in SSY is expected with increasing catchment area because additional erosion processes such as gully erosion, bank erosion and mass movement become possible (de Vente and Poesen, 2005). At the same time, the storage of sediment in the drainage network is not as important in small catchments (Dunne, 1979), which is the case for the studied catchments that have steep slopes and limited floodplains where sediments could be stored (in contrast to what could be deduced from the calculated SDR data). Thus, as Restrepo *et al.* (2006) concluded for the sub-catchments in the Magdalena river basin (Colombia), it is likely that catchment area, with a limited variation from 56.6 to 796.5 km^2, does not have an important effect on the spatial variability of SSY in this area.

Human impact and land-use management have been reported to be responsible for increases in the SS delivery in some catchments (see Walling and Probst, 1997; Walling, 2006). In this area, land-use also appears to play a role in SS availability and delivery. SSY shows a negative correlation with the percentage of native forest ($r = -0.6$) (LF% in Table V) and a positive correlation with the percentage of pasture ($r = 0.7$). Native forests are likely more favourable for soil conservation in the studied area because native forests are typically public forests intended for ecosystem conservation and not the production of timber. In contrast, the management of plantations of exotic species (LW% in Table V) leads to land disturbance and an increase in soil erosion and sediment availability, as reported by Olarieta *et al.* (1999) for this region. Recently, Borrelli and Schütt (2014) also reported an increase in soil erosion susceptibility after forest harvesting in central Italy. SSY also shows a positive correlation with the percentage of highly erodible lithologies ($r = 0.9$).

The PCA results based on a correlation matrix analysis with Varimax rotation indicate that there are three main PCs that explain a cumulative variance greater than 98%. The loads for the variables that were considered in the PCs from the PCA are presented in Table VI. Table VI shows that the variables weighted more highly for PC1 (load >0.7) (which explains 50% of the total variance of the data matrix) are, SSL, *A*, LW (exotic plantation percentage) and *Z* (regolith depth) on the positive axis and *P* (precipitation), *R* (runoff), Kr (runoff coefficient) and LF (native forest percentage) on the negative axis. PC2 (which explains 26% of the total variance) shows a load greater than 0.7 for LU (other land-use percentage), and HE (high erodibility) on the positive axis and LF (native forest percentage), *S* (slope) and ME (medium erodibility) on the negative axis. PC3 (22% of the total variance) is characterized by SSY and LP (percentage of pasture) on the positive axis and maximum elevation ($Elev_{max}$) and LE (low erodibility) on the negative axis.

The factorial plane PC1 versus PC2 (Figure 8) shows that SSY and SSL are positively affected by the percentage of exotic plantations (LW) and regolith depth (*Z*); those factors are located in the right part of Figure 8, whereas the percentage of native forest (LF) is located in the left half, which implies that native forest cover may reduce SS availability and delivery. The locations of the studied catchments in the factorial plane (Figure 8, bottom right) show that the Urola and Oria

Table V. Spearman correlation matrix between the variables presented in Table I. In brackets significance of Spearman's r

	P	R	Kr	A	Elevmax	S	LW	LF	LP	LU	Z	LE	ME	HE	SSL
R	0.90 (0.04)	1.00													
Kr	0.90 (0.04)	1.00	1.00												
A	-0.60 (0.28)	-0.70 (0.19)	-0.70 (0.19)	1.00											
Elevmax	-0.30 (0.62)	-0.50 (0.39)	-0.50 (0.39)	-0.10 (0.87)	1.00										
S	0.21 (0.74)	-0.21 (0.74)	-0.21 (0.74)	0.05 (0.93)	0.41 (0.49)	1.00									
LW	-0.70 (0.19)	-0.60 (0.28)	-0.60 (0.28)	-0.10 (0.87)	0.70 (0.19)	-0.10 (0.87)	1.00								
LF	1.00	0.90 (0.04)	0.90 (0.04)	-0.60 (0.28)	-0.30 (0.62)	0.21 (0.74)	-0.70 (0.19)	1.00							
LP	0.10 (0.87)	0.20 (0.75)	0.20 (0.75)	0.30 (0.62)	0.90 (0.04)	-0.10 (0.87)	-0.60 (0.28)	0.10 (0.87)	1.00						
LU	-0.30 (0.62)	0.10 (0.87)	0.10 (0.87)	-0.40 (0.50)	-0.20 (0.75)	-0.67 (0.22)	0.50 (0.39)	-0.30 (0.62)	0.10 (0.87)	1.00					
Z	-0.97 (0.00)	-0.97 (0.00)	-0.97 (0.00)	0.67 (0.22)	0.41 (0.49)	0.00 (1.00)	0.67 (0.22)	-0.97 (0.00)	-0.15 (0.80)	0.10 (0.87)	1.00				
LE	-0.20 (0.75)	0.10 (0.87)	0.10 (0.87)	-0.60 (0.28)	0.30 (0.62)	-0.56 (0.32)	0.70 (0.19)	-0.20 (0.75)	-0.50 (0.39)	0.80 (0.10)	0.05 (0.93)	1.00			
ME	0.30 (0.62)	-0.10 (0.87)	-0.10 (0.87)	0.40 (0.50)	0.20 (0.75)	0.67 (0.22)	-0.50 (0.39)	0.30 (0.62)	-0.10 (0.87)	-1.00	-0.10 (0.87)	-0.80 (0.10)	1.00		
HE	-0.70 (0.19)	-0.60 (0.28)	-0.60 (0.28)	-0.60 (0.28)	-0.30 (0.62)	-0.50 (0.39)	0.20 (0.75)	-0.70 (0.19)	0.60 (0.28)	0.30 (0.62)	0.67 (0.22)	-0.20 (0.75)	-0.30 (0.62)	1.00	
SSL	-0.60 (0.28)	-0.70 (0.19)	-0.70 (0.19)	1.00	-0.10 (0.87)	0.05 (0.93)	-0.10 (0.87)	-0.60 (0.28)	0.30 (0.62)	-0.40 (0.50)	0.67 (0.22)	-0.60 (0.28)	0.40 (0.50)	0.60 (0.28)	1.00
SSY	-0.60 (0.28)	-0.50 (0.39)	-0.50 (0.39)	0.80 (0.10)	-0.50 (0.39)	-0.21 (0.74)	-0.10 (0.87)	-0.60 (0.28)	0.70 (0.19)	0.10 (0.87)	0.56 (0.32)	-0.40 (0.50)	-0.10 (0.87)	0.90 (0.04)	0.80 (0.10)

Table VI. Loads of each variable considered in the PCs (principal components) obtained from the principal component analysis

	P	*R*	Kr	*A*	SSL	SSY	$Elev_{max}$	*S*	LW	LF	LP	LU	*Z*	LE	ME	HE
PC1	−0.89	−0.96	−0.98	0.78	0.53	0.81	0.11	−0.07	0.74	−0.70	−0.13	0.14	0.93	−0.43	0.01	0.34
PC2	−0.42	−0.24	0.18	−0.02	0.46	−0.29	−0.22	−0.93	0.33	−0.70	0.29	0.99	0.30	0.55	−1.00	0.90
PC3	−0.16	−0.09	0.06	0.62	0.71	0.49	−0.96	−0.24	−0.53	0.05	0.93	0.03	−0.18	−0.72	−0.02	0.28

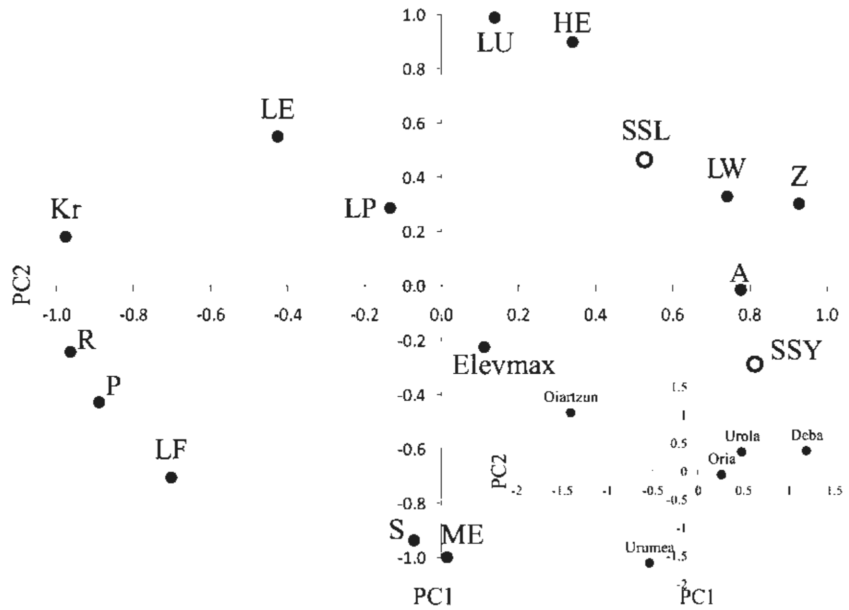

Figure 8. Distribution of the analysed variables and the catchments (shaded area in the left bottom) in the PC1 versus PC2 factorial plane obtained by principal component analysis (PCA).

catchments and especially the Deba catchment are the most affected by the previously mentioned variables, with a high percentage of exotic forest and a significant regolith depth. The relationship between SSY and soil depth is not very intuitive, however, a deeper regolith would mean a higher amount of soil to be eroded and delivered in the form of sediment. Having said that, it cannot be discarded the effect of collinearity, due to the positive correlation of soil depth with exotic plantations and of these lasts with SSY. These variables, in conjunction with the higher human impact (human density and infrastructure construction) of those catchments, provide SSs that can be transported by the rivers. As a consequence, the SSY and SSL calculated for these catchments were higher. In contrast, Urumea and Oiartzun are located in the left half of the factorial plane, which is characterized by a higher percentage of native forest, lower human impact and, as a result, lower SSY and SSL, especially in Urumea.

The hydroclimatic variables (*P*, *R* and Kr) show relationships with SS that are contrary to the expected relationships, as concluded from the correlation matrix. This result is observed because, in this region, hydroclimatic factors do not limit SS transport and delivery, and there are other factors (including land-use and geomorphic factors) that control the spatial differences in the availability of SS and therefore SSY and SSL.

Conclusions

Knowledge of sediment yield from small catchments is very important in gaining a wider overview of SS delivery to coastal oceans and for regional studies. In addition, there is a significant lack of data on SS delivery to the ocean and its environmental controls in the Atlantic region of southern Europe. In this study, the data regarding SS delivery from the Gipuzkoa province to the Bay of Biscay were calculated using high temporal resolution data (discharge and SSC) from five gauging stations. The uncertainty inherent to SSC calibration models was considered in the transformation of SSC data into SSY estimates. The followed approach provided a more confident comparison of SSY data from different catchments. For catchments with areas ranging from 56.6 km^2 to 796.5 km^2, the SS delivery varied from approximately 4400 ± 20 to 172 600 ± 84 641 t $yr.^{-1}$, and the SSY ranged from 46 ± 0.48 to 217 ± 106 t km^{-2} $yr.^{-1}$.

The temporality of sediment delivery is important at interannual and seasonal scales because of environmental and, more particularly, meteorological variability. To add confusion, human influences on sediment erosion and delivery through civil engineering works cannot be minimized. This variability reinforces the argument that long-term, high-resolution observation programmes are required both to gain a better understanding of the factors and processes that control the physical erosion of soils and fluvial sediment transport and to obtain reliable approximations of SS deliveries to the ocean. The database used in this study captures a wide range of meteorological situations, including very wet years such as 2012–2013 and extraordinary events such as those that occurred on the 5 and 6 November 2011. Anthropogenic impacts, including the excavation works undertaken in the Urola River basin, were also considered within the studied period. However, obtaining longer-term measurements will allow the detection of effects from other meteorological-, environmental- and human-induced changes on SS availability.

In this study, various hydroclimatic and environmental catchment characteristics were analysed to explain the spatial variability of SS delivery in this area. The hydroclimatic variables did not produce the expected effect on SS delivery because they were inversely related to SSY, contrary to effects that have been observed in different regions of the world and on a global scale. Thus, in the study area, precipitation and runoff are not considered to be key limiters of SS delivery, and other environmental factors related to sediment availability must be controlling the spatial variability of SS delivery to the ocean. The direct relationships between SSY and catchment area were also contrary to what is usually found, likely because of the small range of catchment area and the steep relief of the region, which together with the scarcity of floodplains produce a lack of space where sediment can be deposited.

Based on the current analyses, the potential controlling factors of SS availability and SSY in the study region were determined. The major factors that affect SS availability, and hence SSY, were determined to be land-use and, in particular, vegetation (exotic plantations versus native forest) and regolith depth.

These findings confirm those reported in earlier studies that analyse the often complex relationship between SS, hydroclimatic factors, spatial scale and other environmental characteristics. Strong relationships between SSY and one or more catchment characteristics can be found locally. However, these relations can hardly be generalized because the sediment fluxes of a catchment are the integrated effect of a series of tectonic, climatic and geomorphic processes (Hovius and Leeder, 1998). Nonetheless, the SSYs and controlling factors discussed in this paper help address the paucity of information on SS delivery in the Atlantic area and can provide valuable quantitative information for stakeholders to make more informed decisions on land-use management by taking into consideration the effects of soil erosion and river SS transport.

Acknowledgements—This work was supported by the Department of Land Planning and Environment of the Gipuzkoa Provincial Council (Basque Country), the University of the Basque Country (UFI 11/26), the Basque Government (Consolidated Groups IT 598-13 and IT620-13), the Spanish Ministry of Science and Innovation (CGL2011-26236) and the Spanish Ministry of Economy and Competitiveness (CAUSE project, CTM2012-39500).

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