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Sediment export from French rivers to the sea

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ABSTRACT: Knowledge of sediment exports from continental areas is essential for estimating denudation rates and biogeochemical cycles. However, the estimation of current sediment fluxes to the sea is often limited by the availability and quality of sediment discharge data. This study aims to quantify the relative contributions of French rivers to the sediment discharge to the ocean. Sediment fluxes were assessed using the French river quality database, which is characterized by a low temporal resolution but long-term measurement periods. An improved rating curve approach (IRCA) using daily discharge data, which allows the estimation of mean annual sediment loads from infrequent sediment concentration data, was used to calculate sediment fluxes. The resulting mean annual sediment loads show that French rivers export *c.* 16.21 Mt yr^{-1} of sediments to the sea. Among the 88 defined French rivers flowing to the sea, the four largest basins (Loire, Rhone, Garonne and Seine) export 13.2 Mt yr^{-1}, which corresponds to 81.3% of total exports. No relationship was found between the mass of exported sediment and the size of the drainage basins. This is due to the variety of river basin typologies among these rivers, including lowland rivers in temperate climates, such as the Seine on the one hand and rivers draining mountainous areas in Alpine/Mediterranean areas on the other hand, such as the Rhone. The latter contributes 60% to the total sediment export for France while its drainage area is only 19% of the total area considered. Differences between the river basins considered are also shown by temporal indicators describing the duration of the exports, which may be linked with sediment production processes over drained areas. Copyright © 2012 John Wiley & Sons, Ltd.

KEYWORDS: sediment budget; French river basins; suspended sediment fluxes; sediment exports to sea

Introduction

Knowledge of sediment fluxes is required to estimate denudation rates and to quantify continental inputs to coastal areas (Walling and Webb, 1981; Milliman and Meade, 1983; Milliman and Syvitski, 1992; Ludwig and Probst, 1998), which are major components of biogeochemical cycles. Sediment fluxes to the ocean strongly influence the carbon budget at global or regional scales (Ludwig *et al.*, 1996; Schäfer *et al.*, 2002; Van Oost *et al.*, 2007) and enhance the transportation of nutrients (Meybeck *et al.*, 2006), pesticides (Hooper *et al.*, 2001) and trace metals (Salomons and Förstner, 1984; Audry *et al.*, 2004).

Numerous models have been developed for estimating the denudation rate of continental areas and predicting sediment concentrations in rivers. A first set of models was based on the relationship between sediment yields and drained areas and described generally decreasing specific sediment yields (the ratio of sediment yields on the drained area) for increasing drained areas (Schumm and Hadley, 1961; Milliman and Meade, 1983). However, the generic character of this relationship is questionable (Walling, 1983; Church and Slaymaker, 1989), as catchment area is not the only factor that explains sediment fluxes. Other concepts, such as the spatial variability of environmental basin properties, should be considered. Accordingly, additional explanatory factors based on geological, morphological or climatic features of river basins as well as land-use patterns have been progressively included in these models (Church and Slaymaker, 1989; de Vente and Poesen, 2005; de Vente *et al.*, 2006; Syvitski and Milliman, 2007). For example, the global model elaborated by Ludwig and Probst (1998) calculates sediment fluxes to oceans at the global scale from an empirical equation that combines the main factors influencing sediment redistribution: runoff intensity, basin slope, rock hardness and yearly rainfall variability. Such global models represent interesting comprehensive attempts to link sediment exports with sediment production processes, but these models still need to be calibrated and validated with observed sediment concentration values; therefore, they depend on good quality sediment load datasets.

Meanwhile, estimates of sediment loads from rivers have been compiled from published data for a few large rivers worldwide (Holeman, 1968; Holland, 1981). The most frequently used databases are the World River Sediment Yields Database from the Food and Agriculture Organization (FAO) (FAO, 2008), the GEMS/GLORI database (Meybeck and Ragu, 1995) and the Land-Ocean Interactions in the Coastal Zone (LOICZ) database (Milliman *et al.*, 1995). These compilations integrate numerous and quite dissimilar river basins, covering various regions in the world. However, the heterogeneity of the origins of these data and, thus, their quality is a major limitation. Factors associated with this heterogeneity may include the measurement method used, the period of measurement and the flux calculation method, which impairs the estimation of regional or global sediment budgets. Another factor that complicates our knowledge regarding sediment delivery from a river to its coastal areas is the relatively short duration of the observations conducted: monitoring often covers only periods of a few years, rather than decades (Syvitski *et al.*, 2003), and the available data may not be representative of the actual sediment flux. Moreover, these data often result from studies realized before the 1970s, and thus, they do not integrate the most recent land-use changes that have occurred and may not represent current basin behaviour in terms of sediment exports. In some cases, it may be difficult to trace the origin of the data and the descriptions of both the monitoring period and calculation method. As an example, the sediment load value of the Rhône River given by Meybeck and Ragu (1995) is cited from Milliman and Syvitski (1992), who cite Milliman and Meade (1983), who refer to Jansen *et al.* (1979).

With respect to environmental issues, sediment budgets have to be assessed on decadal time scales to take account of environmental or anthropogenic variability, such as that related to land-use cycles or change, and to smooth seasonal and yearly climatic variability (inducing fluctuations in catchment systems and hydrological regimes). However, data from observations carried out for periods of this length are seldom available, and on such time scales, data typically lack temporal resolution. For example, for rivers in France, as for many European rivers, the temporal resolution of the available sediment concentration data is not better than monthly on average, whereas fluctuations in sediment fluxes are expected to occur much more rapidly, which is a limitation for the use of these data for sediment flux calculations (Morehead *et al.*, 2003; Moatar *et al.*, 2006). However, when the measurement period is sufficiently long, it is possible to calculate long-term average sediment fluxes with an acceptable reliability from monthly measurements (Delmas *et al.*, 2011). This method is called an improved rating curve approach (IRCA). Considering the effects of discharge variations on sediment transfers, IRCA differentiates between increasing and decreasing flows. In addition an available sediment stock indicator is introduced as an additional constraining factor. Consideration of the sediment stock available in a river bed is indeed essential to estimate the potential sediment concentration response to discharge dynamics (Doomen *et al.*, 2008).

The objective of this study is therefore to estimate sediment exports from mainland France to the ocean as accurately as possible using different methods depending on the available data. Next we use the data to investigate which factors control the spatial and temporal variations in sediment yield.

Materials and Methods

The databases

We compiled and mapped the trajectory and the catchment area of the 88 French rivers delivering a significant discharge to the sea. For this part of the work, we used BD Carthage ®, which is a GIS vector layer covering the entire river network in France, in combination with a digital elevation model at 50-m resolution (from BD Alti ® IGN) for the calculation and mapping of drained areas at each considered station. The delineated basins cover *c.* 80% of the metropolitan territory of France.

Water discharge and sediment concentration data were collected from national databases. The national HYDRO database provides daily data (with daily means automatically calculated from continuous stage records) covering long periods and spanning the entire territory of France. Sediment concentration data were kindly provided from the national water quality survey (RNB, Réseau National de Bassin) of French water agencies, which have been monitoring water quality for many rivers since 1970, typically with one measurement conducted per month.

The discharge and concentration datasets were combined where both monitoring stations matched in space and time. Each location with paired stations thus constitutes a river basin outlet, defining a drainage area.

We used three different methods as a function of the availability of data to estimate the sediment load at the 88 outlets. When a station near the outlet of a river basin was available in the French river quality database, we estimated and calculated the sediment exports using IRCA. This method could be applied for 15 rivers, covering 65% of the surface area of metropolitan France. For 16% of drained areas, corresponding to small coastal rivers, no water quality station was available near the mouths of the rivers: for these rivers an alternative method was developed. For the Rhône River (19% of the total drained area), more accurate monitoring results were available from the Rhône River Observatory Station in Arles (Eyrolle *et al.*, 2010) with better than daily sediment concentrations and discharges. From these data, a daily dataset could be constructed from 2001 to the present time.

Mean annual sediment loads: calculation/ estimation methods

Generally, computation of the mean annual suspended sediment flux (MASSF) requires estimates of daily sediment concentration and water discharge data:

$$MASSF = \left(\frac{1}{N} \sum_{n=1}^{N} C_n Q_n \right) \times 365.25 \quad (1)$$

where C_n and Q_n are the daily sediment concentrations and the water discharges, respectively.

For the Rhône river Equation (1) could be directly applied. For the rivers for which data from a water quality station were available, we applied the IRCA method presented in Delmas *et al.* (2011) to estimate daily concentration data. The IRCA method was developed to estimate MASSF from infrequent datasets. It differentiates between rising and falling discharges and also considers daily discharge sequences rather than constructing one-to-one relationships between daily discharge data and concentration estimates. Thus, the effect of discharge variations is introduced in the model. Moreover, the IRCA method uses a sediment stock indicator (S), which is estimated as a function of the discharge variation, as described in Figure 1. The stock indicator function S(t) is calculated from Q(t) using a station-independent procedure. Strong reductions of S are assumed to occur during rising flows, while smoothed and delayed increases of S occur as the flow decreases. The rating curves used in IRCA have the following form:

$$\text{For rising discharges } C_R = a_R Q_R^{b^R} + a_R \delta S \quad (2)$$

$$\text{For falling discharges } C_F = a_F Q_F^{b^F} + a_F \delta S \quad (3)$$

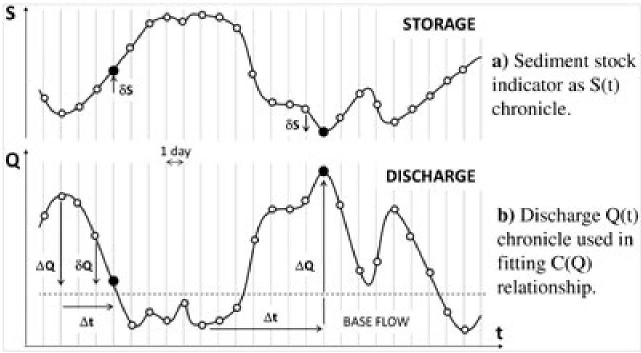

Figure 1. Representation of the variables used for the IRCA fittings with the aim of exploiting the temporal dynamics of river flows (b) and related dynamics of sediment stocks (a). White spots correspond to daily *Q* measurements. Black spots indicate infrequent *Q* values for which a concentration record is available.

where a_R, b_R, a_{5R} and a_F, b_F, a_{5F} are coefficients, the value of which was obtained through optimization (see below);

C_R is the sediment concentration (to be estimated) during rising discharges, C_F the sediment concentration to estimate during falling discharges;

Q_R is the instantaneous discharge (mean daily value from continuous stage records) during rising discharge events, and Q_F the instantaneous discharge during falling discharges; and δS is the daily variation of the sediment stock.

Because Q corresponds to mean daily discharges and C to the instantaneous sediment concentration, this calculation supposes that the instantaneous concentration is representative of the daily concentration. As we consider mainly large river basins, we can assume that daily variations are relatively unimportant (Morehead *et al*., 2003; Moatar *et al*., 2006). The coefficients in Equations (2) and (3) were optimized using PEST (Doherty, 2004), so that no log-transformation of the data and thus no correction to avoid bias induced by such transformation was needed (Ferguson, 1986, 1987). Cheviron *et al.* (under review) calculated the uncertainty on the MASSF as estimated from IRCA. Evidently, this uncertainty depends on the number of data points available. Here, the data collected from monthly sampling cover at least 10 years (and generally more than 25 years), and thus the number of pairs always exceeded 120 couples of data for the selected stations. Cheviron *et al.* (under review) calculated that the uncertainty on MASSF due to this sampling frequency is expected to be 10%. A longer measurement period leads to only a small further reduction in uncertainty: when more than 300 data points are available, uncertainty is predicted to be less than 10%.

For those rivers where no data were available at the outlet, we attributed the mean specific sediment load obtained for river basins located nearby, with a similar drainage basin area for which sufficient data were available to apply IRCA. MASSF was then estimated by multiplying the mean specific sediment load by the basin area.

Estimation of the accuracy, bias and imprecision of the IRCA method

Although the work by Cheviron *et al.* (under review) provides a basis for estimation of the accuracy of IRCA, we performed an additional test using data from river basins in the USA. The USGS dataset consisted of 16 stations with daily SS concentration and flow data. For each station, 100 virtual datasets were constructed with a sampling frequency similar to that of the French dataset. Then, the IRCA method was applied to each of the virtual sampling programs, and 100 MASSF estimates (F_i) could be computed for each river basin. As daily data are available for these stations, the actual MASSF was directly calculated for each station (and noted here as F_{ref}). A mean absolute error on F_i was computed for each river basin relative to the reference sediment load (F_{ref}) as follows:

$$Er_i = 100\left(\frac{|F_i - F_{ref}|}{F_{ref}}\right) \text{ and } Er = \frac{1}{n}\sum_{i=1}^{n} Er_i \qquad (4)$$

where n is equal to 100 in this analysis (100 estimates for each station).

The root mean square error was calculated as:

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(F_i - F_{ref})^2} \qquad (5)$$

Moreover, as suggested by Moatar *et al.* (2006), the bias was also calculated:

$$e_i = 100\left(\frac{F_i - F_{ref}}{F_{ref}}\right) \qquad (6)$$

We calculated the median bias, e_{50} (median of e_i) for the 100 replicates at each station. The imprecision is defined as the difference between the 90th and 10th percentiles of the relative errors :

$$\Delta e = e_i^{90} - e_i^{10}. \qquad (7)$$

Temporal variability

The temporal variability is calculated using the $Ts_{50\%}$ indicator as presented in Meybeck *et al.* (2003), which corresponds to the percentage of time necessary to carry 50% of the suspended sediment flux. We also calculate the $Ts_{80\%}$, which is defined as the percentage of time necessary to transport 80% of the suspended sediment flux. These calculations were performed using the available daily data for each year and for the whole measurement period. The same calculations were made for water discharges.

Results and Discussion

IRCA evaluation

The results shown in Figure 2 indicate good correlation between the median of the calculated loads and the actual loads, with a coefficient of determination of 0.97. The slope of the regression line is very close to 1 and the intercept very close to 0, indicating that there is no systematic bias. This is confirmed by the low average bias (2.2%).

The highest median negative bias, approximately −13%, was observed for the Dan River at Paces (VA) whereas the maximum bias of 19% was observed for the Kaskaskia River near Venedy Station (IL) (Table I). The RMSE varied from 2.13 t km^{-2} yr^{-1} for the Illinois River at Valley City (IL) to 43.4 t km^{-2} yr^{-1} for Stillwater River at Pleasant Hill (OH), with a mean of approximately 11 t km^{-2} yr^{-1}. The highest RMSE was actually observed for a small river basin (Stillwater river at Pleasant Hill with a drainage area of 1300 km^2) while the lowest RMSE values were observed for the largest basins. The resulting mean relative error between the sediment flux estimated from IRCA and the reference flux (Fref) was approximately 12%, with the lowest

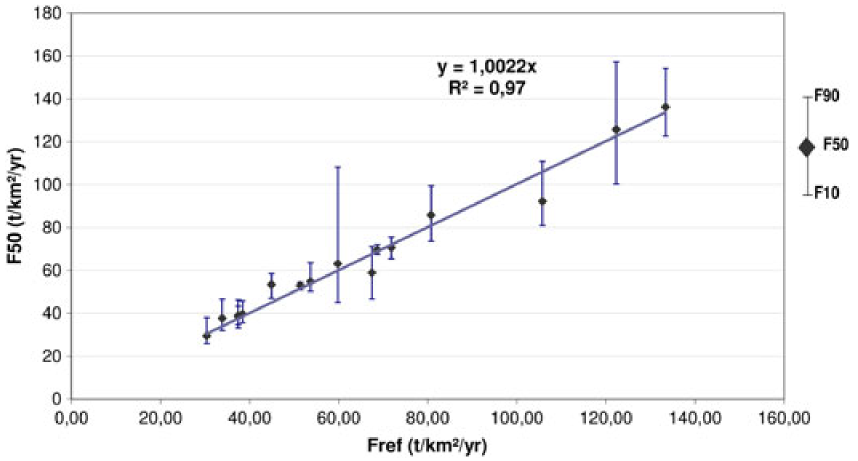

Figure 2. Relationship between the sediment flux median (F50) calculated with IRCA for 100 different replicates (showing the same temporal sampling resolution as that of the French River Quality Database) and the actual sediment flux calculated with daily data for 16 watersheds of the USGS database. The upper bar corresponds to the deviation between F50 and F90, and the lower bar corresponds to the deviation between F50 and F10 for each station considered.

Table I. Measured sediment load (mean SSYm), estimated sediment load (mean SSYe), standard deviation (SD), relative error (Er%), median bias (e50) and RMSE, for each considered station from the USGS

Station	Area (10^3 km²)	Period	mean SSYm (t km^{-2} yr^{-1})	mean SSYe (t km^{-2} yr^{-1})	SD	Er%	e_{50}	RMSE (t km^{-2} yr^{-1})
Kaskakia River at Cooks Mills, IL	1.22	1979–1997	30,37	30,81	5,47	11.88	−2.99	5.49
Des Moines River near Saylorville, IA	15.13	1961–2004	33,82	38,47	5,69	16.44	11.44	7.35
Muskingum River at Dresden, OH	15.52	1952–1974	37,42	38,74	3,50	7.95	3.04	3.74
Iowa River at Iowa City, IA	8.47	1959–1987	37,43	39,41	5,36	12.66	4.06	5.72
Sacramento River at Sacramento, CA	60.88	1957–1979	38,41	40,03	3,96	8.87	3.44	4.28
Kaskaskia River near Venedy Station, IL	11.38	1980–1997	44,91	53,26	4,44	18.69	19.12	9.45
Mississippi River at St. Louis, MO	1 805.22	1980–2008	51,35	52,94	1,77	3.57	3.21	2.38
Muskingum River at McConnelsville, OH	19.22	1978–1991	53,66	56,27	6,94	8.77	2.33	7.41
Stillwater River at Pleasant Hill OH	1.30	1963–1975	59,81	73,60	41,13	38.21	5.62	43.38
Roanoke River at Randolph, VA	7.68	1968–1981	67,47	58,93	10,11	16.43	−12.50	13.24
Illinois River at Valley City, IL	69.26	1980–2008	68,68	69,76	1,84	2.47	1.40	2.13
Maumee River at Waterville, OH	16.39	1950–2003	71,82	70,45	3,79	4.42	−1.54	4.03
Scioto River at Higby, OH	13.29	1953–1982	80,76	86,22	10,63	11.18	6.25	11.95
Dan River at Paces, VA	6.70	1954–1981	105,74	94,52	12,91	14.14	−12.77	17.11
Little Miami River at Milford OH	3.12	1978–1989	122,35	126,05	24,51	16.29	2.80	24.78
Yadkin River at Yadkin College, NC	5.90	1951–1989	133,41	138,23	14,23	7.92	2.10	15.02
Average values (for the 16 stations)	64,84	66,73	9,77	12.49	2.19	11.09		

value being 2.5% and the highest being 38%. These results indicate good accuracy and consistency of the method regarding the temporal resolution considered (Moatar *et al.*, 2006). The results also agree with the uncertainty predictions derived by Cheviron *et al.* (under review).

It is not straightforward to evaluate the uncertainty affecting the sediment fluxes that were estimated by extrapolation for non-gauged basins. For these basins, the determination of sediment fluxes in the so-called 'analogous' or 'extrapolation' method (where the average specific sediment yield of neighbouring basins of similar size is used to calculate the sediment budget), it is not possible to calculate and provide a value for the imprecision or accuracy of the method.

The uncertainty of the estimates for these ungauged basins may be higher than that for the gauged basins. An idea of the magnitude of this uncertainty can be obtained by calculating the mean MASSF as well as the standard deviation for those basins for which data are available, which are situated in geomorphologically and climatologically similar areas. Generally, the standard deviations obtained were of the same order of magnitude as the mean MASSF value for the region. Moreover, one should keep in mind that we used the extrapolation method only for relatively small basins. Even if we consider an (unlikely) error of 100% overestimation, or 100% underestimation for all these catchments, the calculated increase or decrease of the total sediment flux for France would only be 1.2 Mt yr^{-1} (only 6% of the total exports).

Resulting suspended sediment exports to the sea

The total drainage area of the 88 French rivers flowing to the sea (i.e. having their outlet to coastal areas located in France) covers 443 833 km², which represents 80% of the French continental area. More than 75% of this area is drained by the four largest French rivers: the Loire, Rhône, Garonne and Seine.

The resulting MASSF values are presented in Table II and Figure 3. From these calculations, the total export of sediments to French coastal areas was estimated to be approximately 16.2 Mt yr^{-1}, exported from a contributing area of 438.5×10^3 km².

For sediment discharges estimated using IRCA method, Cheviron *et al.* (under review) estimate the uncertainty generated by the sampling frequency to be on the order of 10%. Moreover, if we suppose errors in C and Q measurements of 20%, it induces an uncertainty of 20% on the estimation (Cheviron *et al.*, under review). Given the rather stable and linear behaviour of the method

Table II. Drained areas associated with French rivers flowing to the sea and their estimated mean annual sediment loads; the last column indicates the estimation method used (giving a quality index for the resulting sediment load)

Zone	River basin names	Areas (10^3 km²)	MASSF (Mt yr^{-1} and %)	Estimation method
Loire	Loire	110.2 25.1%	0.86 5.3%	IRCA
Rhône	Rhône	83.6 19.1%	9,63 59.5%	Direct calculation
Garonne	Garonne, Dordogne, Isle, Dronne, Dropt	71.3 16.3%	1,86 11.5%	IRCA
Seine	Seine	64.8 14.8%	0.79 4.9%	IRCA
Adour and Gaves	Adour, Gave d'Oloron, Gave de Pau	13.1 3%	0.48 3%	IRCA
Vilaine	Vilaine	10.2 2.3%	0.07 0.4%	IRCA
Meuse	Meuse	7.1 1.6%	0.15 0.9%	IRCA
Brittany	Moros, Bélon, Aven, Étel, Laïta, Élorn, Rivière d'Auray, Odet, Aulne, Blavet, Aber-Wrac'h, Aber-Benoît, Gouët, Jaudy, Arguenon, Trieux, Gouessant, Léguer, Rance, Aber-Ildut, Couesnon, Penfeld, Scorff	11.9 2.7%	0.17 1.0%	SSL-extrap
North	Wimereux, Slack, Scie, Liane, Bresle, Authie[a], Arques, Canche, Somme[b], Dun, Saâne, Yères, Durdent, Maye	12.1 2.8%	0.12 0.7%	SSL-extrap IRCA (a) SSL-extrap* (b)
Aquitaine	Boudigau, Eyre, Auzance, Falleron, Vie, Seudre, Lay[1], Sèvre niortaise, Charente[b]	19.6 4.5%	0.35 2.2%	SSL-extrap IRCA (1) SSL-extrap* (b)
Southeast	Paillon, Loup, Huveaune, Gapeau, Siagne, Argens[a], Var[a], Roya, Cagne, Touloubre, Arc	8.8 2%	0.98 6%	SSL-extrap SSL-extrap* (a)
Cevennes	Libron, Lez, Vidourle, Hérault[a], Orb	5.5 1.3%	0.19 1.2%	SSF-extrap IRCA* (a)
Pyrenees (to Mediterranean Sea)	Tech, Agly, Têt, Aude	8.5 1.9%	0.38 2.3%	SSL-extrap
Normandy	Thar, Divette, Saire, Ay, See, Douve, Sélune, Sienne, Valmont, Seulles, Vire, Touques, Dives, Orne, Veules	11.6 2.6%	0.14 0.9%	SSL-extrap
Total		438.4 100%	16.2 100%	

IRCA corresponds to data obtained from the IRCA method applied to datasets with a sufficient number of measurements; IRCA* generally refers to small river basins or Mediterranean basins where rapid flood event are of major importance in sediment exports, and the structure of the data may not be adapted for this type of calculation; SSL-extrap refers to sediment loads estimated for small river basins by extrapolating the corresponding specific sediment load value; SSL-extrap* refers to larger river basins for which we adapted the previous estimation method.

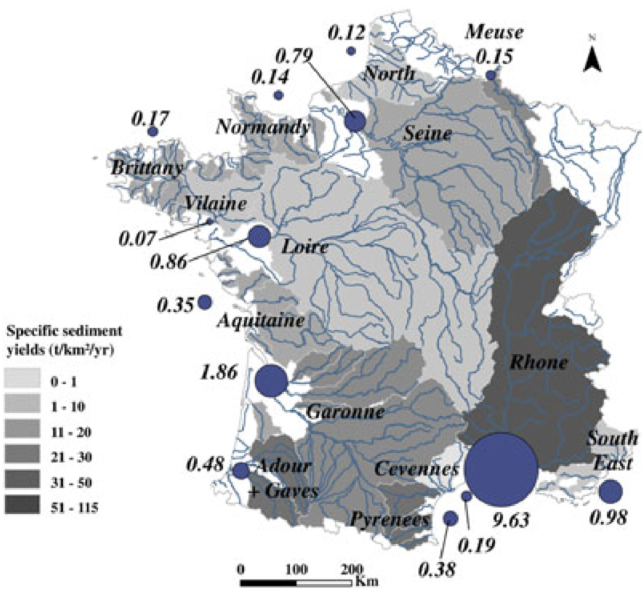

Figure 3. Estimated suspended sediment loads from French rivers flowing to the sea (Mt yr^{-1}): the diameter of circles is proportional to the suspended sediment loads expressed in Mt yr^{-1}. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

regarding errors sources, uncertainties resulting from sampling frequencies and measurement errors on C and Q combine themselves: to assess this uncertainty we first take into account 20% of uncertainty due to C and Q uncertainties and then 10% due to the sampling frequency. For the analogous method, we suppose 100% uncertainty. As a consequence, given these extreme hypotheses, the total sediment exports from French rivers to sea cannot be considered below 12 or higher than 20 Mt yr^{-1}.

The four largest French rivers export 13.2 Mt yr^{-1} of sediments, i.e. 81.3% of the total amount. However, there is no direct relationship between sediment export and drainage area. In particular, the Rhône River exports nine times more than the Loire River, although the Loire drains a larger area. The Rhone delivers 9.6 Mt yr^{-1} to the Mediterranean Sea, corresponding to almost 60% of the total export from continental France to the sea, while it drains less than 20% of the total area considered. Additionally, the Seine, which covers *c.* 15% of the French areas considered, only exports *c.* 5% of the suspended sediments out of the total area. These variations between river basins with respect to specific sediment exports and, thus, denudation rates, highlight the spatial variability involved in sediment redistribution processes. The Rhône drains a large part of the Alpine mountains with strong topographic gradients (Ollivier *et al.*, 2010), where erosion rates are high.

In contrast, the Seine is a characteristic lowland river, without considerable mountainous upstream areas, and thus, it carries a low suspended sediment load (Billen *et al.*, 2007).

Considering the four major rivers in France, the quantity of sediments routed to the seas is therefore not particularly determined by the size of the drained areas but by their environmental and geomorphologic properties. To provide an overview of this situation, Figure 4 shows the amount of sediment exports being transported towards the sea for comparison with the contributing source areas, which highlights strong discrepancies in basin behaviours. Almost 70% of the sediments are exported to the Mediterranean Sea, associated with a source area of only 24% of the total drained area. The rivers that flow into the Atlantic Ocean discharge only 23% of the sediments, while they drain more than 50% of the source. These contrasting findings are explained by striking differences in the climates and the geomorphologic properties of the studied basins. Mediterranean areas are characterized by degraded soils under an erosive climate, with low vegetation density and relatively steep topography, inducing higher connectivity which, in turn, favours considerable sediment production and export (Delmas *et al.*, 2009). Conversely, the Seine and Meuse are lowland rivers meandering through low slopes, thus inducing less sediment production and more deposition within the drained areas.

Some quantitative measures illustrate the diversity of the basins leading to this wide range in sediment yields; the Rhône delivers $501 \times 10^3\,m^3\,km^{-2}\,yr^{-1}$ of water to the sea, while $225 \times 10^3\,m^3\,km^{-2}\,yr^{-1}$ are exported by the Loire. The Garonne has a mean specific discharge of $372 \times 10^3\,m^3\,km^{-2}\,yr^{-1}$, and that of the Seine is $256 \times 10^3\,m^3\,km^{-2}\,yr^{-1}$. Figure 5(a) shows that no relation exists between the specific sediment yield and the drainage area for the major French rivers. Figure 5(b) shows that there is a good relationship between MASSF and the mean altitude of each river basin. This may be explained by the related behaviour of erosion and sediment exports over slopes from upstream areas to the outlet because the highest basins generally present the highest drainage densities and highest connectivities from eroded areas to the outlet of the catchments.

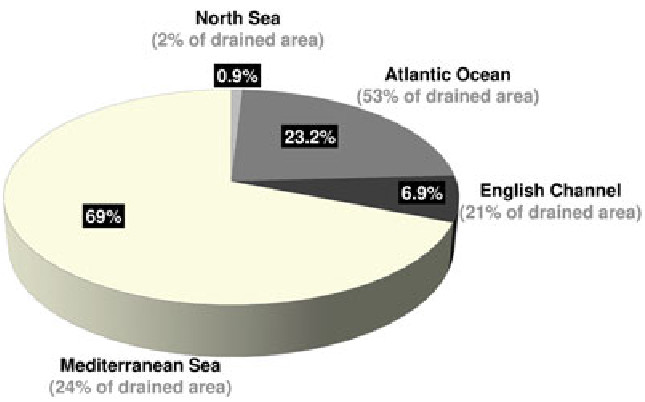

Figure 4. Proportion of sediment exports in each sea and their corresponding contributing area.

Table III presents indices of temporal variability of discharge and sediment flux for the major rivers. The temporal variability in water discharge is not significantly different between basins, as 50% of the water is often delivered within 20% of the time (between 14% and 30%), and 40 to 60% of the time is necessary to carry 80% of the water flow. Interestingly, the river that appears to exhibit the most regular flow over time is the Rhône. This is the unexpected consequence of the coexistence of various hydrologic regimes taking part in the global basin behaviour, where oceanic, continental and Mediterranean rainfall regimes are encountered. Storm events in the lower part of the basin, the southern Alps or the Cevennes zone induce large variations of discharge from various spatial origins, while snow and glacier melting cause high flows in winter (Ollivier *et al.*, 2010). Moreover, high $Tw_{50\%}$ values may be associated with man-made flow regulation (Meybeck *et al.*, 2003).

There is more variation between rivers for sediment discharge in comparison with water discharge: sediment transfers are more concentrated in time. Thus, 50% of the sediments are transferred in only 2% of the time for the Rhône and the

Table III. Temporal variability indices for water discharge and suspended sediment load for the major French rivers flowing to the sea

		Water discharge		Sediment load	
		$Tw_{50\%}$ (*)	$Tw_{80\%}$ (*)	$Ts_{50\%}$ (*)	$Ts_{80\%}$ (*)
Meuse		18.1	45.3	8.3	26
Seine		22.5	53.7	9.9	27.7
Loire		21	48.9	9.5	30.6
Garonne and tributaries	Garonne	19.9	48.9	1.8	8.2
	Dordogne	21.5	50	7.6	27.9
	Dronne	13.7	38.6	4.4	20.8
	Isle	18.1	49.7	2	12.9
Adour and Gaves	Gaves	22.9	53.8	3.4	16.2
	Adour	17.2	47.3	9.1	20.5
Rhône		30.1	61.7	1.7	11

(*) $Tw_{50\%}$: percentage of time necessary to carry 50% of the water volume
$Tw_{80\%}$: percentage of time necessary to carry 80% of the water volume
$Ts_{50\%}$: percentage of time necessary to carry 50% of the sediment load
$Ts_{80\%}$: percentage of time necessary to carry 80% of the sediment load

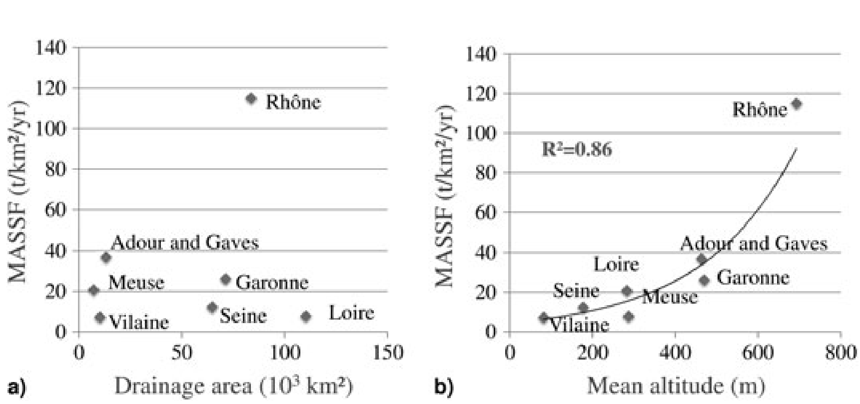

Figure 5. Relationship between the MASSF and (a) the drainage areas and (b) the mean altitude.

Garonne, whereas 10% of the time is necessary to transport 50% of sediments for the Loire. These results show that sediment exports depend not only on the water flows but also on specific environmental parameters: evidently, the Mediterranean climate with severe but short storms in summer will lead to more significant peaks in sediment flux compared with the temperate oceanic climate in the Loire basin where rainfall events have generally a lower intensity and a longer duration.

The indices of temporal variability presented in Table III were calculated over the entire period of measurement relative to each river, but additional yearly calculations exhibit high inter-annual variabilities. For example, in the Rhône River, 80% of the sediment load was exported in *c.* 9% of the time in 2008 and 2009, but it took 27% of the time in 2007. For the Garonne River, 80% of the sediment load was exported during 4% of the time (13 days) in 2003 and during 36% of the time (133 days) in 2005. These inter-annual discrepancies reinforce the argument that long-term observations are required to obtain reliable estimates of long-term average sediment fluxes. However, due to the limited number of sediment monitoring programs in place, the sediment load values used in regional or global budgets often result from two- or three-year periods of measurement, which do not capture the high temporal variability of sediment exports, especially their inter-annual variability. For example, many studies (Milliman and Syvitski, 1992; Ludwig and Probst, 1998; Meybeck and Ragu, 1995) have reported a specific sediment yield value of 340 t km^{-2} yr^{-1} for the Rhone River (this value refers to measurements cited since 1979). The specific sediment load obtained in the present study for the Rhône River was 115 t km^{-2} yr^{-1}, i.e. three times lower. Ollivier *et al.* (2010) have compiled various sediment load values for the Rhône, and the value obtained from Walling and Webb is on the same order of magnitude as that of Pardé (1942), who calculated the Rhone exports from its tributaries. This estimated sediment load is therefore a major overestimation because we cannot consider that all of the sediments from the tributaries reach the outlet of the basin. Additionally, since 1942, the Rhône River has been highly regulated by dam construction, which clearly plays a major role in the retention of sediments. Moreover, the land use in this area has changed during the last century due to reforestation policies in the Rhône basin (Piégay and Salvador, 1997; Liébault and Piégay, 2002). These policies may thus affect sediment redistribution processes through changes in the landscape, reducing the quantities of sediment exported in the river channel. In the compilation proposed by Ollivier *et al.* (2010), we can see that the nearest mean annual sediment load to our calculated one is that of Sempéré *et al.* (2000), which is based on a 10-year measurement period and shows an average of $9.9 \pm 6.4 \times 10^6$ t yr^{-1} (here, we estimated 10.35×10^6 t yr^{-1} of sediment exports from the Rhône).

Based on published sediment yield data and sediment fluxes estimated by Walling and Webb (1983); Owens and Batalla (2003) proposed a method for calculating the total sediment exports in Europe. They attributed mean specific sediment yields to the large biogeoclimatic zones defined by Walling and Webb (1983): 40 t km^{-2} yr^{-1} for the humid environments of northern Europe, 150 t km^{-2} yr^{-1} for Mediterranean humid environments in mid-southern Europe and 500 t km^{-2} yr^{-1} for semiarid regions in southern Europe. These estimates are much higher than the results of the present study. For the Rhone River basin, which is included in the Mediterranean humid environment, they considered a sediment yield value that exceeds our estimates by 35 t km^{-2} yr^{-1} (30%), corresponding to more than 3 Mt yr^{-1} of sediment exports from the Rhone (more than the combined exports due to the Seine and Garonne). In their definition of humid environments, including both the Seine and Loire, their attribution of 40 t km^{-2} yr^{-1} is also a large overestimation (more than 300%). Finally, the map shown in Owens and Batalla (2003) (from Walling and Webb, 1983), includes the Garonne River in the 'semiarid regions' endowed with a sediment yield of 500 t km^{-2} yr^{-1}, which is almost 20 times the sediment yield calculated in this study. We found that the mean specific sediment yield in metropolitan France is approximately 36.9 t km^{-2} yr^{-1} (0.4 t ha^{-1} yr^{-1}). This value is three times lower than what has been found in previously published studies on European specific sediment loads (Walling and Webb, 1983; Lal, 2003), which have reported values of *c.* 134 t km^{-2} yr^{-1} (*c.* 1.3 t ha^{-1} yr^{-1}), despite very similar contexts. Such efforts to calculate regional or global budgets are thus restricted by the limited amount of data available. Consideration of the origin of data measurements and their monitoring period is thus essential, particularly when the aim is to develop regional budgets. The latter is also essential when studying the effects of regional- or global-scale changes due to climatic evolution or anthropogenic effects on sediment delivery to oceans.

In terms of global or regional budgets, a linkage is generally studied between gross erosion estimations and sediment exports through the use of the mean regional Sediment Delivery Ratio (SDR). For example, Lal (2003) used the European sediment yield value proposed by Walling and Webb (1983) to directly estimate gross erosion: an assumed mean SDR of 10% led to an estimated mean gross soil erosion rate of 13.4 t ha^{-1} yr^{-1} for Europe. However, based on the soil erosion map proposed by Cerdan *et al.* (2010), we estimated the average gross erosion rate (due to rill and interrill erosion) for the four largest French basins of *c.* 1.4 t ha^{-1} yr^{-1} (which is comparable with the mean value for Europe). For the Seine river basin and the Rhône river basin erosion rates are comparable, with *c.* 114 t km^{-2} $yr^{-1}$for the Rhone, and *c.* 180 t km^{-2} yr^{-1} for the Seine; it is thus surprising considering sediment exports from both rivers since the Rhône river exports *c.* 10 times more than the Seine river. The ratio of gross erosion (calculated from rill and interrill erosion) on sediment exports calculated here ranges from 6.8% for the Seine River to more than 100% for the Rhône River. To better understand such differences, it seems essential to consider others sediment redistribution processes within river basins. Delmas *et al.* (2009) proposed a global approach in order to characterize river basins by considering rill and interrill erosion, mass movements, drainage density and sediment deposits. They proposed different indices and show that the deposit index of the Seine river basin is twice as much as the Rhone basin, and also that the Rhône river basin contains twice as many areas prone to mass movements as the Seine river, and a higher drainage density. The consideration of various properties that control sediment redistribution processes may help to better explain sediment exports and also their origin and budgets: higher ratio in the Rhone river basin compared with the Seine may be explained by other processes mobilizing sediments, such as mass movements. For such a sediment budget approach, it is thus essential to know sediment exports from river basins, to be able to link them to sediment redistribution processes occurring in the drained areas.

Conclusions

The assessment of correct sediment budgets is often made difficult by the poor availability and reliability of sediment flux data (Meybeck *et al.*, 2003; Walling and Fang, 2003). To remedy these deficiencies and meet the identified demands, this study aimed to propose a new database of sediment exports from French areas. In this context, it is essential to consider homogeneous, long-term datasets to allow simple and relevant comparisons to be made between sediment exports calculated from different basins and to budget these exports. We thus collected homogeneous data for French rivers that are characterized by a low temporal resolution but also by long-term representation, which allows consideration of the mean functioning of the river basins.

Taking into account the structure of the available data, the IRCA method was used (Delmas *et al.*, 2011) to estimate the mean annual sediment load from low temporal resolution sediment concentration data by using an improved rating curve approach based on daily discharge data. The accuracy of the method was tested here on the basis of daily datasets from US basins (from the USGS database) characterized by temperate to Mediterranean climates. The mean relative error in the mean annual sediment flux estimation we obtained was 12%. This validated the method for the calculation of mean annual sediment exports from French rivers to the sea.

Application of this method showed that French rivers export 16.21 +/− 4 Mt of sediments per year to the sea. The four largest basins (Loire, Rhone, Garonne and Seine) export 13.2 Mt per year, which corresponds to 81.3% of the total exports to the sea. The resulting sediment load estimates show that nearly 70% of the French suspended solid exports are delivered to the Mediterranean Sea, while 23% are exported to the Atlantic Ocean. There appears not to be a straightforward relationship between the mass of exported sediment and the size of the basins. This is due to the variety of basin typologies present, from lowland rivers in temperate climates, such as the Seine River, to that of the Rhone River, which is characterized by mountainous upstream and Mediterranean downstream regions. The Rhone River alone exports more than 50% of these sediment discharges, while it drains only 20% of the total area considered. The differences between these major rivers were also emphasized by our analysis of the temporal variability in the sediment exports. The temporal variability of sediment loads is important and rivers in different settings show significant differences in temporal dynamics. This underlines the need for a long-term database for the calculation of mean sediment fluxes to accurately represent the mean functioning of these river basins. Therefore, obtaining measurements over at least a decadal time scale is important to take into account environmental or anthropogenic variability, such as land-use changes.

Sediment export data are essential for the calculation of regional or global sediment budgets, and current data are rarely sufficiently accurate. We have shown that the method employed in this study can be useful to refine these global assessments. Such an approach may be realized in other areas of the world to improve our knowledge regarding sediments being exported to oceans and to construct a validation set for modelling studies.

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