Assessment of dam trapping efficiency from water residence time: Application to fluvial sediment transport in the Adour, Dordogne, and Garonne River basins (France)

Eric Maneux
Département de Géologie et Océanographie, Université Bordeaux 1, Talence, France

Jean Luc Probst
Laboratoire des Mécanismes de Transfert en Géologie, Université Paul Sabatier Toulouse, France

Eric Veyssy and Henri Etcheber
Département de Géologie et Océanographie, Université Bordeaux 1, Talence, France

Abstract. Dam-trapping efficiency can be estimated by using the hydraulic residence time. On the regional scale, the global impact of several dams can be assessed by taking into account the spatial organization of dams along the river network. Therefore, in this study, a method is proposed to estimate the global-trapping efficiency, TEw, for any watershed containing more than one dam. This method is applied to the Adour, Dordogne, and Garonne River watersheds (southwestern France). The spatial organization of dams and its impact on TEw and on sediment yields measured at 37 TSM sampling stations over 2 years are discussed. Positive correlation between drainage areas and river sediment loads corrected from dam regulation using TEw, as well as comparisons between TEw-corrected sediment yields and sediment yields measured upstream from dams, point out the interest of the method in order to reconstitute the natural sediment yields.

1. Introduction

Dams and reservoirs are useful tools to control water resources, to allow irrigation, and to avoid high-flood disasters. Nevertheless, these useful capacities to store water also lead to unintended consequences which affect the erosion/transport processes through watersheds. Particularly, dams and reservoirs can modify the geochemical composition of river water [*Kempe*, 1983] and fluvial sediment transport capacity [*Palmer and O'Keeffe*, 1990; *Walling and Probst*, 1997]. The change in transport capacity has major consequences on river and water resource management, such as eutrophication [*Humborg et al.*, 1997], diminution of the reservoir storage capacity [*Shalash*, 1982; *Hay*, 1994], channel incision [*Kondolf and Swanson*, 1993], and hydrogeomorphological change [*Mercier*, 1998].

In addition, most of those disturbances genuinely modify the sediment delivery ratio of watersheds [*Walling*, 1983], significantly complicating the analysis of river system responses to global warming, climatic changes, and land use and cover changes (LUCC) [*Meyer et al.*, 1992; *Knox*, 1993].

Indeed, the present-day global mass budget of sediment exportation to the oceans by riverine systems is evaluated with data coming from very different sources [*Holeman*, 1968; *Walling and Webb*, 1983; *Milliman and Meade*, 1983; *Milliman and Syvitski*, 1992; *Mulder and Syvitski*, 1996; *Ludwig and Probst*, 1996, 1998]. Moreover, even though total suspended matter (TSM) riverine fluxes have been available since the beginning of the century, reliable data with high frequency and long duration of sampling has only been obtained over the last few decades. Unfortunately, most of these data were obtained on anthropized river systems that are highly subjected to the dam impact [*Vörösmarty et al.*, 1997]. Furthermore, hydrological research and engineering studies were previously focused on the impact of a particular individual dam and information was only available for large dams such as the Aswan dam on the Nile River [*Shalash*, 1982; *Chang*, 1988]. Only a few, recent studies have tried to assess the regional impact of dams on river systems [*Hay*, 1994; *Humborg et al.*, 1997; *Vörösmarty et al.*, 1997]. As the major hydrological and geomorphological issues are the determining of predam river sediment exportations, present-day soil erosion rates, and sediment delivery ratio, the determining of the global and regional trapping efficiency of sediment by dams and reservoirs should lead to a great improvement. Trapping efficiency, TE, is used to determine the life span of dams and reservoirs [*Smith*, 1990; *Hay*, 1994]:

$$\mathrm{LS} = (WD_s)/(L_s\mathrm{TE}), \tag{1}$$

where LS is life-span (year), W is the bulk density of bottom sediment (t m^{-3}), D_s is storage capacity (m^3), L_s is the average suspended sediment load (t yr^{-1}), and TE is the trapping efficiency (%). TE could be estimated from sedimentologic and bathymetric field data. Nevertheless, the estimation of TE from hydrological data and reservoir features may help to evaluate the impact of dams on river systems. TE may thus be a function of the ratio between storage capacity, V, and natural drainage basin, A [*Brown*, 1944]. In order to take into account the spatial variation of runoff, TE may be a function of the hydraulic residence time, $\Delta\tau$, which is the ratio of the total storage capacity, V, to the annual water discharge, Q_{yr} [*Brune*, 1953]:

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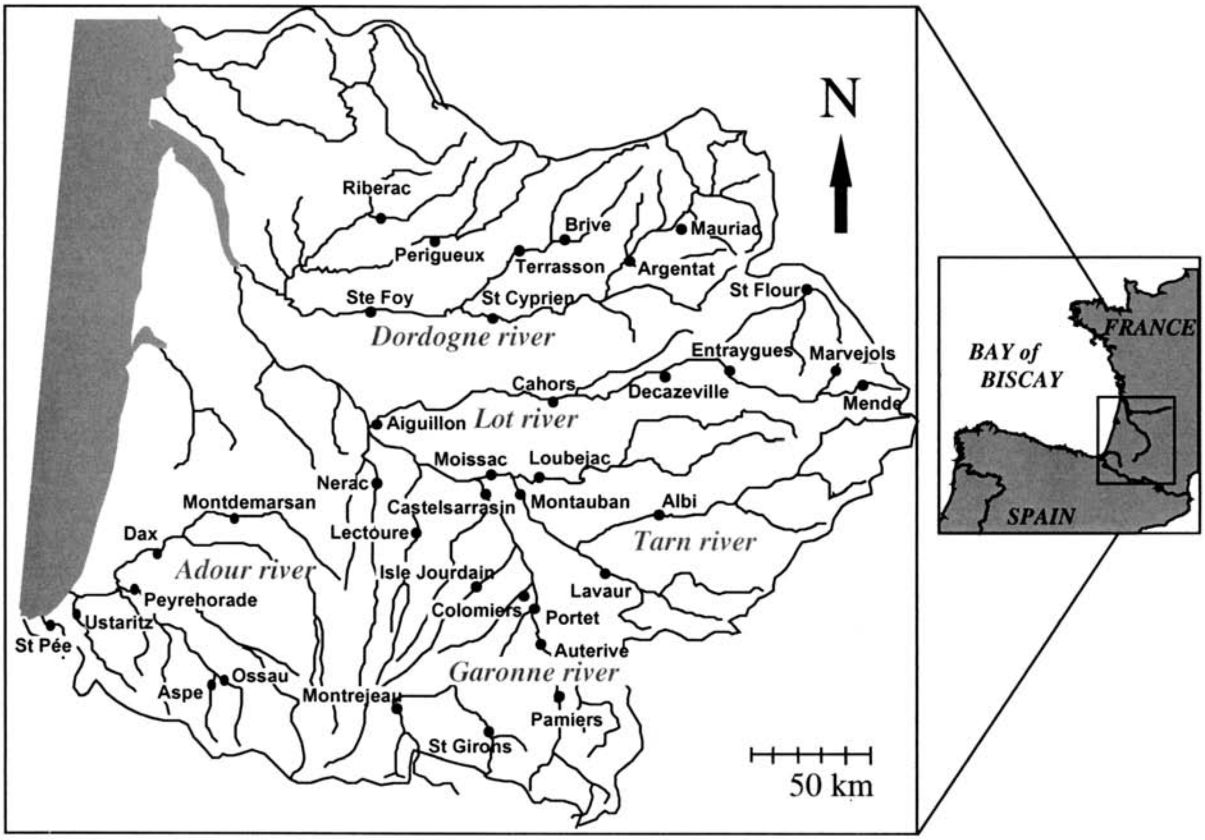

Figure 1. Adour, Dordogne, and Garonne River networks and TSM sampling station locations.

$$\mathrm{TE} = 100[1 - 1(1 - 0.1\Delta\tau)] \quad \text{with} \quad \Delta\tau = \frac{V}{Q_{yr}}, \qquad (2)$$

where $\Delta\tau$ is water residence time (year), V is storage capacity (hm^3), and Q_{yr} is annual runoff ($\mathrm{hm}^3\ \mathrm{yr}^{-1}$). Recently, *Vörösmarty et al*. [1997] applied the equation originally developed by *Brune* [1953] and modified by *Ward* [1980], in order to estimate trapping efficiency from water residence time for the largest world reservoir:

$$\mathrm{TE} = 1 - \frac{0.05}{\sqrt{\Delta\tau}}, \qquad (3)$$

where $\Delta\tau$ is water residence time (year) and TE is trapping efficiency (%) [*Ward*, 1980].

The aim of the present study is to test the reliability and the utility of (3) in a regional model of sediment transport through different watersheds. This work was done using TSM flux data on 37 watersheds in southwest France [*Maneux*, 1998], features of 125 Dams gathered in the European Lakes Dams and Reservoirs Database (ELDRED), and regional hydrological databases (HYDRO, CARTHAGE).

2. Materials and Methods

2.1. Sampling Sites

TSM concentrations were checked in 44 gauging stations distributed throughout the three watersheds (Figure 1) of the Garonne, the Dordogne, and the Adour Rivers (southwestern France). These watersheds drain the Aquitanian basin between two major relief areas: the Pyrenean mountains (maximum altitude: 3400 m) and the Massif Central mountains (maximum altitude: 1800 m), under temperate oceanic climatic conditions (mean annual rainfall from 600 mm yr^{-1} up to more than 2500 mm yr^{-1}). The surface areas of the studied watersheds range from 130 to 15,700 km^2. The mean annual water discharges range from 3 to 280 $\mathrm{m}^3\ \mathrm{s}^{-1}$, and the mean annual specific drainage ranges from 6 up to 54 L $\mathrm{s}^{-1}\ \mathrm{km}^{-2}$.

2.2. TSM Concentration and Sediment Yield

The sampling was voluntarily performed by school people for 44 stations during the years 1995 and 1996. During these years, the hydroclimatic conditions were not exceptional: for the two main watersheds the 1995 water discharges were 600 $\mathrm{m}^3\ \mathrm{s}^{-1}$ for the Garonne River at La Réole and 310 $\mathrm{m}^3\ \mathrm{s}^{-1}$ for the Dordogne River at Ste Foy; the 1996 water discharges were 810 and 266 $\mathrm{m}^3\ \mathrm{s}^{-1}$, respectively, whereas the mean interannual values are 630 and 280 $\mathrm{m}^3\ \mathrm{s}^{-1}$, respectively. Nevertheless, in the Tarn watershed (three stations), a 50-year flood occurred.

River waters were taken in the main channel, ~1 m below the surface, with bottles handled from bridges. The sampling frequency was around one sample per week and was increased to one per day during flood events. This allowed us to obtain data sets ranging from 40 to 120 samples per station. In this study we focus on suspended load, and we do not take into account bed load transport, considered as negligible in this region in comparison to suspended load. Indeed, the coarse fraction is slightly represented, whereas fine particles (<63 μm) correspond to 86–95% of the total suspended matter (Table 1). TSM contents were recovered by filtration of the river water sample through 0.45 μm Whatman GF/F glass

Table 1. Examples of TSM Grain Sizes Measured With a Malvern Granulometer

	Basin Area, km^2	Water Discharge, $m^3\ s^{-1}$	C_{TSM}, mg L^{-1}	Clays and Fine Silts, <16 μm	Silts, 16–63 μm	Very Fine Sands, 63–125 μm	Fine Sands, 125–250 μm	Medium Sands, 250–500 μm
Dordogne (Sept. 12, 1996)	13,800	510	8.3	34.5%	52.1%	10.3%	3.1%	0.0%
Garonne (Sept. 12, 1996)	53,000	3,827	493	61.8%	33.1%	4.4%	0.6%	0.0%
Ariège (Oct. 6, 1996)	3,500	187	436	73.9%	21.0%	4.1%	1.0%	0.0%

filters which were weighted with a 1/10 mg balance. As in many hydrological studies, we used the common relation between suspended sediment concentration, C, and the water discharge, Q, observed in hysteresis loops [*Williams*, 1989]. This C–Q relation enables us to estimate TSM concentrations according to an empirical relationship or rating curve between C and Q [*Loughran*, 1976; *Ferguson*, 1986; *Walling and Webb*, 1998; *De Vries and Klavers*, 1994]. In most cases, the relationship used to estimate TSM concentrations from water discharge, Q, is a power law as follows:

$$C = \alpha Q^{\beta}. \tag{4}$$

Thus the total suspended load or TSM flux is usually estimated for T period as

$$F = \sum_{i=1}^{T/dt} C_i Q_i\, dt, \tag{5}$$

where missing TSM concentrations were replaced by the estimates according to (4). Such relationships were observed (Figure 2) and used in most cases in order to calculate the annual TSM flux, F [*Maneux*, 1998]. The reliability of each TSM flux was determined with a qualitative note, which is based on five parameters (Table 2): the significance level of the correlation between TSM concentration and river discharge, the number of samples, the ratio between the highest river discharge corresponding to a sample and the highest river discharge of the studied period, and the number of samples collected during 2- and 5-year floods. The final notes range from 0 to 10, and we assumed that the TSM fluxes are significant enough when the note is >4. Finally, TSM fluxes of 37 stations were assumed to

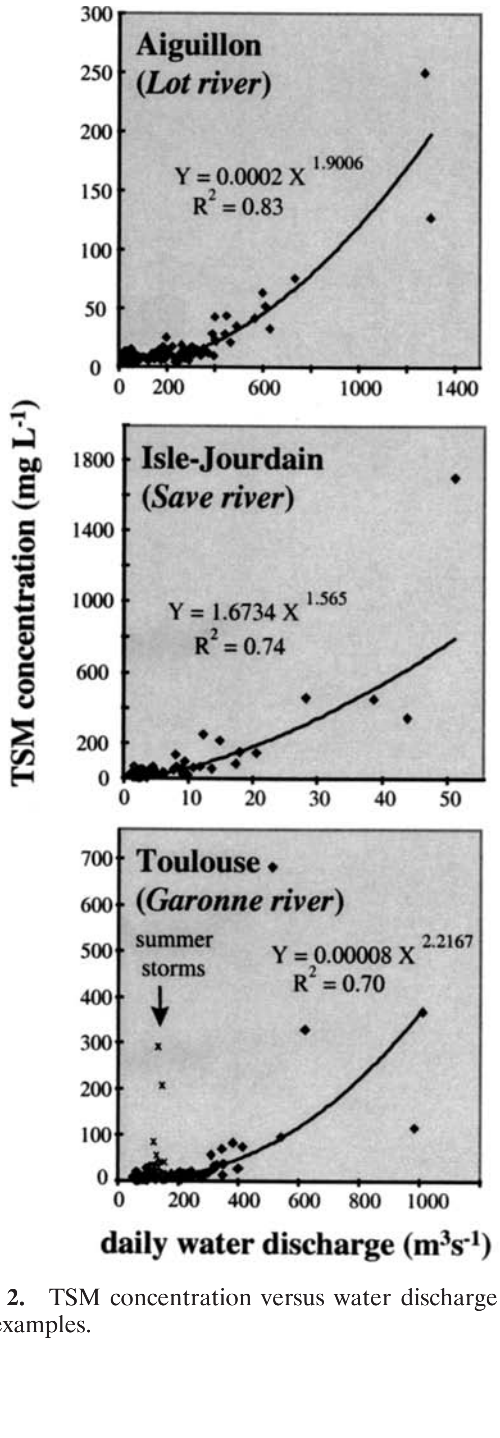

Figure 2. TSM concentration versus water discharge rating curve examples.

Table 2. Methodology for Reliability Assessment of TSM Annual Load

Criteria	Note
Number of TSM samples	
<50	0
50–100	1
>100	2
Number of 2-year floods sampled	
none	0
one	1
two or more	2
Number of 5 year floods or higher sampled	
none	0
one	1
two or more	2
The r^2 of the C–Q relationship significant for a significance level of	
5–1%	0.5
1–0.1%	1
0.1–0.01%	2
(Sampled Q_{max}) (Q_{max} in 95 and 96)[a]	
<0.75	0
0.75–0.9	1
>0.9	2

[a]Maximum water discharge (sampled Q_{max}) for which TSM concentration exists.

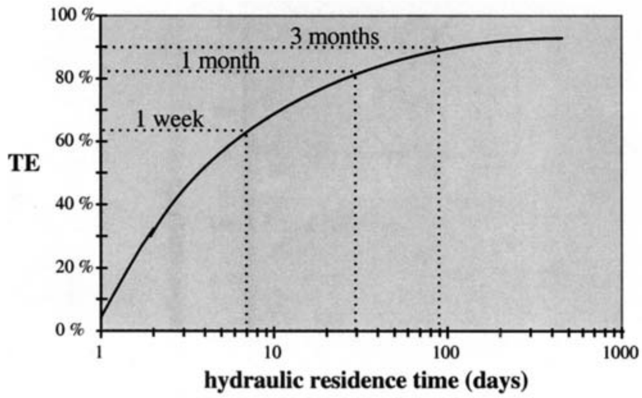

Figure 3. Trapping efficiency versus hydraulic residence time, i.e., plot of equation (3) [*Vörösmarty et al.*, 1997].

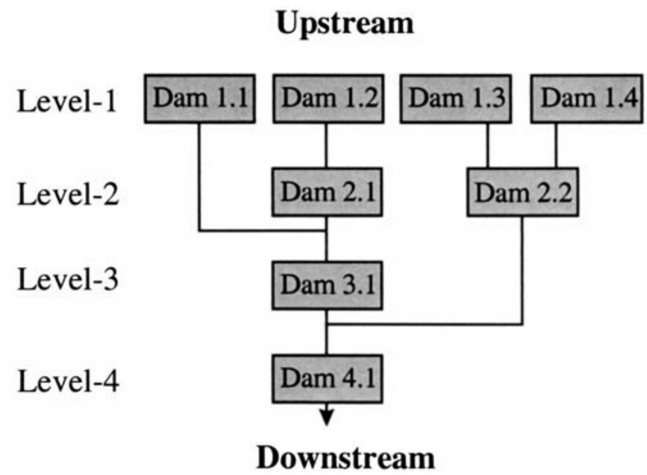

Figure 4. Schematic dam classification.

be significant, and specific yields were calculated since all the drainage basin areas are known.

2.3. Determination of TE

In the studied area, most of the rivers are regulated by dams and reservoirs: 155 dams higher than 15 m or with a total capacity greater than 0.5 hm^3 are referenced in the ELDRED database. For 125 of these dams, total storage capacity, natural drainage area, and geographical position are available. As the average annual runoff is not available for a third of the dams, it was estimated from the drainage area and the specific water discharge of the nearest gauging station on the river. These parameters enabled us to estimate the hydraulic residence time and therefore the trapping efficiency according to (3). The TE prediction curve from $\Delta\tau$ shows that if $\Delta\tau$ exceeds 1 week, TE is superior to 65%, and if $\Delta\tau$ exceeds 3 months, TE is higher than 90% (Figure 3).

In order to determine TE at a given gauging station for a river regulated by several dams, *Vörösmarty et al.* [1997] propose to add the storage capacities $(V_1 + V_2 + V_3 \ldots)/Q$, and to calculate a global hydraulic residence time for the entire watershed, $\Delta\tau = (V_1 + V_2 + V_3 \ldots)/Q$, which is used in (3) for TE calculation of the entire watershed. This method of TE estimation could lead to an overestimation of the real trapping efficiency of the watershed when multiple trapping through sequential dams occurs [*Vörösmarty et al.*, 1997; *Meade*, 1995]. Moreover, we state that if a dam with a high total storage capacity ($V_1 \ggg V_2, V_3, \ldots$) is located in the upper part of the river network, it affects only a small fraction of the entire drainage basin area (basin area of dam 1 watershed: $S_1 \lll S_2, S_3, \ldots$), i.e., it affects only a small fraction of sediment load, with the assumption that sediment loads are proportional to water discharge. This is not taken into account in the approximation of *Vörösmarty et al.* [1997]: a high-storage capacity in the upper reaches may be applied to the sediment load of the entire watershed although it affects only a small part of the sediment load.

In the present study, a Geographical Information System (GIS) was used to take into account the spatial organization of the river network, basin limits, and dam locations in order to resolve the problem of multiple trapping through sequential dams. Thus georeferenced databases (a digital elevation model (DEM), digitalized river network, and basin limits (CARTHAGE) were linked with tabular databases describing gauging stations (HYDRO), sampling sites, and dam features (ELDRED). This allowed us to determine exactly the dam positions and succession along the river network. Next, dams were classified like rivers with the *Strahler*'s [1964] classification. Thus, the level 1 dam is located upstream; a level 2 dam is located downstream from one or several level 1 dams; and a level 3 dam is located downstream from one or several level 2 dams (Figure 4). For each dam, n corresponds to its own watershed n. Q_n is the annual runoff of the watershed n. F_n is the annual TSM flux of the watershed n.

At the upstream level 1, the TEw of a watershed is equal to the TE of the dam located at the outlet. For level 2 dams and above, the trapping efficiency which affects the sediment flux at the exutory of the whole watershed, TEw, is a weighting of the dam trapping efficiency, (TE_n) by their respective sediment flux (F_n). Thus, in the simple case of two successive dams (level 1, TE_1; level 2, TE_2), we can distinguish two subcatchment areas (Figure 5) with their respective annual runoff (Q_1 and Q'_1) and sediment flux (F_1 and F'_1). The sediment flux F'_1 is only affected by the level 2 dam, i.e., is only affected by TE_2. However, the sediment flux F_1 is affected successively by the two dams, i.e., by their respective trapping efficiency (TE_1 and TE_2). The percentage of F_1 which is intended to pass through the level 1 dam is $1 - TE_1$. Then this residual load is affected

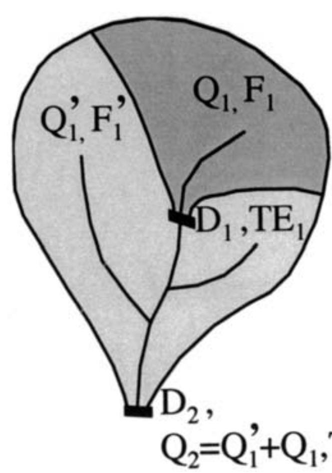

Figure 5. Schematic case of two successive dams.

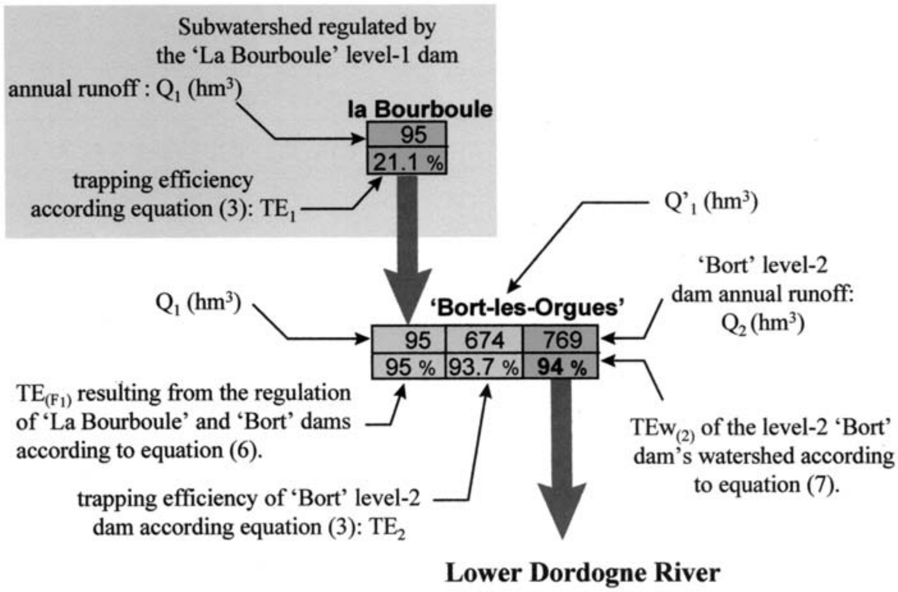

Figure 6. Example of TEw evaluation for the upper Dordogne River basin at the level 2 dam of Bort-les-Orgues.

by the level 2 dam; that is to say, a percentage TE_2 of the residual load $(1 - TE_1)$ is trapped by the level 2 dam. Therefore the total trapping efficiency affecting F_1, $TE_{(F_1)}$, is the combination of TE_1 and TE_2 as follows:

$$TE_{(F_1)} = TE_1 + TE_2(1 - TE_1). \tag{6}$$

This equation is the main improvement of the methodology of *Vörösmarty et al.* [1997] where the TE of a dam is only applied to the sediment load passing through it in the case of multiple trapping through sequential dams. The global trapping efficiency, $TEw_{(2)}$, of the whole level 2 watershed results from the weighting of $TE_{(F_1)}$ and $TE_{(F'_1)}$ by their sediment fluxes F_1 and F'_1, respectively. Unfortunately, the sediment fluxes for each subcatchment are not known. Thus, as the sediment load is assumed to be proportional to the water discharge [*Colby*, 1956; *Walling and Webb*, 1988; *Probst*, 1992], the weighting could be performed with their respective annual runoff Q_1 and Q'_1:

$$TEw_{(2)} = \frac{TE_{(F_1)}Q_1}{Q_2} + \frac{TE_2(Q_1)}{Q_2}. \tag{7}$$

In the same way, n level (i) dams can be taken into account to estimate a global TEw for a level $(i + 1)$ dam watershed:

$$TEw_{(i+1)} = \frac{1}{Q_{(i+1)}}\left[\sum_1^n (TE_{(F_1)}Q_i)\right] + \frac{TE_{(i+1)}}{Q_{(i+1)}}\left[Q_{(i+1)} - \sum_1^n (Q_i)\right]. \tag{8}$$

The example of the upper Dordogne river is shown in Figure 6. In order to estimate the TEw at a sampling or a gauging station, we can consider in (8) a local $TE_{(i+1)}$ equal to zero.

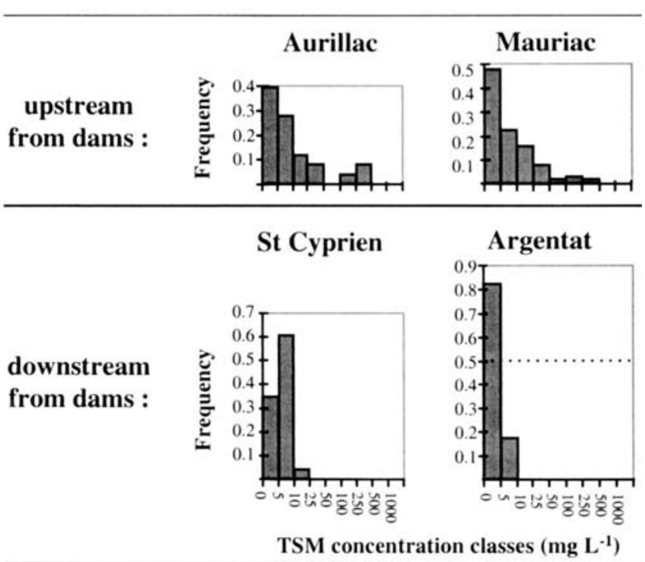

Figure 7. TSM concentration frequency for four sampling stations of the Dordogne River basin.

3. Total Suspended Matter Concentrations and Sediment Yields

The first reliable and significant information about the impact of sediment trapping capacity on river water quality is the TSM concentrations. Mean annual concentrations observed range from 3 mg L^{-1} for the Dordogne River at Argentat up to 100 mg L^{-1} for the Tarn River at Moissac, which presents the highest instantaneous TSM concentration observed (2000 mg L^{-1}) [*Maneux*, 1998]. Frequency histograms of TSM concentrations show that for highly regulated rivers such as the Dordogne, there are two types of histograms (Figure 7): upstream from dams, the TSM flood concentrations are always >100 mg L^{-1} and may reach 500 mg L^{-1}. On the contrary, downstream from dams, TSM concentrations rarely exceed 10 mg L^{-1}, even during flood periods.

As TSM concentration has been measured along the river

Table 3. Annual TSM Load, Sediment Yield, and TEw

Station Name	River Name	Basin Area, km^2	Mean Annual Water Discharge, $m^3\ s^{-1}$	Field TSM Load, $t\ yr^{-1}$	Field Sediment Yield, $t\ km^{-2}\ yr^{-1}$	TEw, %	Corrected TSM Load, $t\ yr^{-1}$	Corrected Sediment Yield, $t\ km^{-2}\ yr^{-1}$
St-Pée	Nivelle	170	6	10,100	59	0	10,100	59
Ossau	Gave d'Ossau	500	20	12,900	26	21	16,300	33
Aspe	Gave d'Aspe	640	32	11,300	18	0	11,300	18
Ustaritz	Nive	850	32	47,700	56	0	47,700	56
Montdemarsan	Midouze	2,050	23	23,900	12	9	26,300	13
Peyrehorade	Gave	5,570	185	180,000	32	5	190,000	34
Dax	Adour	7,830	90	202,400	26	5	213,700	27
Mauriac	Auze	130	3	2,100	16	0	2,100	16
Brive	Corrèze	970	19	14,700	15	10	16,200	17
Riberac	Dronne	1,010	12	9,200	9	0	9,200	9
Périgueux	Isle	2,160	29	29,000	13	0	29,000	13
Terrasson	Vézère	2,690	61	44,000	16	18	53,700	20
Argentat	Dordogne	4,480	108	12,600	3	87	100,200	22
St Cyprien	Dordogne	8,700	82	43,400	5	62	113,500	13
St Foy	Dordogne	14,930	279	150,000	10	44	268,000	18
Colomier	Touch	530	4	10,400	20	0	10400	20
St Girons	Salat	680	22	24,300	36	0	24,300	36
Lectoure	Gers	970	8	40,000	41	0	40,000	41
Isle-Jourdain	Save	980	4	57,800	59	0	57,800	59
Nérac	Baïse	1,330	12	84,000	63	5	88,600	67
Pamiers	Ariège	1,600	41	30,500	19	20	38,200	24
Montréjeau	Garonne	2,250	70	18,800	8	3	19,300	9
Auterive	Ariège	3,450	66	115,500	33	14	134,500	39
Toulouse	Garonne	10,030	188	287,600	29	6	307,200	31
Castelsarrasin	Garonne	15,070	207	545,500	36	7	589,100	39
Mende	Lot	270	5	9,700	36	0	9,700	36
St-Flour	Lander	340	3	7,100	21	0	7,100	21
Marvejols	Colagne	480	6	25,700	54	0	25,700	54
Entraygues	Lot	2,210	34	19,600	9	70	65,000	29
Decazeville	Lot	6,460	118	34,800	5	62	90,400	14
Cahors	Lot	9,200	136	99,500	11	53	213,500	23
Aiguillon	Lot	11,640	145	125,000	11	70	223,000	19
Lavaur	Agout	2,550	48	74,800	29	40	123,600	48
Albi	Tarn	4,540	90	626,500	138	25	829,800	183
Loubejac	Aveyron	5,200	55	73,000	14	25	97,500	19
Montauban	Tarn	9,330	155	868,000	93	50	1,735,900	186
Moissac	Tarn	15,740	210	1,401,200	89	44	2,480,000	158

network at different sampling stations, geographical variations of TSM annual fluxes and sediment yields could be estimated (Table 3). Indeed, sediment yields range from 3 t $km^{-2}\ yr^{-1}$ for the Dordogne River at Argentat to 138 t $km^{-2}\ yr^{-1}$ for the Tarn River at Albi. The highest values were observed for the Tarn River because of a high potential of erosion in the drainage basin and because TSM data were recorded during a 50-year flood. The lowest sediment yields are estimated downstream from dams in the lower parts of the Dordogne and Lot Rivers (3–10 t $km^{-2}\ yr^{-1}$), while sediment yields exceed 20 t $km^{-2}\ yr^{-1}$ upstream from dams in the upper reaches.

4. Trapping Efficiency From Dam to Watershed Level

In the studied area, trapping efficiency was estimated for 125 dams referenced in the ELDRED database using (3). TE values range from 0 to 95%. Seventy-four dams (60%) present water residence times greater than 10 days; that is to say, their TE exceeds 70%. Moreover, TE of the larger dams is >70%, since the total water storage capacity exceeds 50 hm^3. On the watershed scale, the maximal dam level for each main subcatchment area ranges from level 2 for the Adour River up to level 9 for the Lot River. The mean annual runoff, the mean basin area, and the mean TE for each dam level can be estimated (Table 4). According to (8), TEw can be estimated along the river network at any point corresponding, or not, to a dam. Thus the spatial evolution of TEw along the river network can easily be highlighted. For example, Figure 8 is a schematic representation of TEw for dams and sampling stations in the Lot watershed. TEw of watersheds, for which TSM flux data is available, are represented for the whole studied area in the Figure 9.

5. Potential Impact on Sediment Transport

A first evaluation allows us to describe the individual impact of dams on the regional scale. Figures 8 and 9 show that the lowest TEw values are observed in the upper parts of the main watersheds and of course upstream from dams. However, the highest TEw values were estimated for the sampling stations located in the lower parts of watersheds, where the probability of being affected by dam regulation is higher, although their individual TE generally decreases rapidly to zero when the drainage basin area exceeds 3000 km^2 (Table 4) and where dams control a greater percentage of the total annual runoff at the outlet. The lower parts of the Lot, Dordogne, and Tarn

Table 4. Dam Statistical Features for Each Order Level in Five Regional Main Watersheds[a]

	Adour River				Dordogne River				Garonne River				Lot River				Tarn River			
	nb	Q, hm^3	S, km^2	TE, %	nb	Q, hm^3	S, km^2	TE, %	nb	Q, hm^3	S, km^2	TE, %	nb	Q, hm^3	S, km^2	TE, %	nb	Q, hm^3	S, km^2	TE, %
Level 1	29	47	119	29	18	142	177	59	30	56	66	66	6	65	85	53	16	169	235	85
Level 2	3	71	42	76	5	610	778	39	2	606	622	48	3	973	1,826	55	6	507	725	34
Level 3	···	···	···	···	2	1,302	1,648	79	2	658	660	29	1	1,255	2,370	90	2	1,159	1,572	3
Level 4	···	···	···	···	1	2,428	3,270	83	2	2,610	2,929	0	1	1,362	2,484	35	2	1,459	2,160	0
Level 5	···	···	···	···	1	2,974	3,270	80	1	3,910	4,595	0	1	1,545	2,752	74	1	2,800	4,900	49
Level 6	···	···	···	···	1	3,406	4,412	0	1	3,958	4,650	0	1	1,949	3,278	0	···	···	···	···
Level 7	···	···	···	···	1	8,799	13,650	0	···	···	···	···	1	3,784	9,300	0	···	···	···	···
Level 8	···	···	···	···	···	···	···	···	···	···	···	···	1	4,415	10,700	16	···	···	···	···
Level 9	···	···	···	···	···	···	···	···	···	···	···	···	1	4,573	11,194	30	···	···	···	···

[a]nb, dam number per level; Q, mean annual runoff in hm^3; S, mean drainage basin area in km^2; and TE, mean dam trapping efficiency in % estimated from equation (3).

Rivers are good examples with downstream high level dams (Table 4).

Thus, although level 1 dams control 35, 29, 30, 11, and 57% of the total annual runoff for the Adour, Dordogne, Garonne, Lot, and Tarn watersheds, respectively, these dams with high individual TE do not affect greatly the TEw of the main watersheds. This is the case for the Adour and the Garonne River basins for which TEw does not exceed 20% (Figure 9). In contrast, TEw of the Lot, Dordogne, and Tarn watersheds are higher because of the succession of dams along the lower river network. Indeed, 30% of the total annual runoff for the Dordogne River finally flows through two level 4 and level 5 dams with individual TE exceeding 80% (Table 4). These dams enhance the impact of numerous upper dams. Therefore the global TEw may locally exceed 95% in several places. For the TSM monitoring station of Argentat, TEw may even reach 87% (Figure 9). These estimations are consistent with the TSM concentrations and sediment yields observed at these stations (Figure 7 and Table 3). On the contrary, the Lot River watershed does not present many level 1 dams but has the highest number of successive dams along the main river channel (level 9 dam order). As the two highest level dams present significant individual TE (16 and 30%), the resulting TEw is relatively high (70%) for the lower sampling station of Aiguillon. Thus the dam geographical organization along regulated rivers seems to be the first parameter which determines the impact of sediment trapping in reservoirs, and finally our method quantifies the regional dam impact on sediment transport through watersheds.

Indeed, in the studied area, the sedimentation rates in reservoirs are not available. Nevertheless, mean annual TSM fluxes calculated for 37 watersheds can help us to estimate the reliability of the estimated TEw. The first controlling factor used to determine the intensity of TSM fluxes is the water discharge [*Colby*, 1956; *Walling and Webb*, 1988; *Probst*, 1992]. Moreover, for a given bioclimatic area, the amount of water discharge is proportional to the drainage basin area. Thus, indirectly, the TSM fluxes could even be correlated with the drainage area. This is truly observed for the larger watersheds with drainage basin areas >1000 km^2 (Figure 10a). This relationship allows us to distinguish two clusters of points: one corresponding to the Tarn River (white squares) and the other corresponding to all the other rivers. This difference is due to a spatial variation in soil erosion processes. Indeed, although the studied watersheds are in an oceanic, temperate, climatic zone, the upper reaches of the Tarn River are in the Mediterranean climatic zone. Moreover, the principal sediment sources are highly erodible red marls in some upper subcatchments of the Tarn River.

6. Reconstitution of Natural Sediment Yields

In order to assess the reliability of the TEw estimation, we propose to correlate the drainage basin area with field TSM fluxes corrected from the dam regulation as follows (Figure 10b):

$$F_{\mathrm{TSM}}^{\mathrm{corrected}} = \frac{F_{\mathrm{TSM}}^{\mathrm{observed}}}{1 - \mathrm{TEw}}. \tag{9}$$

If one reconstitutes the natural sediment fluxes by correcting the observed fluxes according to (9), one can see in Figure 10b that the cluster of points is less scattered and that the correlation coefficient is better. This result shows that the data collected in this study and the method used to calculate TE allows us to assess the natural TSM fluxes at a regional scale such as the Adour, Dordogne, and Garonne River basins. Consequently, as seen in Figure 11, it has been possible to reconstitute the natural sediment yields for different river basins. Indeed, the reconstituted values of lower stations are far from those measured in the upper part of the basin before dam regulation.

All this is new information: TEw and natural reconstituted specific yields are of strong interest for the assessment of soil erosion and fluvial sediment transport processes in the studied watersheds. Indeed, soil erosion rate in the Garonne watersheds [*Probst*, 1992; *Sehmi*, 1996] and sediment river inputs to the Gironde estuary [*Etcheber*, 1986; *Veyssy et al*., 1996] have already been estimated. Thus the mean specific yields were previously estimated at 24 t km^{-2} yr^{-1} for the Dordogne River and at 42 t km^{-2} yr^{-1} for the Garonne River. Thanks to hydrological and dam databases and our method, TEw is estimated at 31.2% for the Dordogne River and at 30.5% for the Garonne River. TEw allowed us to conclude that present-day natural specific yields are probably ~35 t km^{-2} yr^{-1} for the Dordogne River and ~60 t km^{-2} yr^{-1} for the Garonne River. Moreover, if studies on sedimentation processes in the coastal zones and in the continental margin are often correlated with present-day sediment inputs to the Bay of Biscay [*Jouanneau et al*., 1999; *Maneux et al*., 1999a], reconstitution of past erosion rates from sedimentation rates must take into account the

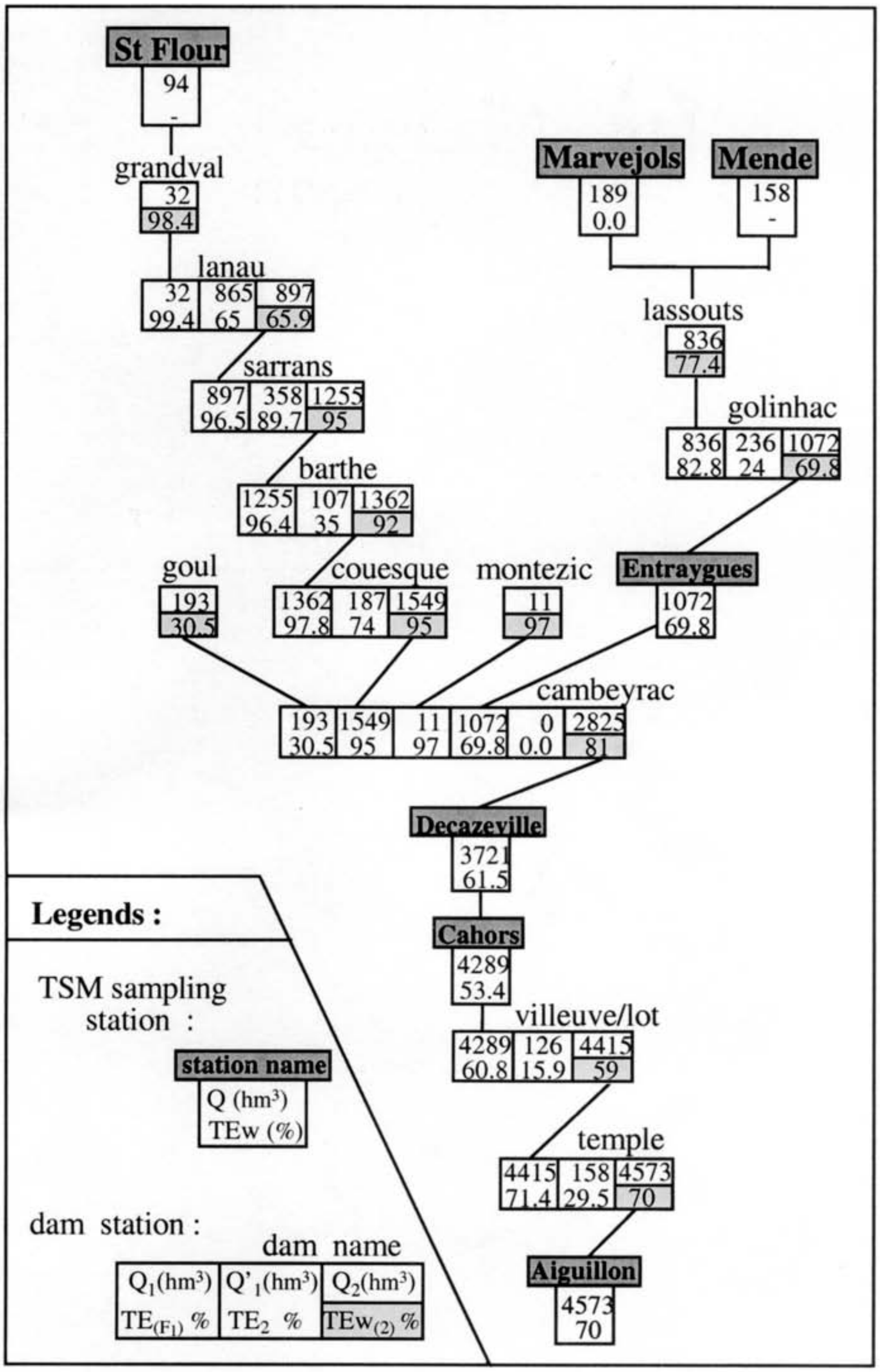

Figure 8. Spatial evolution of annual runoff and TEw of dams and TSM sampling station along the river network of the Lot River, upstream from Aiguillon.

present-day regulation of river sediment fluxes by dams and reservoirs. Finally, we even expect that this work can help forecast the losses of water storage capacity by bottom sedimentation, all the more so since dam life spans are often overestimated.

7. Conclusion

The hydraulic residence time of each dam can easily be estimated from water storage capacity and annual runoff of the natural drainage area. It allows us to determine the trapping efficiency of river sediment for one dam. Thus, in this work, the ELDRED database was used to estimate the trapping efficiency of the 125 dams of the main watersheds of southwestern France: the Adour, Dordogne, and Garonne River watersheds. We highlight here the interest of such a database. Nevertheless, on the regional scale, the global impact of several dams can only be assessed by taking into account the spatial organization of dams along the river network. It could be determined with the integration into a Geographical Information System of ELDRED, with other available regional databases which describe water discharges (HYDRO), and watershed features (CARTHAGE). Therefore a method to estimate the global

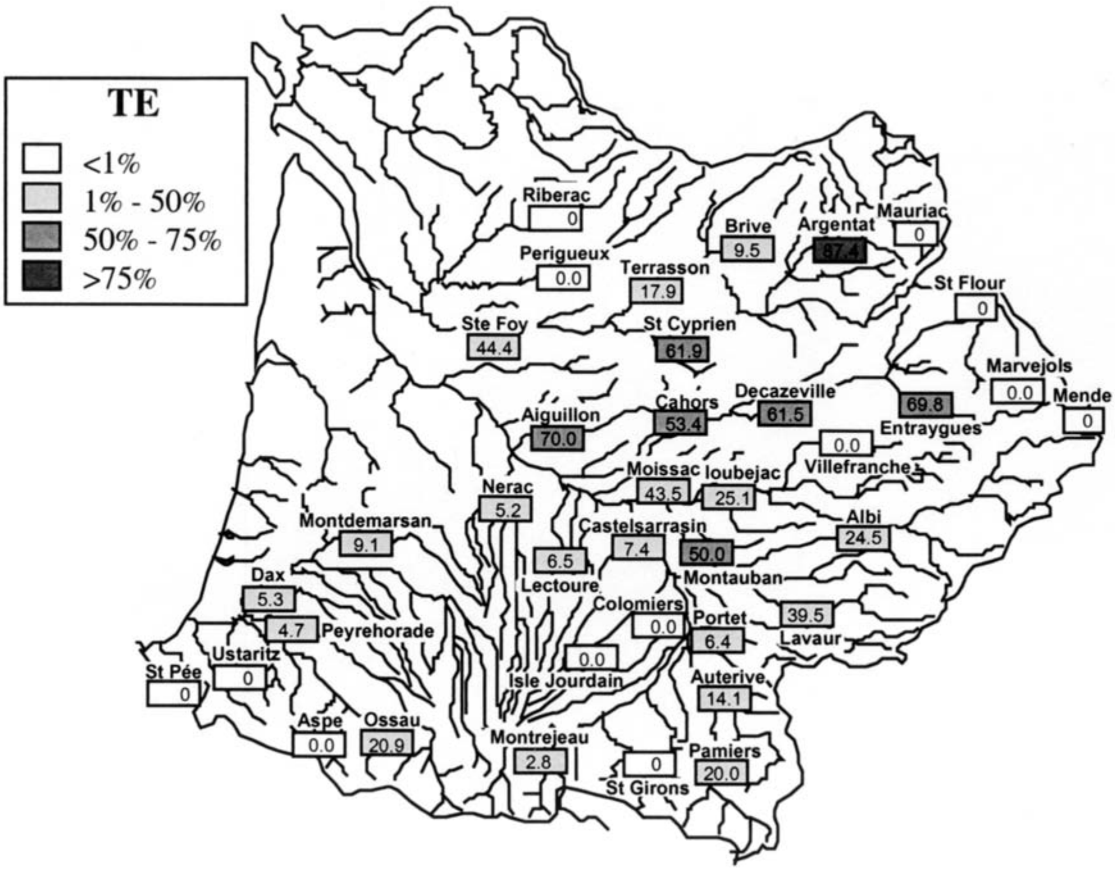

Figure 9. TEw at TSM sampling stations.

trapping efficiency, TEw, for any watershed containing more than one dam, can be proposed in this study. This method makes it possible for the first time to quantify the dam impact for a whole regional watershed and to gain a better understanding of the impact of the spatial organization of dams on river sediment trapping. Thanks to a TSM flux survey in 37 sampling stations during 2 year periods, we can assess the reliability of this method: the positive correlation between annual river sediment fluxes and drainage areas is better if the fluxes are corrected from dam regulation using the trapping efficiency, TEw, and the TEw-corrected sediment yields are in accordance with sediment yields measured upstream from dams.

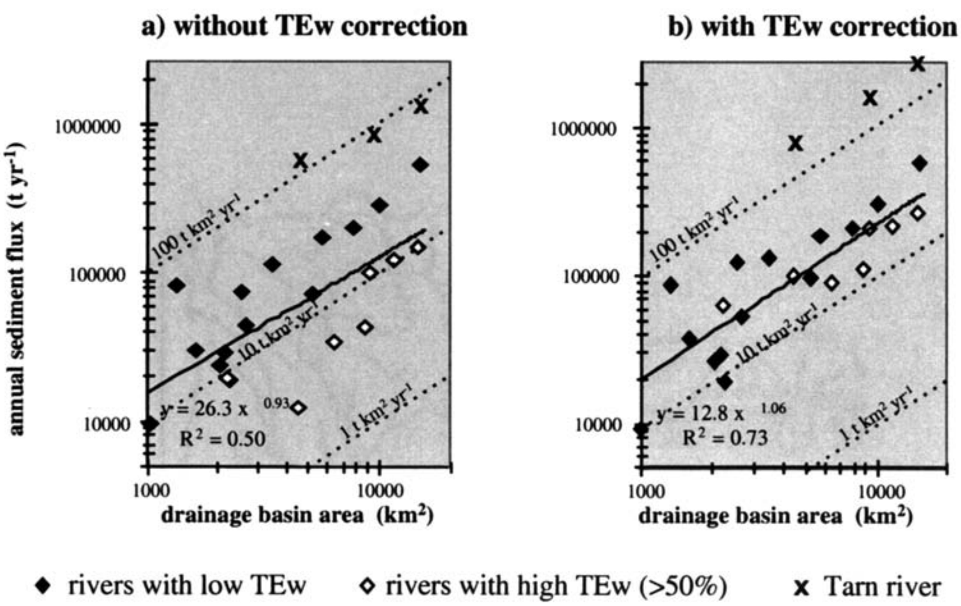

Figure 10. TSM annual fluxes versus drainage basin area for the 24 watersheds larger than 1000 km^2.

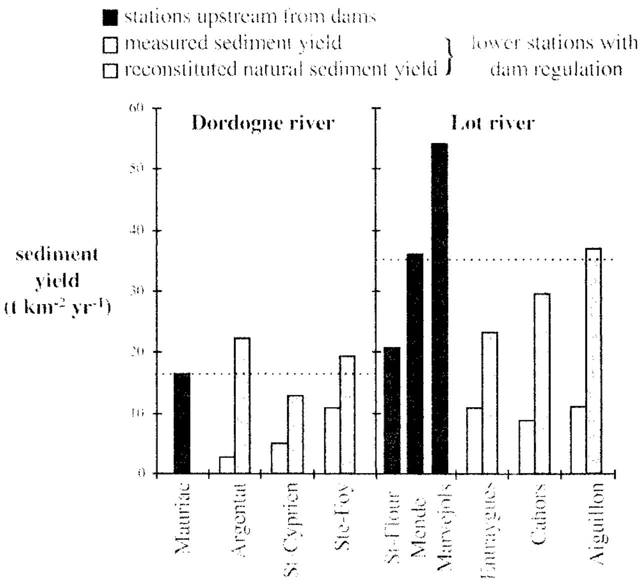

Figure 11. Comparison between the natural sediment yields reconstituted using the TEw correction method and the mean sediment yields observed during 2 years.

These results have allowed us to propose the correction of the annual sediment load with the TEw to reconstitute the natural sediment yields. We point out the interest of this method, which helps us to assess the natural sediment delivery ratio of regulated rivers [*Maneux et al.*, 1999b]. Indeed, many efforts are made to correlate the Land Use and Cover and geomorphological and climatic features with the sediment yields of world rivers [*Pinet and Souriau*, 1988; *Pernetta and Milliman*, 1995; *Meybeck and Ragu*, 1996; *Mulder and Syvitski*, 1996; *Ludwig and Probst*, 1998], but most of the TSM flux data do not take into account dam sediment trapping. Thus this work highlights that if dam databases are available, regional trapping efficiency can be estimated easily and reliably from water residence time and that it would be a good assessment to appreciate the impact of dams on natural sediment flux on regional or global scales.

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H. Etcheber, E. Maneux, and E. Veyssy, Département de Géologie et Océanographie, UMR CNRS 5805, Université Bordeaux 1, Avenue des Facultés, 33405 Talence, France. (maneux@geocean.u-bordeaux.fr)

J. L. Probst, Laboratoire des Mécanismes de Transfert en Géologie, UMR CNRS 5563, Université Paul Sabatier, Toulouse, France.

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