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Variability of suspended sediment yields within the Loire river basin (*France*)

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SUMMARY

Suspended sediment fluxes and their variability in time and space have received much attention over the past decades. Large databases compiling suspended sediment load (*SL*) data are often used to serve these purposes. Analyses of these databases have highlighted the following two major limitations: (i) the role of lowland areas in sediment production and transfer has been minimised, and studies on small-scale catchments (with a drainage area of $\leqslant 10^2$ km^2) are practically non-existent in the literature; and (ii) inhomogeneous data and calculation methods are used to estimate and compare the *SL* values.

In this context, the present study aims to complete the existing studies by providing a reliable comparison of *SL* values for various catchments within lowland river basins. Therefore, we focused on the Loire and Brittany river basins (*France*). 111 small to large catchments covering 78% of this area and representative of the basins landscape diversity were chosen. We first present a large database of area-specific suspended sediment yields (*SY*) calculated from the suspended sediment concentration and flow discharge data over 7–40 yr of measurements at gauging stations. Two calculation methods are used, and the calculated loads are confined within a factor of 0.60–1.65 of the real values. Second, we analyse the temporal and spatial variability of the calculated *SY* values. Finally, using a nested catchment approach, we provide insight into sediment transport from upstream to downstream gauging stations and into the role of small- and medium- scale catchments in sediment production and transfers.

The *SL* values at the outlet of the catchments range from $2.5 * 10^2$ to $8.6 * 10^5$ t yr^{-1}, and the *SY* values range from 2.9 to 32.4 t km^{-2} yr^{-1}. A comparison with the limited values available in the literature for this region corroborates our estimations. Sediment exports from the Loire and Brittany river basins are very low compared with mountainous regions and European exports. However, a strong spatial variability within this territory exists. The expected results on the *SY* spatial pattern distribution and the correlation between *SY* values and basin sizes are not observed.

An analysis of the *SY* values at different time steps shows a strong effect of the seasonal availability of detached particles to be transported with a high concentration of suspended sediments during the winter and lower values during the summer and autumn. Annual variations are also observed, with export values varying by a factor 2 to 10 between years for one catchment and the amplitude of the annual variations varying between catchments. The influence of rainfall in the sediment exports is predominant, but investigations on physical characteristics of each catchment (e.g., lithology, slope, land use) are required to better understand the production and transfer processes within a drainage basin. These annual variations imply that long-term data are required to provide mean *SY* values representative of the catchment functioning. From our calculations, 18 complete years of data are required to obtain a mean *SY* value with less than 10% of variation on average around the mean.

From our results on nested catchments over a long-time scale (40 yr), it appears that most of the suspended sediment load entering the water system is transported downstream. Covariations of the annual-*SY* values are generally observed for two gauging stations located on the same river. The nested catchment approach is an interesting tool for the identification of active sediment sources within a large catchment and for the construction of detailed sediment budgets.

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1. Introduction

Suspended sediment load (*SL*) values provide insight into drainage basin sediment production and transfers. The construction of detailed sediment budgets (Walling and Collins, 2008) and basin sediment management policies (Owens, 2005) rely on the mean values of the sediment load calculated at the catchment outlet. In this framework, it is essential to provide accurate average *SL* estimations and to understand the spatial and temporal variability of these values. To this aim, global and European *SL* databases (e.g., Milliman and Meade, 1983; Milliman and Syvitski, 1992; Vanmaercke et al., 2011) have often been developed to aid in the comparison between basin sediment export capacity and to establish orders of priority for basin management.

The results from these investigations indicate that sediment fluxes are controlled by the combination of hydroclimatic and geomorphologic factors (Jansen and Painter, 1974; Ludwig and Probst (1998); Ludwig and Probst, 1998). Particular attention has been given to the scale dependence of suspended sediment exports, and it is common to attempt to establish a relationship between area-specific sediment yields (*SY*, $t\ km^{-2}\ yr^{-1}$) and drainage areas (*A*, km^2). A negative correlation (e.g., De Vente and Poesen, 2005; Meybeck et al., 2003) is expected between both variables due to a decrease in sediment production and an increase in sediment deposition on gentle slopes as the catchment area increases. However, this assumption is disputable because contradictory results have been reported (De Vente and Poesen, 2005; Vanmaercke et al., 2011).

Further investigations on *SL* values have indicated the strong temporal variability of the sediment exports of the catchments that exists at different time scales. Sediment transport from local sources to the basin outlet strongly depends on the magnitude of the climatic events that set particles in motion and on the quantities of the detached particles that are momentarily stored on-land or in-channel and available for transport, i.e., the sediment stock. At the event time scale, hysteresis patterns are used to characterise the provision and sources of this sediment stock and its exhaustion (Williams, 1989). At the season time scale, higher concentrations of suspended sediments are expected in summer due to extreme storm events (Walling and Webb, 1996). However, in primarily agricultural low land areas, higher concentrations of suspended sediments can be observed in winter compared with other seasons (Delmas et al., 2011) and are due to changes in landscape (such as bare soils in winter) and variations in precipitation levels during the year. Finally, at the interannual time scale, discrepancies in the amount of sediment exports are observed between years (e.g., Horowitz, 2003; Dang et al., 2010). Based on a set of indicators, Meybeck et al. (2003) have highlighted the temporal variability of sediment fluxes within a drainage basin and between catchments. In that study, the authors have proposed a typology of the sediment export capacity of the basins that reflects the sediment flux regime.

However, databases elaborated to draw these comparisons encounter two major limitations, primarily due to inhomogeneities of compiled data that concern the following: (i) the differences in the calculation methodologies due to a different space/time scale resolution of the data (Walling and Webb, 1996) and (ii) the spatial and size distribution of the catchments (Vanmaercke et al., 2011).

Two primary calculation methodologies are commonly used to estimate the *SL* values, as follows: i) reservoir sedimentation rates (e.g., De Vente et al., 2005) and ii) in river measures of either the suspended sediment concentration *C* values or of the turbidity from which the *C*-values are calculated, and the fitting of empirical power laws that link *C*-values to flow discharges *Q* (e.g., Webb et al., 1997). The first method provides information on the volumes stored in reservoirs, such as dams. However, the difficulty in estimating these volumes leads to high associated uncertainties (Salas and Shin, 1999). The data from reservoirs are valuable long-term sediment transfer records (from 20 to 100 yr) and offer insight into major changes in sediment exports at a decadal time step. However, a detailed understanding of interannual or seasonal variability in sediment exports cannot rely on those rates. Conversely, the $C(Q)$ power laws provide this detailed information over very few decades. However, the accuracy and resolution of the $C(Q)$ power laws strongly depend on the frequency of the measured $C-Q$ data at the gauging station (Horowitz, 2003). For small catchments, the use of a turbidimeter provides accurate hourly to daily measurements over a few years and allows for the characterisation of sediment exports for each event but does not provide long-term average *SL* values. Conversely, medium or large catchments are less frequently monitored, and daily to monthly measurements of the in-river suspended sediment concentration are the most frequent time steps available for these data. Thus, power laws have received much attention in the past decade, and many authors have proposed different equations to reduce the associated uncertainties, to consider infrequent $C-Q$ data (Phillips et al., 1999; Asselman, 2000; Delmas et al., 2011) and to correct the underestimation generally observed when using classic power laws (Cheviron et al., 2014). Still comparing the loads derived from different equations appears to present a bold challenge.

Until now, *SL* values have been estimated for different sizes of river basins. However, *SL* estimations for small catchments with an area of $A \leqslant 10^2\ km^2$ remain scarce (Vanmaercke et al., 2011). The authors have also indicated the unequal spatial distribution of the available data. Certain areas concentrate the research efforts (Walling and Webb, 1996). For example, the Yellow River in Asia and its tributaries for which the estimated sediment exports can be as high as 53,500 $t\ km^{-2}\ yr^{-1}$ (Walling and Webb, 1996) have been the subject of numerous publications, whereas plain river basins are less documented. Similarly, at a medium catchment scale in Europe, the Mediterranean area has concentrated much of the research efforts along with mountainous catchments (Piégay et al., 2004; Mano et al., 2009; Navratil et al., 2011; Coynel et al., 2004) or coastal rivers (Estèves and Ludwig, 2003). All of these studies display sediment export values at least twice as high compared with those obtained from the limited studies on small lowland catchments (e.g., Sogon et al., 1999; Lefrançois et al., 2007; Oeurng et al., 2010).

Inter-catchment *SY* variability has been investigated at different time and space scales; however, the internal variability of large river basins and the role of small-scale catchments in sediment production and transfers has been less discussed. Recent investigations using nested catchment approaches (Duvert et al., 2011; Armijos et al., 2013) have provided new insight into *SL* variability and into erosion/deposition patterns within drainage basins of Central and Latin America. However, these studies are limited in space and time for the $C-Q$ time series, thus affording a limited overview of the internal fluxes of the entire basin.

Analysis of the available *SL* values across the French territory confirms the lack of data in the lowland areas and for small size catchments. Numerous estimations exist for large rivers, for example, the Rhône river (e.g., Pont et al., 2002), the Seine river (e.g., Roy et al., 1999), the Garonne river (e.g., Schäfer et al., 2002), and the Loire river (e.g., Ludwig and Probst, 1998; Delmas et al., 2012). The latter is the largest of all of the rivers in France and is considered to be "one of the last wild rivers of Europe" but has undergone several alterations due to human activities, such as sediment extraction and dam and dyke construction (Garcin et al., 2006), which may influence sediment transport and volumes. However, studies on sediments in the Loire river have primarily focused on nutrients and dissolved loads in the upper area of the basin (Grosbois et al., 2000) or on sediment dynamics in secondary channels of the river (e.g., Rodrigues et al., 2006). To our knowledge, no study has been performed with the goal of understanding the temporal and spatial variability of sediment transport within the Loire river basin.

In this context, the objectives of the present study are the following: (i) to develop and discuss a homogeneous (in data and calculation methodologies) database of *SY* values over a decadal time scale (from 7 to 40 yr) for small- to large-sized catchments in the Loire and Brittany river basins, (ii) to highlight the temporal and spatial variability of sediment fluxes within this area, and (iii) to understand the role of small and medium size catchments in sediment production, transport, and contribution to the overall Loire river basin budget.

2. Material and methods

2.1. Study site

The French metropolitan territory is divided into six river basin districts, and for each district, a river basin agency is in charge of the water resources. The Loire Brittany river basin (named *LBRB* hereafter) is one of the districts and represents 28% of the territory ($\sim$155,000 km^2).

From a geological viewpoint, the centre of the *LBRB* lies on the sedimentary formations of the Parisian basin and the Aquitaine basin. This area is primarily dominated by floodplains and croplands. The eastern and western parts of the study area lie on old granitic formations. To the east, the Massif Central includes a mountainous area with steep forested slopes (maximum = 134.7%), the highest point of the study site (1849 m), and the Limagne basin. In contrast, the Armorican basin in the western part of the *LBRB* is also a mountainous area (maximum altitude = 385 m) but displays gentler slopes (maximum = 86.9%) and is dominated by croplands.

From an administrative and hydrological viewpoint, the *LBRB* is divided into three primary areas for which sediment exports to the sea have been recently estimated (Delmas et al., 2012). The Loire river basin drains an area of approximately 117,800 km^2 from its source to the Atlantic Ocean, and the sediment delivery to the ocean is approximately 0.86 Mt yr^{-1}. The Brittany region is approximately 30,000 km^2. Suspended sediment exports from the Breton rivers have been estimated at 0.24 Mt yr^{-1}. The remaining area is the Vendée and is composed of small watersheds in the Atlantic coastal area.

The selection of 111 catchments results from a compromise between the available data and the requirement to be representative of the diverse characteristics of the Loire river basin. The selected catchments are distributed throughout the *LBRB* (Fig. 1) in a variety of climatic, geologic, and geomorphologic contexts representing the intrinsic landscape diversity and accounting for approximately 78% of this territory, with a total surface of 122,960 km^2. The *Loire* river and its three principal tributaries (with a river length >300 km), the *Allier* river, the *Cher* river, and the *Vienne* river are the largest drained areas among the *LBRB*. The mean altitude of the catchments vary from 36 m for the *Ognon*, a catchment close to the Loire estuary, to 1127 m for the *Allier* basin's head (Fig. 2). The mean annual rainfall values range from 672 mm for the *Loir* river basin's head, a tributary of the mid-Loire river, to 1233 mm on the *Odet* Breton catchment. The drainage basin areas range from 13 km^2 for the Breton catchment *Lestolet* to 110,250 km^2 for the *Loire* river basin close to its estuary. Overall, the catchments are located in a lowland temperate area and are not subjected to flashfloods. During the study period, no significant land use changes occurred because major changes transpired at the beginning or at the end of this period. Parcel consolidation modified the landscape in the early 1970s, and for a limited number of years, new agricultural practices emerged. These recent changes do not affect the results for the study period.

2.2. Data collection and calculation methods

The 111 selected catchments were mapped using the *Watershed* tool in the Spatial Analyst program (ArcGIS10) and the use of a digital elevation model at a 50 m resolution (BD Alti® IGN). The water flow discharge data (Q) are collected from the national database HYDRO FRANCE and correspond to the daily mean values calculated from continuous stage records. The Loire Brittany River Agency database OSURWEB provides instantaneous suspended sediment concentration values (C) that correspond to once-in-a-month sampling from a water quality sampling program referring

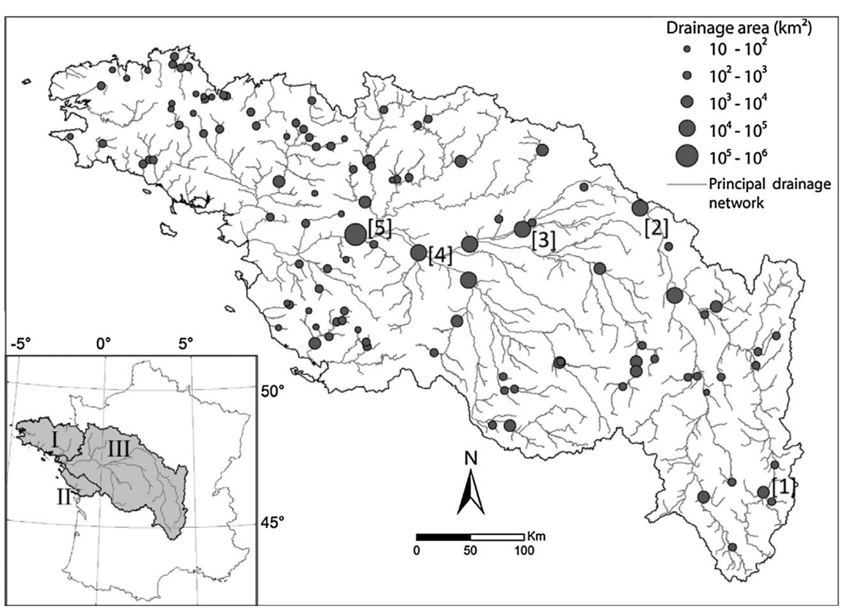

Fig. 1. Localisation of the 111 catchment outlets and their drainage area. Arabic numerals under the square brackets indicate the five stations located on the Loire river from upstream (Armijos et al., 2013) to downstream (Collins et al., 2005). Roman numerals indicate the three administrative regions: I Brittany, II Vendée, and III the Loire river basin.

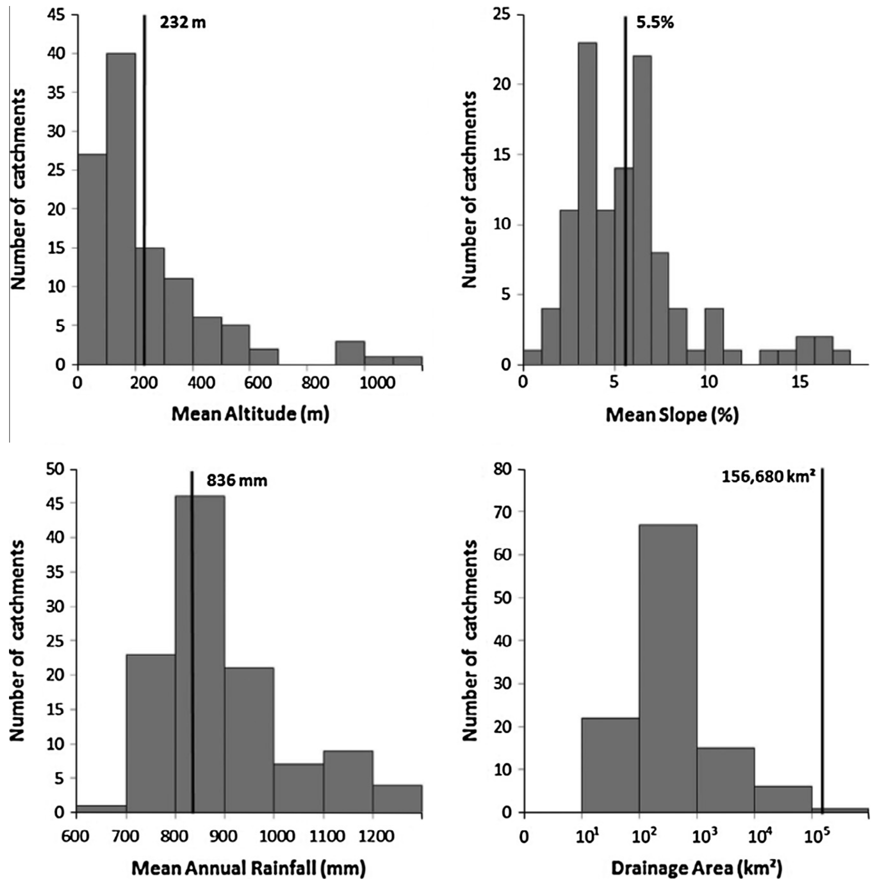

Fig. 2. General characteristics of the 111 selected catchments. The bold lines and numbers represent the values calculated for the entire Loire Brittany river basin.

to the ISO norm 5667-1 (AFNOR norms T90-511, T90-512, T90-513). The samples are collected at the water surface and in the middle of the river (from bridges), and are then filtered using a 0.45 μm filter in the laboratories that are labeled with an ISO norm to ensure the repeatability of the measurements. Then, the Q and C data are associated in space and time according to the methodology presented by Delmas et al. (2012).

For the prediction of suspended sediment loads, we used the relationships based on the classic $C(Q)$ power law linking suspended sediment concentration (C) and water flow discharge (Q) but including a correction term to overcome the underestimation generally observed in classic rating curves (Cheviron et al., 2014). We chose two methods proposed by Delmas et al. (2011). These methods were specifically developed to overcome the lack of data especially on suspended sediment concentration and were tested on high frequency data from the USGS database. We briefly present both methods below. Each relationship was adjusted on existing $C-Q$ couples using the PEST software (Doherty, 2004) and was then extrapolated to the entire flow discharge time series.

The Storage method (Eq. (1)) integrates a storage-dynamic correcting factor $a_5\delta S$, in which a_5 is a parameter obtained through optimisation and δS accounts for the daily variation of the sediment stock.

$$C = aQ^b + a_5\delta S \quad (1)$$

The IRCA (*Improved Rating Curve Approach*) (Eq. (2)) is based on the subdivision of the Q datasets in the following three samples: rising, falling, and base flow discharge data. The average suspended sediment concentrations associated with the base flow Q data are extrapolated to the entire base flow Q population. IRCA manages rising and falling discharge data according to Eq. (2).

$$\begin{cases} \text{For rising discharges}: \ C_R = a_R Q_R^{b_R} + a_{5R}\delta S \\ \text{For falling discharges}: \ C_F = a_F Q_F^{b_F} + a_{5F}\delta S \end{cases} \quad (2)$$

where C_R and C_F correspond to the sediment concentration to be estimated for the rising and falling discharges, Q_R and Q_F, respectively, the instantaneous discharge (the mean daily value from continuous stage records) for the rising and falling discharge, a_R, b_R, a_{5R} and a_F, b_F, a_{5F}, respectively, which are fitted parameters in rising and falling equations obtained through optimisation. The δS value accounts for the daily variations in the sediment stock (as in Eq. (1)).

The statistical representativity of our data was tested for each catchment: the Wilcoxon test was applied to the three sample types at each station to verify that the Q data (in rising, falling, and base flow discharge) for which the C values were available were representative of the corresponding Q population at this station (rising, falling, and base flow discharge populations). If the data were representative, then the IRCA was favoured. If the data were not representative, then the following two samples were considered for the Wilcoxon test: Q data within base-flow conditions and outside base-flow conditions (regardless of the rising and falling discharge). If the Q data were representative of the Q population, then the Storage method was then applied. The IRCA was applied to 83 stations, whereas the Storage method was applied to 28 stations.

The mean SL values are calculated from the entire flow discharge time-series. The mean specific sediment yields (SY) are calculated as the mean sediment load divided by the basin area.

2.3. Uncertainties on sediment load estimations

The recent study by Cheviron et al. (2014) has provided information on the performance of the IRCA when combining the effects of bias on the C and Q data and the infrequent C data. One of the major outcomes of that previous study is that IRCA is capable of managing infrequent C data. Compared with a simple $C = aQ^b$ rating curve, IRCA is more sensitive to the number of available C measurements than to the sampling frequency. For example, with more than 200 $C - Q$ couples at each site, the error on the calculated values with IRCA is in the [−20%,+20%] interval. In the present study, 38 of the 111 catchments presented more than 200 $C - Q$ couples (~16 yr of monthly sampling). For the 73 remaining stations, the minimum number of $C - Q$ couples corresponding to a minimum of ~7 yr of monthly sampling is 84. In this case, the error corresponds to a maximum of 30%.

When estimating suspended sediment fluxes at very fine time scale (e.g. daily or yearly) or space scale(e.g. transect), other uncertainties due to the lateral and vertical gradient in suspended sediment concentration (Horowitz et al., 1990), to the daily flow variations (Moatar et al., 2006) or the scale dependency of uncertainties (Walling and Webb, 1981) have to be taken into account.

In the present study where mean sediment fluxes are estimated over a decadal time scale, we assumed our case to be the worst-case scenario, i.e., with a systematic error for the Q values in the [−5%,+5%] interval, a random error on C within the [−30%,+30%] interval and a C sampling frequency every 30 days on average. In this case, the authors showed that IRCA provides estimations of mean sediment fluxes values in the 0.60–1.65 range.

2.4. Analysis of the temporal and spatial variability of the SY values

First, the data are analysed on a seasonal basis, and we investigate the variability of the C and Q data at this time scale. Then, the data are analysed on a yearly basis (calendar years). For certain catchments, the complete flow discharge time-series data are not available at this time-step. Thus, years for which data are missing were not considered in this analysis. Only the *Isac* catchment presents a lack of complete annual flow discharge time-series and is excluded from the dataset for the temporal variability analysis. For the 110 remaining catchments, we investigate the interannual and the inter- and intra-catchment variability using the annual-*SY* values. We also use one of the metrics proposed by Meybeck et al. (2003) to quantify this variability and to characterise each catchment according to its flux duration, i.e., the percentage of sediment transported within a given period. We calculate the $Ts_{50\%}$ value, which is the time required to transport 50% of the total annual suspended load. Finally, on a hydrological yearly basis, the *SY* data are compared with the specific annual rainfall amount available for the years between 1998 and 2010.

The effect of the annual *SY* variability on the mean *SY* values is investigated. Using the 39 catchments for which more than 30 complete years of data are available, the moving averages of the *SY* values are calculated for each catchment and various time steps from 2 to 42 yr of data and are compared with the mean values obtained for the entire time period. For each time step and catchment, the coefficient of variation of the moving average to the mean value is calculated as the ratio of the standard deviation to the mean.

3. Results and discussion

3.1. SY values at the outlet of the 111 catchments

A large specific sediment yield database is developed in this study using homogeneous data and calculation methods. Table 1 provides the mean *SY* values calculated from the entire flow discharge time-series, drained areas, number of complete years of the Q time-series available, and the river names for the 111 catchments. The data are presented arbitrarily in alphabetical order. For the 13 rivers characterised by at least two gauging stations, the catchments are ranked in increasing order of drained areas and differentiated by a number in the square brackets. The database displays a wide range of *SY* values. The estimated sediment loads range from 2.5×10^2 t yr^{-1} to 8.6×10^5 t yr^{-1}, with a mean value of 3.2×10^4 t yr^{-1} (std = 1.2×10^5). The *SY* values range from 2.9 t km^{-2} yr^{-1} to 32.4 t km^{-2} yr^{-1}, with a mean value of 11.7 t km^{-2} yr^{-1} (std = 5.1).

Fig. 3 provides the size distribution of the mean *SY* values. 95% of the catchments have a *SY* value between 3 and 20 t km^{-2} yr^{-1}. The remaining 5% correspond to 6 catchments distributed as follows: two Breton catchments, the *Isac* and the *Ille*, with *SY* values under 3 t km^{-2} yr^{-1}, and four catchments, the Vendeen basin the *Grand Lay [2]*, and three catchments located in the Loire river basin (the *Moine*, the *Furan* and the *Beuvron*), with values above 20 t km^{-2} yr^{-1}. All of these catchments are small- to medium-sized (A < 600 km^2).

By comparison, the values found in the literature for analogous catchments in the Brittany region are similar to those found in this study. Lefrançois et al. (2007) and Vongvixay et al. (2010) reported sediment exports from 12 to 36 t km^{-2} yr^{-1} for three Breton catchments with A < 5 km^2.

The Loire river values found in the literature range from 4 t km^{-2} yr^{-1} (Jansen and Painter, 1974), i.e., 2 times less than our prediction, to 27 t km^{-2} yr^{-1} (Ludwig and Probst, 1998), which is 3.5 times greater than our findings. For example, Meybeck et al. (2003) found a value of 13.87 t km^{-2} yr^{-1}, whereas Négrel and Grosbois (1999) estimated the *SY* value for the Loire river at the gauging station of Orléans to be 9.5 t km^{-2} yr^{-1} during May 1995 and March 1996. This station is located between the *Loire [2]* and *Loire [3]* stations in this study and agrees quite well with our estimations at those stations (10.40 and 9.30 t km^{-2} yr^{-1}, respectively). To our knowledge, no other estimations of specific sediment yields using data from gauging stations exist for catchments within our study area.

However, compared with other small and medium size French catchments up to 10^3 km^2 (Mano et al., 2009; Oeurng et al., 2010), the catchments presented in this study display lower values of sediment exports. This finding is not surprising given that low *SY* values are generally observed in lowland areas compared with the value calculated for Mediterranean and mountainous regions (Delmas et al., 2009; Vanmaercke et al., 2011). In contrast, the Loire river exports less sediment than do other large French rivers, for which the values range from 16 t km^{-2} yr^{-1} for the Rhine river (Ludwig and Probst, 1998) up to 111 t km^{-2} yr^{-1} for the Rhône river (Delmas et al., 2012). Concerning the contribution from the Loire and Brittany basins to the global sediment exports from earth to sea, the *SY* value of this area is below the mean values calculated for Europe's contribution, which is between 30–35 t km^{-2} yr^{-1} (Collins, 1986 and Holeman, 1968) and 88 t km^{-2} yr^{-1} (Ludwig and Probst, 1998).

Compared with nearby rivers, the contribution of the sediment exports to the sea by the Loire river appears low. Nonetheless, there is still an internal diversity of the *SY* values that can be observed. Fig. 4 displays the spatial distribution of the *SY* values and the shape of the basins. The values are grouped into seven classes. Boundaries were chosen to highlight extreme values of the range of the calculated *SY* values, but no spatial distribution of the values was found. Higher values are generally expected in upstream portions of basins in which the slopes are steeper, thus causing the erosion and transport to be more significant compared with that in lowland areas. However, the *SY* values appear to be homogeneously distributed over the Loire river basin, displaying none of the spatial patterns that are generally observed (e.g., Delmas et al., 2009; Vanmaercke et al., 2011). Two catchments located in the southeastern part of the upstream Loire basin and

Table 1
Drainage area, mean specific sediment yields (*SY*), basin number attributed, and station code (from HYDRO FRANCE) of the 111 selected watersheds. The number of complete years of *Q* time-series available are presented in brackets next to the mean *SY* values. Rivers for which several stations are available are presented in increasing order of drained areas and are differentiated by the numbers under square brackets.

River name	Basin code	Area (km^2)	SY ($t\ km^2\ yr^{-1}$)	Station code	River name	Basin number	Area (km^2)	SY ($t\ km^2\ yr^{-1}$)	Station code	River name	Basin number	Area (km^2)	SY ($t\ km^2\ yr^{-1}$)	Station code
Acolin	1	389	9.68 (17)	K1833010	Flume	38	92	10.12 (21)	J7214010	Nohain	75	476	5.01 (41)	K4094010
Allier [1]	2	519	4.71 (18)	K2090810	Furan	39	175	29.09 (31)	K0614010	Odet	76	203	15.37 (39)	J4211910
Allier [2]	3	2260	5.50 (35)	K2330810	Gorre	40	180	16.42 (19)	L0914020	Nil	77	319	11.88 (13)	K5363210
Allier [3]	4	14347	12.22 (28)	K3650810	Gouessant	41	244	7.18 (28)	J1313010	Ognon	78	146	8.44 (16)	M8205020
Andelot	5	209	13.51 (37)	K3153010	Gouët	42	136	10.41 (29)	J1513010	Oudon [1]	79	133	6.62 (19)	M3711810
Arconce	6	591	14.91 (38)	K1173210	Goyen	43	89	5.19 (41)	J4014010	Oudon [2]	80	1417	11.12(20)	M3861810
Aron	7	1466	19.65 (31)	K1773010	Grand Lay [1]	44	130	25.25 (38)	N3001610	Ouette	81	119	8.72 (22)	M3514010
Aumance	8	927	11.92 (28)	K5383010	Grand Lay [2]	45	405	9.03 (8)	N3031610	Oust [1]	82	28	13.22 (33)	J8002310
Autise	9	244	13.52 (28)	N5101710	Guindy	46	122	14.42 (26)	J2034010	Oust [2]	83	253	12.91 (9)	J8022320
Auzance	10	59	9.24 (3)	N2013010	Horn	47	50	12.82 (40)	J3014310	Petite Boulogne	84	89	13.13 (12)	N1014010
Besbre	11	453	8.24 (12)	K1533020	Huisne	48	1911	11.51 (24)	M0421510	Petite Creuse	85	853	15.85 (40)	L4411710
Beuvron	12	38	32.44 (33)	M6014010	Ille	49	103	2.94 (20)	J7103010	Petite Maine	86	192	11.70 (7)	M7433110
Blavet [1]	13	88	3.95 (11)	J5212120	Illet	50	111	7.12 (19)	J7114010	Queffleuth	87	95	11.81 (21)	J2614020
Blavet [2]	14	566	6.28 (6)	J5402120	Isac	51	548	2.91 (0)	J9202510	Rance	88	143	14.04 (26)	J0611610
Bouble	15	561	18.32 (29)	K3373010	Jaudy	52	165	13.36 (26)	J2023010	Rosette	89	113	6.26 (32)	J1114010
Bourbince [1]	16	339	18.75 (28)	K1363010	Jolan	53	64	15.30 (17)	K3074010	Sarthe	90	906	14.90 (29)	M0050620
Bourbince [2]	17	819	17.67 (42)	K1383010	Laïta	54	852	11.36 (37)	J4902011	Scorff	91	299	13.59 (38)	J5102210
Brame	18	232	13.18 (9)	L5323010	Lay	55	1723	10.29 (2)	N3511610	Semme	92	174	14.03 (9)	L5134010
Brenne	19	261	10.43 (35)	K4873110	Layon	56	919	12.69 (38)	M5222010	Smagne	93	185	11.92 (36)	N3222010
Cher [1]	20	1669	3.48 (8)	K5210910	Leff [1]	57	42	17.11 (12)	J1803010	Tardes	94	859	5.73 (34)	K5183010
Cher [2]	21	1836	5.85 (5)	K5220910	Leff [2]	58	341	9.02 (35)	J1813010	Taude	95	46	10.46 (24)	M0674010
Cher [3]	22	4520	8.26 (32)	K5490910	Lestolet	59	13	19.27 (9)	J5205210	Trieux	96	414	12.55 (19)	J1721720
Cher [4]	23	13678	12.27 (22)	K6720910	Lié	60	299	13.03 (29)	J8133010	Urne	97	44	15.42 (13)	J1405310
Chére	24	60	5.11 (15)	J7803020	Loing	61	122	19.79 (39)	N3024010	Vaige	98	238	12.79 (21)	M0653110
Chevré	25	151	12.70 (21)	J7083110	Loir	62	1157	4.94 (30)	M1041610	Végre	99	400	11.66 (27)	M0583020
Clain	26	2853	6.02 (35)	L2501610	Loire [1]	63	3249	8.98 (40)	K0550010	Vendée	100	156	12.67 (9)	N7101810
Cosson	27	749	4.12 (4)	K4793010	Loire [2]	64	35575	10.40 (12)	K4180020	Vie	101	122	14.67 (11)	N1001510
Couesnon	28	856	16.03 (38)	J0201510	Loire [3]	65	40487	9.30 (11)	K4800010	Vienne [1]	102	3387	14.07 (31)	L0700610
Creuse	29	1233	7.41 (41)	L4220710	Loire [4]	66	80999	9.07 (22)	L8000020	Vienne [2]	103	19817	11.41 (42)	L7000610
Dhuy	30	211	6.14 (16)	K4383110	Loire [5]	67	110241	7.83 (12)	M5300010	Vilaine [1]	104	57	11.17 (22)	J7000610
Dore	31	105	7.27 (21)	K2821910	Mandouve	68	29	12.47 (17)	J1524010	Vilaine [2]	105	147	9.43 (39)	J7010610
Duniéres	32	217	3.16 (24)	K0454010	Marillet	69	50	9.07 (3)	N3304120	Vilaine [3]	106	567	8.21 (22)	J7060620
Ellé	33	575	11.45 (37)	J4742010	Mayenne [1]	70	827	15.76 (15)	M3060910	Vilaine [4]	107	4146	11.86 (28)	J7700610
Elorn	34	201	15.57 (41)	J3413020	Mayenne [2]	71	2901	14.42 (35)	M3340910	Vincou	108	286	11.91 (41)	L5223020
Erdre [1]	35	99	13.17 (40)	M6323010	Merdereau	72	118	16.24 (23)	M0114910	Vonne	109	304	7.51 (38)	L2253010
Erdre [2]	36	465	7.40 (41)	M6333020	Mére	73	59	16.89 (10)	N7114010	Yar	110	58	13.28 (28)	J2314910
Evron	37	139	9.93 (25)	J1324010	Moine	74	366	21.48 (15)	M7213020	Yon	111	41	17.33 (18)	N3403010

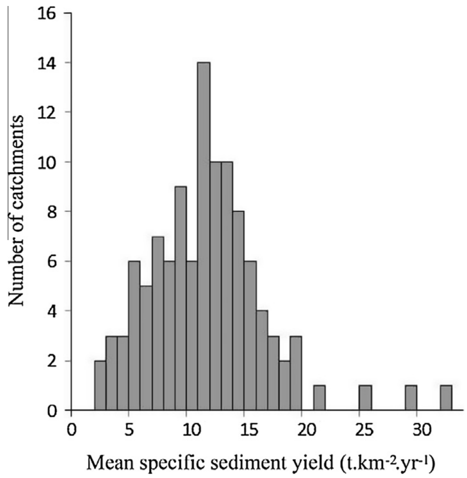

Fig. 3. The size distribution of the mean specific sediment yield calculated for the 111 watersheds.

the direct tributaries to this river illustrate the discrepancies found over the entire river basin. For approximately the same drainage area (~200 km^2), the two catchments located in the Massif Central, the *Furan* and the *Duniéres*, display opposite extreme *SY* values of the range, 29.09 and 3.16 t km^{-2} yr^{-1}, respectively. Conversely, the Vonne, a subcatchment of the Loire river, and the *Loire [5]* at its estuary display similar *SY* values (7.51 and 7.83 t km^{-2} yr^{-1}, respectively), whereas their drainage areas are opposite (300 and 10^5 km^2, respectively).

No correlation appears between drainage areas *A* and *SY* values (Fig. 5) considering the 111 catchments. For a given *A* value, the *SY* values may vary by a factor of 2 to 10. This result is contradictory to the conventional findings that indicate clear relationships of the type $SY = f(A)$ (e.g., De Vente et al., 2005. However, this result confirms the recent findings from Vanmaercke et al. (2011), who found no correlation between the variables when considering diverse catchments together. However, we note that for a group of catchments with $A \geqslant 10^4$ km^2, a negative correlation exists (with R^2=0.86). Those catchments correspond to the three principal Loire tributaries at their confluence with this river (the *Cher [4]*, the *Allier [3]*, and the *Vienne [2]*) and to the four downstream gauging stations on the Loire river (*Loire [2–5]*). The most likely explanation for this finding is that there is a threshold phenomenon and that for catchments larger than 10^4 km^2, the common negative trend observed between basin size and sediment yield due to more deposition in large basin applies.

3.2. Temporal and spatial variability of sediment exports

3.2.1. Seasonal variability of the suspended sediment concentration

Variations in the suspended sediment concentration (*C*) are shown in Fig. 6(a). The winter season displays the highest *C* values (*C* median = 21.5 mg L^{-1}), whereas autumn's median *C* value is the lowest (*C* median = 13.3 mg L^{-1}) but has a mean *C* value similar to that for the summer season (~14.7 mg L^{-1}). Conversely, the median value of the ratios between *C* and the area-specific discharge *Qspecific* (Fig. 6(b)) is higher during the summer (8.9) than it is during all of the other seasons, and the lowest value is found in the winter season (1.5). However, the mean values of the *C*/*Qspecific* ratio reveal that the highest ratio is found in the autumn season (37.6 vs. 32.8 for summer). The Kruskal–Wallis test is applied to the four seasonal subdivisions of the *C* and *C*/*Qspecific* values. The results indicate that all four populations in both cases are significantly different.

The *C* values are more homogeneous in autumn than in summer, whereas the opposite is observed for the ratio *C*/*Qspecific*. These contrasts can be explained by a progressive exhaustion of the sediment stock until the autumn season while precipitations slowly increase between summer and autumn followed by a renewal and a remobilisation of the sediment stock and more significant rain events during the winter. In addition, the evolution of the vegetation cover throughout the year generates a different hydrologic and sedimentary response to the rainfall events. Winter bare soils or winter crops combined with higher precipitation amounts lead to more erosion (Ronfort et al., 2011) and sediment transport than in other periods. Our results on the Loire river basin corroborate those of Delmas et al. (2011) on French rivers. Those authors observed the same trends in the seasonal *C* values and the *C*/*Qspecific* values and include snow melt runoff and evapotranspiration as explaining factors for the temporal variability of those data.

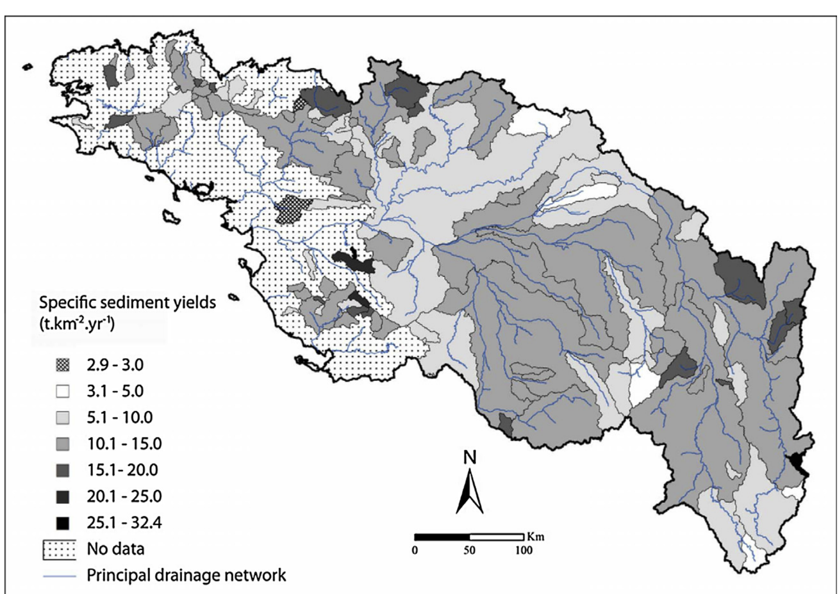

Fig. 4. The mean specific sediment yield estimated for the 111 catchments in the Loire Brittany river basin. Catchments that are nested in other catchments are presented on top.

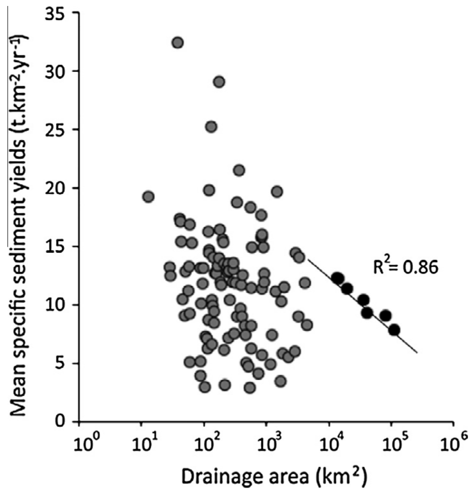

Fig. 5. Relationship between the 111 mean specific sediment yields at a basin outlet and their drainage area. The drainage area axis is presented as log transformed for a better representation of the data. The black dots (and the associated regression line) represent gauging stations at the confluence between the three principal Loire tributaries and this river (the *Allier [3]*, the *Cher [4]* and the *Vienne [2]*) and to four gauging stations on the Loire river (*Loire [2–5]*).

3.2.2. Interannual variability in SY

The annual variability in the *SY* values has been investigated for 42 yr from 1970 to 2011 and for the 110 catchments altogether. The results are presented in Fig. 7. Note that the number of basins for which data are available progressively increase between 1970 and 2010 and reflect the increasing demand for data on water systems due to the evolution of water policy.

Concerning the annual-*SY* values, the maximum median value is observed in 2001 with 24.37 t km^{-2} exported, whereas in 1989, the median value is of 3.48 t km^{-2}. However, considering catchments individually, we note that they do not display the highest or lowest values of their own range for those specific years. For example, 17 of the 61 catchments for which annual-*SY* data are available in 1989 present the lowest *SY* value of their own range in this year. This result indicates that the trend in variations observed for the annual-*SY* values at the *LBRB* scale does not apply to individual catchments. A potential explanation for these findings is that specific variations of the annual-*SY* values are linked to internal variations in the precipitation amounts.

Fig. 8 presents the relationship between the annual specific rainfall amount and the annual specific sediment yield for all of the catchments. A weak but significant correlation ($R^2 = 0.39$, *p*-value $\leqslant$0.0001) is found between both variables. The scattering around the trend line is large.

From these results, three conclusions may be drawn. First, the annual *SY* values are heterogeneous, and the total load exported by the 110 catchments by year varies. Therefore, to investigate sediment fluxes and provide a reliable and stable mean *SY* value, it is very important to consider this annual variability. We estimate (Fig. 9) that 18 yr (with a complete *Q* time-series) are required to obtain a mean *SY* value with less than 10% variation on average and 30 yr for less than 5% variation.

Second, the interannual variability in the *SY* values may be explained by the annual differences in the precipitation amounts, and Fig. 8 presents the positive relationship between both variables. Indeed, rainfall strongly influences flow discharge. In the *LBRB*, strong rainfall events occur as expected during the winter but may also occur during the summer. The combination of changes in land use and land cover throughout the year (Cerdan et al., 2010) and crop rotation over the year with rainfall events may produce an opposite sediment response at the catchment outlet according to the time of the year when soils are bare or inversely protected by crops. Strong interannual variability in erosion rates in connection with annual rainfall variations have also been reported in the literature (Evrard et al., 2010) and confirm the predominant role of rainfall event intensity and of crop type and spatial distribution (Cerdan et al., 2010; Ronfort et al., 2011) in erosion and sediment fluxes. To better consider the annual rainfall variation in sediment load estimations, one possible perspective would be to construct rating curves for wet and dry years independently. While variables such as lithology or topography may explain the differences in mean sediment production and transfers, the observed temporal variability may also reflect the exhaustion of the sediment stock or its remobilisation from in-stream deposits. Sediments momentarily stored within river systems can represent as much as 80% of the total sediment load present in the channel (e.g., Collins et al., 2005, Navratil et al., 2010), and their remobilisation depends on the flow discharge and, thus, on climatic conditions.

Finally, our results indicate a certain trend in the variations of the annual-*SY* values within the *LBRB* with years having low or high sediment production rates. Thus, even if the Loire river basin is heterogeneous in its physical properties and in the annual-*SY* at our resolution scale, it may be perceived as a homogeneous whole compared with other large entities in national or international perspectives.

3.2.3. Inter- and intra-catchment variability

The annual variability in the *SY* values for each catchment is presented in Fig. 10. Certain catchments display low interannual

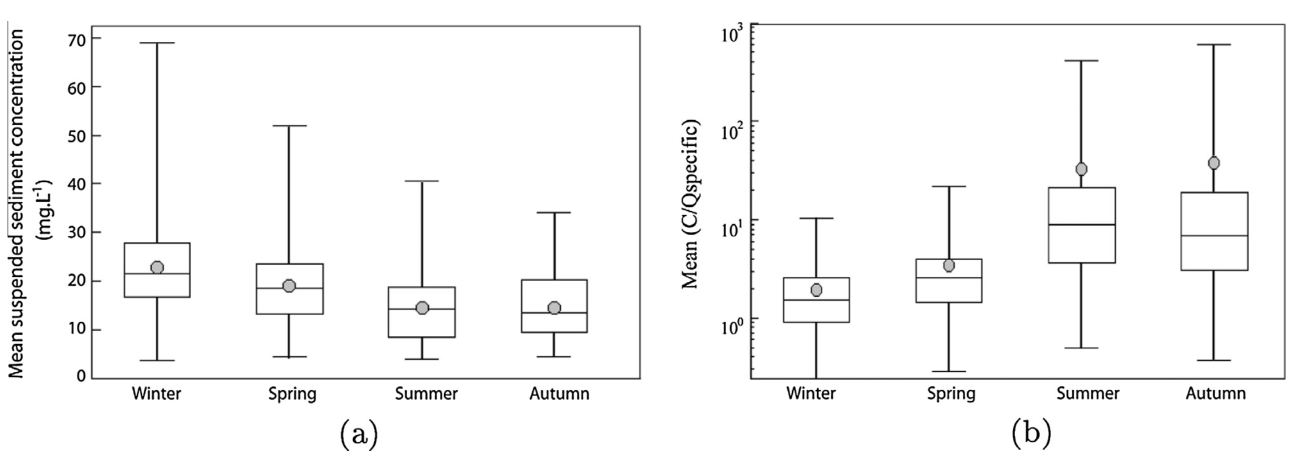

Fig. 6. Boxplots showing the seasonal variability of the suspended sediment concentration. The grey circles represent the mean values.

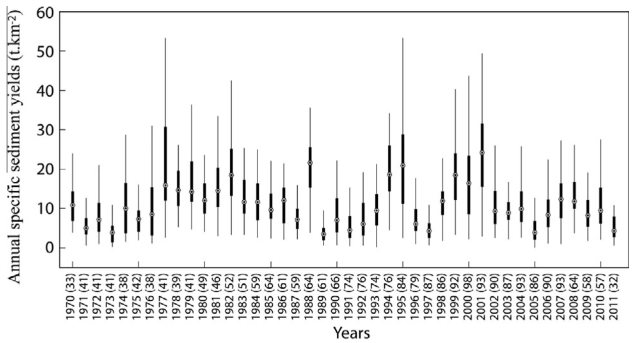

Fig. 7. Boxplots showing variations of calculated specific sediment yields for each year. The number of stations for which data are available for the specified year is in brackets

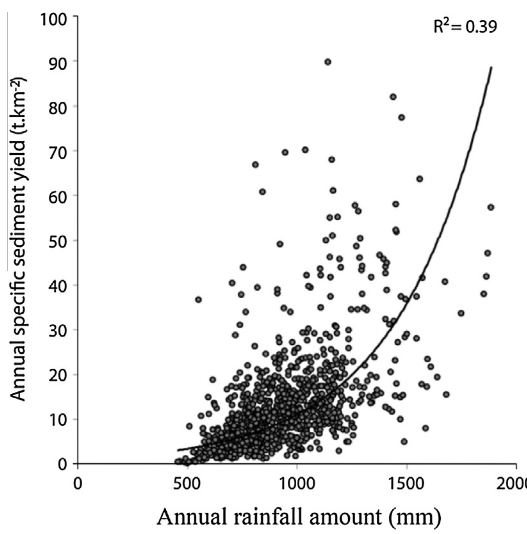

Fig. 8. Specific rainfall amount and the *SY* value calculated for each hydrological year and catchment. The total number of data points is 991 ($R^2 = 0.9$, p-value $\leqslant 0.0001$).

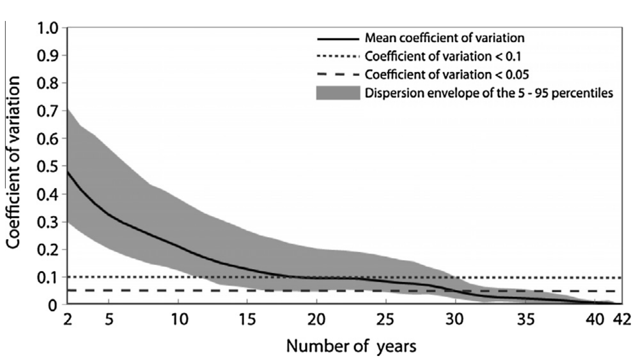

Fig. 9. Variation and dispersion of coefficients of variation between the moving average and the mean *SY* values for an increasing number of years in the moving average calculation. The bold line represents the mean coefficient of variation for all 39 catchments. The dispersion envelope corresponds to the 90%-confidence interval (5th and 95th percentiles).

variability, whereas this variability is very high for other catchments. For example, on the *Moine* river, the *SY* values range from 1.02 t km^{-2} in 1995 to 97.08 t km^{-2} ten years later in 2005, representing a factor of ~100 between both years. This catchment is not an isolated case because other catchments display high ratios between their maximum and minimum values of *SY*. Such differences in amplitude between years have been reported, for example, for the Têt catchment (Serrat et al., 2001), which is located in the French Pyrenees and is characterised by a Mediterranean climate with short violent storm events. Surprisingly, our catchments displaying strong interannual *SY* variability are not located in the mountainous areas of the study site in which strong rain events are observed but are instead located in the lower parts of the Loire basin and in the Vendeen coastal area.

Indicators of flux duration (Meybeck et al., 2003) are used to quantify the variability of sediment fluxes. Here, we compare the percentage of time required to export 50% of the sediment load ($Ts_{50\%}$) annually for each basin (Fig. 11). Similar to the annual *SY* values, the catchments display strong intra- and inter-catchments discrepancies in the $Ts_{50\%}$ values. For example, between 1 and 130 days may be required for one catchment to export half of its solid flux (example taken from the *Andelot* catchment located in the *Allier* river basin).

However, considering the 110 catchments together, the interannual variability in the $Ts_{50\%}$ values is less pronounced than for the *SY* values. Moreover, the pattern of variations observed from Fig. 7, with minimum and maximum median values in 1989 and 2001, respectively, do not apply to the annual values of this indicator. Given that the rainfall amount and especially extreme events exert a certain level of control on the volumes of sediments transported to the outlet, we hypothesised that it also had an influence on the time of transport (the less time required to transport half of the sediment load, the more sediment yield at the outlet). However, no relationship was found between annual values of *SY* and of $Ts_{50\%}$. This result indicates that quantities of sediment transported to the outlet depend not only on rainfall amount or on its intensity but also on the time of year when strong rainfall events occur, as explained in Section 3.2.1, and on the antecedent flow condition and availability of the sediment stock. Moreover, no relationship is found between the basin area and the mean time required to export half of the solid flux ($Ts_{50\%}$), except for the seven catchments with $A \geqslant 10^4$ km^2. For these basins, a weak correlation is found between A and $Ts_{50\%}$ ($R^2 = 0.42$).

Based on the $Ts_{50\%}$ values, Meybeck et al. (2003) proposed a classification of the catchment's solid flux duration in six classes, from a very long to an extremely short duration. According to this classification, a medium duration of solid flux (3.4 to 8% of the time, representing 12 to 29 days per year) concerns 61% of our catchments, whereas 39% are classified as short- or long-term duration fluxes. Only two catchments present very long time flux duration values, and one, the *Beuvron*, is characterised by a very short flux duration value ($Ts_{50\%}$ between 1.4 and 0.4). We found that the Loire river is in the long-term flux duration class (8 to 16.5% of the time), whereas Meybeck et al. (2003) found that this river should be classified in the medium class. This difference can be attributed to the length of the studied period because the previous authors used only one year (1999) to calculate the $Ts_{50\%}$ value, whereas 12 yr were considered in this study. Hence, this result emphasises the requirement for long-term sediment flux records to draw conclusions on the global functioning of the river.

3.3. Contributions from nested catchments

Among the 111 selected catchments, 27 are nested in at least one other catchment and present long-time values of the annual *SY* (a period longer than 18 yr). These catchments are considered in this study to further analyse the dynamics of sediment fluxes and provide insight into sediment transport from upstream to downstream areas. Catchments are grouped by pairs: a nested and a nesting catchment (Fig. 12(b)). Because certain catchments are nested in more than one catchment, in this study, we consider

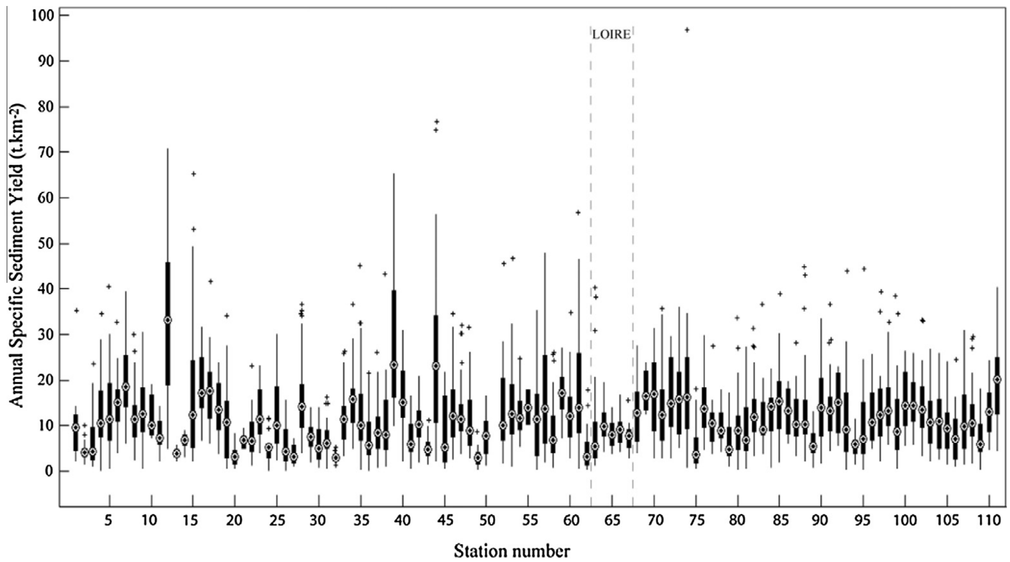

Fig. 10. Boxplots showing the variability of the calculated annual *SY* values for each station. For more details on the station and code number, refer to Table 1.

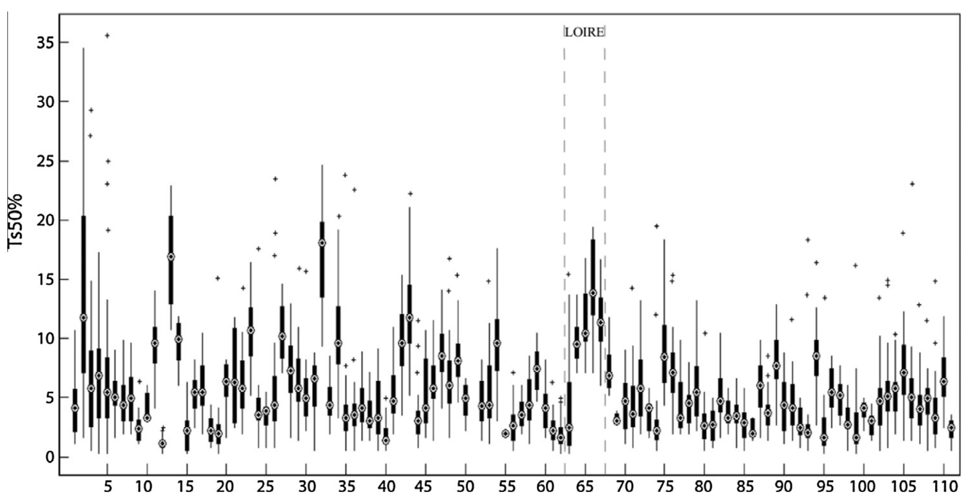

Fig. 11. Boxplots showing the variability of the time required to annually export half of the sediment load ($Ts_{50\%}$) for each station.

a catchment and the smallest one in which it is included. Therefore, in one case, a catchment may be an including one, whereas in another case, it is considered as included in another catchment.

First, for each of the 27 couples of the stations, we calculate the percentages of the drained area and sediment load coming from the upstream station to the downstream station. The results of these investigations are presented in Fig. 12(a), and each dot represents a couple of catchments. A linear correlation exists between the total suspended sediment load at one station and the load coming from the upstream station, according to the percentage of the drainage area contribution ($R^2 = 0.9$). This regression line roughly follows the 1:1 line, which indicates an equal contribution in area and sediment load between both stations.

In a second phase, we consider 6 rivers that are characterised by two or more gauging stations and long-time load records. From these couples, we investigate the annual linearity of sediment transfers from the upstream to the downstream station. The example obtained from the *Erdre* river shows that the interannual variations of the *SY* values at two gauging stations on this river (Fig. 13) display similar trends. Both the annual-*SY* values at the upstream and downstream stations vary in the same manner, except for the year 1985 to 1986, in which a decrease in the *SY* value is observed at the upstream station but the *SY* value increases downstream. However, the proportions in the increase or decrease of the *SY* values between two years and between the two stations are not conserved. An increase in the *SY* values between 1978 and 1979 for the upstream station is approximately 208%, whereas this value is only of 109% at the downstream station. Similar results are observed for the 5 other rivers for which several gauging stations are available.

From these findings, three conclusions may be drawn. First, the fact that a strong correlation exists between the contribution in the sediment load and the area from the upstream to the downstream station and that the trend line follows the 1:1 line (Fig. 12(a)) indicate that there is no in-stream deposition on the way between the stations. This result suggests that there is no scale effect in sediment transport. However, certain couples do not exactly follow the trend line, and for these couples, the nested catchment

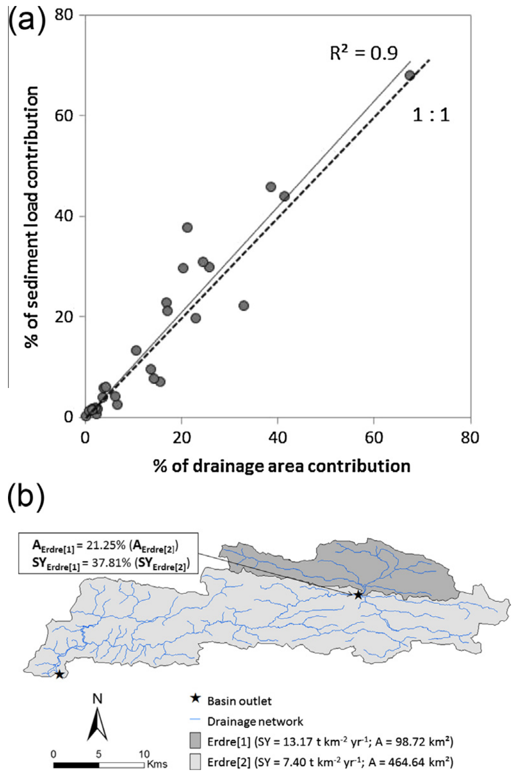

Fig. 12. Contribution of a nested to nesting catchment with (a) percentage of area and sediment load contribution of 27 nested catchments to the first including catchment and (b) example from the *Erdre* river of a couple of catchments.

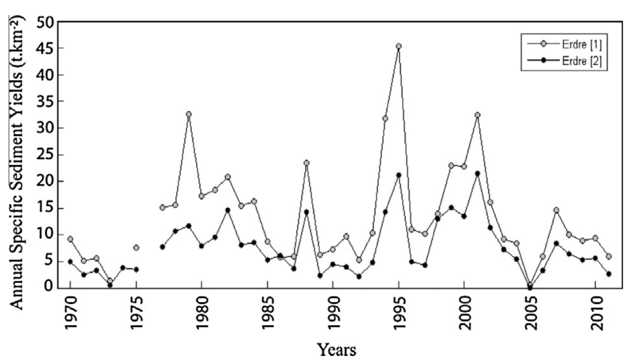

Fig. 13. Annual specific sediment yields calculated for the *Erdre* river at two gauging stations. Between two consecutive points, lines are traced to represent the general trend.

approach allows the identification of active sediment sources and transfers within a drainage area. For dots located above the 1:1 line, high sediment production and transfers are expected to occur in the nested catchment. This configuration enhances the hypotheses that basin heads are very active in sediment production and transfer, whereas most of the sediments are deposited in the plain. Conversely, for dots located under the regression line, more active sources and transfer paths are expected in the downstream part of the catchment compared with the nested one.

Second, it is interesting to note that a linearity in the *SY* values exists between the two stations, although the amplitude of variation between years is not proportional. These variations may be attributed to processes in place along the river network and between both outlets, such as in-stream deposition and remobilisation.

Moreover, in previous sections, we have underlined that no clear relationships could be found between *SY* values and different variables when all of the catchments of the *LBRB* are considered together. However, considering the subunits, such as nested and nesting catchments within this entire territory, a linearity can be found between the processes from one catchment to another. Therefore, investigations into sediment transport should be based on smaller hydrological units rather than the entire *LBRB*.

Finally, the nested catchment approach appears to be a useful tool for the construction of a detailed sediment budget for a catchment. For example, on the Loire river basin, the three main Loire tributaries (*Allier*, *Cher*, *Vienne*) together contribute to 66.1% of the total suspended sediment load at the Loire estuary while accounting for 40.6% of its surface. The small and medium catchments included in the Loire river basin represent 12.7% of the total surface but account for 19.0% of the total suspended sediment load. To complete those sediment budgets, in-stream deposition rates should be estimated to better provide information on the contribution of upstream catchments to the final outlet.

4. Conclusion

So far, very few studies have focused on sediment exports within lowland areas and over a long-time scale. To bridge this gap and complete the existing studies, we use homogeneous suspended sediment concentration data and calculation methods to develop a large specific sediment yield database over a lowland territory: the Loire and Brittany river basins (*France*). We provide 111 values of specific sediment yields for a set of catchments with various landscape and climatic characteristics. Our *SY* values range from 2.91 to 32.44 t km^{-2} yr^{-1}, and these estimations lie within a factor of 0.60–1.65 of the real values. The use of this homogeneous database allowed comparisons to be made among the *SY* values across spatial and temporal scales.

No spatial pattern distribution and no correlation between the *SY* value and the drainage area are observed. These findings suggest that sediment export is a complex process that cannot be evaluated with a single variable, such as the basin size. However, our results clearly indicate that rainfall events exert control in the annual sediment exports. At the interannual time scale and the inter-catchment space scale, strong discrepancies in sediment exports are found, and the annual rainfall amount explains ~40% of the annual specific sediment yields over the entire Loire Brittany river basin. At the seasonal time scale, differences in sediment availability exist because higher suspended sediment concentrations are found during the winter season than in other seasons. Along with the rainfall events, variations of land use and thus of land cover through the year may also take part as controlling factor in annual sediment exports and explain discrepancies in the interannual *SY* variability.

When calculating mean sediment exports, it is crucial to have long-term data to be representative of the catchment functioning. Data over very few years may lead to the under- or overestimation of the mean *SY* value. From our calculation, 18 yr of complete annual data are required to provide a reliable mean *SY* value, which is with a maximum average variation of 10%.

Finally, we provide a conceptual insight into in-stream sediment transport. We use a nested catchment approach to evaluate the sediment contribution coming from upstream catchments to downstream stations. From our calculations, 90% of the total suspended sediment load at a catchment outlet may be explained by the total amount of sediments and drainage area coming from upstream nested catchments. Further investigations into the 6 rivers for which several gauging stations exist show that similar trends in interannual sediment export exist and that a linearity in processes exist from one catchment outlet to the other. This approach is promising for the construction of detailed sediment budgets and for the identification of active sediment sources and transfer zones at the subcatchment scale.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jhydrol.2014.08.045.

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