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The influence of contrasting suspended particulate matter transport regimes on the bias and precision of flux estimates

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Abstract

A large database (507 station-years) of daily suspended particulate matter (SPM) concentration and discharge data from 36 stations on river basins ranging from 600 km^2 to 600,000 km^2 in size (USA and Europe) was collected to assess the effects of SPM transport regime on bias and imprecision of flux estimates when using infrequent surveys and the discharge-weighted mean concentration method. By extracting individual SPM concentrations and corresponding discharge values from the database, sampling frequencies from 12 to 200 per year were simulated using Monte Carlo techniques. The resulting estimates of yearly SPM fluxes were compared to reference fluxes derived from the complete database. For each station and given frequency, bias was measured by the median of relative errors between estimated and reference fluxes, and imprecision by the difference between the upper and lower deciles of relative errors. Results show that the SPM transport regime of rivers affects the bias and imprecision of fluxes estimated by the discharge-weighted mean concentration method for given sampling frequencies (e.g. weekly, bimonthly, monthly). The percentage of annual SPM flux discharged in 2% of time (Ms_2) is a robust indicator of SPM transport regime directly related to bias and imprecision. These errors are linked to the Ms_2 indicator for various sampling frequencies within a specific nomograph. For instance, based on a deviation of simulated flux estimates from reference fluxes lower than ±20% and a bias lower than 1% or 2%, the required sampling intervals are less than 3 days for rivers with Ms_2 greater than 40% (basin size < 10,000 km^2), between 3 and 5 days for rivers with Ms_2 between 30 and 40% (basin size between 10,000 and 50,000 km^2), between 5 and 12 days for Ms_2 from 20% to 30% (basin size between 50,000 and 200,000 km^2), 12–20 days for Ms_2 in the 15–20% range (basin size between 200,000 and 500,000 km^2).

Keywords: Suspended particulate matter; Load estimate; Flux; Accuracy; Precision; Sampling frequency

1. Introduction

Many authors have observed that daily river suspended particulate matter (SPM) concentration (Cs) and specific fluxes (Y) present enormous time and space variations due to runoff (q) and Cs vs. q relationships

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(Williams, 1989), which occur as a result of the interaction of many factors, mainly climate, geology (including soil type), relief, land use (including vegetation) and anthropogenic factors (Meade and Parker, 1985; Milliman and Syvistski, 1992; Walling and Webb, 1996). Land denudation assessments and the related global sediment fluxes to oceans are mainly computed from interannual SPM fluxes and yields (Y^*); they show a wide range (Y^* from less than 10 to more than 10,000 t km^{-2} year^{-1}) (Milliman and Meade, 1983; Milliman and Syvistski, 1992; Ludwig and Probst, 1998). A preliminary assessment of current trends in the annual sediment loads and runoff of 145 major rivers of the world has recently been made from long-term records (>25 years) (Walling and Fang, 2003). It indicates that approximately 50% of sediment load records show evidence of statistically significant upward or downward trends, with the majority showing declining loads. Reservoir construction probably has the greatest influence on land–ocean sediment fluxes, but the influence of other factors resulting in increasing sediment load is not clear (Syvitski et al., 2005). Walling and Fang (2003) pointed out the difficulty of assembling such a database due to the lack of reliable sediment monitoring programmes in many areas of the world.

Global variability of daily SPM fluxes and their driving factors are also very difficult to address, mostly due to lack of representative databases assembled on a global scale (Meybeck et al., 2003), although there are a few national sediment monitoring programmes in the former USSR, the USA, China and Germany, and regional studies such as the UK Land–Ocean Interaction Study (LOIS) (Wilkinson et al., 1997; Philipps et al., 1999). Temporal variations of daily sediment fluxes at a given station cover an enormous range, commonly over 4–5 orders of magnitude (Syvitski and Morehead, 1999; Meybeck et al., 2003). The distribution of daily SPM fluxes is highly skewed: most sediment load is carried to oceans over a short period of time. The most variable fluxes are observed in river basins combining several erosivity factors, such as very high runoff during floods, steep relief, and occurrence of erodible materials.

River SPM is also an important carrier of organic carbon, nutrients, metals and persistent organic pollutants, and is often used to quantify their transport from land to ocean. The SPM concentration per litre of water is also a traditional indicator of water quality for many users. River SPM fluxes are therefore often requested in international surveys, at cross-border river stations and for shared water bodies (lakes, regional seas).

In many part of the world, evaluations of annual suspended sediment load are based on water quality monitoring programmes involving infrequent sampling. When using this type of data, the concentrations are either considered as constant around the sample or are reconstituted on the basis of continuous water discharge (Q) records and of SPM vs. Q relationships (rating curves). The reliability of load estimates by these methods in the context of sampling strategies have long been the subject of much discussion and controversy (Ongley et al., 1977; Walling and Webb, 1981, 1985; Thomas, 1985; Richards and Holloway, 1987; Olive and Rieger, 1988; Ferguson, 1986, 1987; De Vries and Klavers, 1994; Littelwood, 1995; Littlewood et al., 1998; Philipps et al., 1999; Holtschlag, 2001; Coynel et al., 2004). Two types of error characterizing each specific SPM sampling strategy (Walling and Webb, 1981) are commonly defined: bias (or systematic error) and imprecision (degree of dispersion). They are used to (i) assess the potential reliability of loads calculated using various procedures, (ii) demonstrate the influence of sampling strategies on flux reliability, or (iii) optimize sampling frequency or strategies (regular or stratified discharge-based) for a given precision target.

Only a few studies have compared the performance of suspended sediment load estimates from these infrequent samplings for rivers with contrasting characteristics (Ongley et al., 1977; Richards and Holloway, 1987; Philipps et al., 1999; Coynel et al., 2004). Philipps et al. (1999) applied 22 algorithms of load estimation to two rivers in the LOIS study area (3 monitoring stations, range of basins 500–3315 km^2): their results exhibited a number of consistent differences, related to the contrasting water discharge and suspended sediment transport regimes for rivers of different sizes. Basin size was found to be related to both the accuracy and precision of the individual load estimation procedures, with the performance of both measures declining with reduction in drainage area.

In this paper, a large database (507 station-years) of daily SPM concentration and discharge data was assembled, including rivers with contrasting SPM flux regimes from two continents (36 stations on river basins ranging from 600 km^2 to 600,000 km^2 in USA and Europe) in order to:

1. evaluate and compare errors (bias and imprecision) of annual SPM fluxes when using infrequent surveys;
2. test the possibility of linking these errors to indicators of daily sediment transport regime, such as those based on flux duration curves (Meybeck et al., 2003).

For simplicity, we took the discharge-weighted mean concentration method most commonly used by the scientific community and environmental management for a set of rivers with contrasting sediment transport regimes. The initial focus of the study was a selection of US rivers (27 stations), and the results were then validated on EU rivers (9 stations).

2. General methodology and database

General methodology is presented in Fig. 1. The preliminary step (step 0) involved selection of daily SPM flux stations for both US and EU rivers. Flux indicators at each station were determined in step 1A, and reference annual SPM fluxes in step 2A. Different types of survey based on the Monte Carlo technique were simulated in step 3A, and then the related estimated SPM fluxes were calculated (step 4A) for each year according to the discharge-weighted mean concentration method (Philipps et al., 1999, method M18). Errors (biases and imprecision) were calculated from the 50 replicates of the Monte Carlo sorting. These errors were then compared to the indicator set (step 6A) as determined in step 1A. In step 7A a set of curves was drawn up linking biases and imprecisions to the most efficient indicator (Ms_2 = percent of SPM fluxes carried in 2% of time). The European data set was then processed in a similar way (steps 2E–5E). The final steps were the prediction of errors for the EU data set (step 8) based on its Ms_2 indicators and the error curves, which were then compared (step 9) with those determined in step 5E.

2.1. Database selection (step 0)

Two databases on daily suspended sediment for a period of more than 3 years were selected: (i) the U.S. Geological Survey (USGS) database and (ii) a selection of European rivers. The daily USGS database was chosen because of the uniform data collection procedures used by the USGS (Horowitz, 2003). Moreover, recording periods are relatively long, up to 20 years and more, and are accessible on the internet (http://co.water.usgs.gov/sediment/). The database for European rivers is more heterogeneous: it has been assembled, mainly in France, from (i) a hydrological and geochemical observation network in the southwest of France (Coynel et al., 2004), (ii) the Seine River basin studied as part of the PIREN Seine

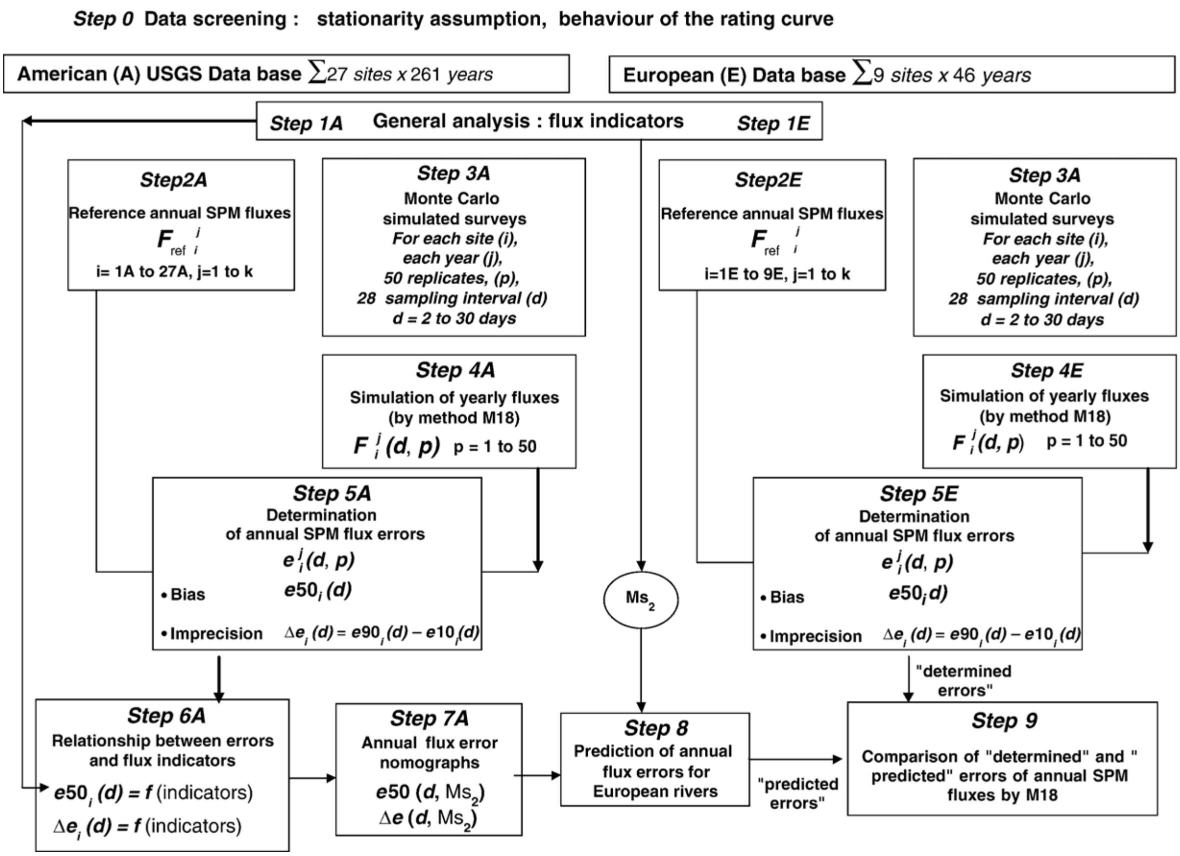

Fig. 1. Methodological steps (A = for US rivers; E = for European rivers).

Table 1
Flow and SPM transport regime characteristics for American rivers (1A to 27A)

No.	River and station	Code	Period	Area (km^2)	q^* ($l\ s^{-1}\ km^{-2}$)	Cs* ($mg\ l^{-1}$)	Cs_{99} ($mg\ l^{-1}$)	C_{90} ($mg\ l^{-1}$)	Cs_{50} ($mg\ l^{-1}$)	Y^* ($t\ year^{-1}\ km^{-2}$)	Ms_2 (%)	Ts_{50} (%)	Vw_2 (%)	Tw_{50} (%)
1A	Tradewater @ Olney, KY	trd	1967–1972	660	14.6	40	140	40	6	18	34.6	3.7	17.7	8.5
2A	Little Black @ Success, MO	lbl	1981–1985	999	26.8	67	256	107	36	27	38.4	4.4	19.5	8.6
3A	Cuyahoga @ Old portage, OH	cuy	1973–1980	1046	14.3	65	371	80	17	33	42.4	3.1	10.1	19.7
4A	Mad @ Arcata, CA	mad	1967–1973	1256	34.8	1598	3894	730	23	1904	60.5	1.3	22.4	7.8
5A	Siuslaw @ Mapleton, OR	sui	1968–1974	1522	31.4	71	195	43	6	145	63.0	1.0	16.8	10.5
6A	Grand @ Painesville, OH	grd	1979–1990	1773	17.1	141	461	105	19	80	50.0	2.0	16.7	11.0
7A	Upper Iowa @ Dorchester, IA	uio	1976–1980	1993	6.5	712	2970	310	38	160	74.5	0.7	18.3	15.1
8A	Coal @ Alum Creek, AZ	coal	1975–1978	2162	17.2	376	872	244	31	215	60.6	1.2	20.5	10.3
9A	Fisher @ Libby, MT	fis	1968–1975	2169	7.4	147	541	116	9	41	56.5	1.3	12.6	12.6
10A	River Raisin @ Monroe, MI	rai	1967–1971	2698	7.6	89	333	75	26	23	48.7	2.1	14.7	13.3
11A	Green @ Mudfordville, KY	gre	1967–1977	4331	20.2	148	700	168	38	98	36.0	3.9	13.7	15.8
12A	Dan @ Paces, VA	dan	1969–1980	6602	12.9	189	716	200	60	84	47.3	2.2	14.5	21.0
13A	Trinity @ Hooper, CA	tri	1970–1978	7386	18.2	731	1877	470	20	506	62.0	1.1	20.5	10.5
14A	Iowa @ Iowa city, IA	iow1	1969–1986	8468	8.2	159	864	192	55	40	32.8	5.1	8.2	19.3
15A	Feather @ Gridley, CA	fea	1965–1988	9517	22.1	35	95	20	8	15	63.2	0.8	17.5	14.7
16A	Des moines @ Saylorville, IA	dmo	1969–1975	15122	5.4	453	1800	664	150	153	22.7	7.2	12.4	13.7
17A	Delaware @ Trenton, NJ	del	1968–1981	17553	20.0	57	290	48	9	38	54.8	1.5	9.9	20.6
18A	Iowa @ Wappelo, IA	iow2	1979–1988	32358	9.3	256	1390	412	122	76	25.4	7.3	8.7	20.9
19A	Mississippi @ Anoka, MN	msp1	1976–1994	49448	5.2	28	97	42	14	5	22.8	7.8	8.6	22.7
20A	Tennessee @ Chattawooga, TN	ten1	1935–1941	55402	15.5	154	671	226	53	85	39.0	3.4	11.0	20.7
21A	Sacramento @ Freeport, CA	sac	1980–1988	65403	10.2	75	336	112	29	26	22.5	7.8	7.2	20.8
22A	Tennessee @ Savannah, TN	ten3	1936–1941	85796	15.6	79	282	125	32	42	27.7	5.5	10.3	18.6
23A	Tennessee @ Pacudah, KY	ten4	1936–1941	104073	15.2	117	490	188	48	60	21.0	7.3	10.1	18.4
24A	Brazos @ Richmond, TX	brz	1967–1985	116518	1.7	1318	4100	1620	220	131	36.5	3.5	15.2	12.4
25A	Missouri @ Culbertson, MT	mis	1972–1985	237030	1.5	425	1834	755	239	21	15.5	10.4	6.2	33.9
26A	Mississippi @ St Louis, MO	msp4	1961–1988	251121	20.1	687	2300	1010	318	447	15.8	11.5	6.2	27.5
27A	Colombia @ Vancouver, WA	clb	1964–1968	623920	9.2	51	318	84	14	25	29.4	5.4	6.3	27.5

research programme (Meybeck et al., 2003), and (iii) from specific environmental monitoring programmes on the Isère (Poirel, 1998) and the Rhine at Maxau (Germany) (De Vries and Klavers, 1994; Asselman, 2000).

First, data was studied from 51 USGS stations exceeding 600 km^2 of drainage area for which continuous daily sediment transport rates and discharge records going back more than 5 years were available. From this sample of SPM surveys, only the rivers with long-term runoff (q* in l s^{-1} km^{-2}) characteristics similar to those found in Europe were retained for further analysis: drier catchments such as the Walla Walla, Pecos and Arkansas rivers, or those located in the Colorado Plateau were excluded. In addition, considerable effort was made to eliminate several disturbed rivers from the analysis. The Cs vs. q relationships (so-called rating curves) were systematically constructed. The obvious influence of reservoirs was then removed by eliminating all stations where rating curves were truncated for minimum and maximum q. Graphical investigation of temporal series of daily SPM fluxes was also used to check data stationarity. Some USGS data originated from pre-damming surveys and are very old, as for the Tennessee (1935–1941, Table 1).

After eliminating streams with obvious artificial disturbance, 27 US stations remained (Table 1). The survey periods ranged from 4 years (the River Coal at Alum Creek, AZ) to 24 years (the River Feather at Gridley, CA) with a median of 8 years. An exception was made for the Mississippi at St. Louis and the Missouri at Culbertson which are artificially controlled by many dams; their data sets were included because of the size of the drainage area and the length of the available records. Several stations are also nested in the US data set (e.g. 14A, 18A, 19A, 25A, 26A, 20A, 22A, 23A, Table 1) which illustrates the difficulty of selecting independent stations with (i) long term daily records, (ii) minor influence of dams, (iii) a broad range of hydrological regimes.

Secondly, 8 French rivers (3 years of records on average) and the Rhine (20 years of records) at Maxau in Germany were chosen with a similar SPM regime range to the US data set (Y* between 9 and 470 t km^{-2} $year^{-1}$) (Table 2).

For both data sets, a minimum drainage area of about 1000 km^2 was generally accepted; in these basins the daily SPM reported in databases are considered to be fully representative of the whole 24 h period, i.e. sub-daily variations are not taken into consideration. The Tradewater River (ky) (A=660 km^2) and the Little Black (A=999 km^2) were the only catchments under 1000 km^2. The use of daily SPM for such basins is an approximation, because even at 1000 km^2 there can be a variation in SPM over 24 h during flood events. For smaller basin areas, the SPM variability at a sub-daily scale cannot be ruled out (Coynel et al., 2004).

The US data set was chosen for this study because it is much larger and more standardized (number of stations, sampling procedures, and length of records) than the EU data set which consists of eight French rivers plus the Rhine. The two data sets present broadly similar features of climate, altitude and relief.

Table 2
Flow and SPM transport regime characteristics for European rivers (1E to 9E)

No.	River and station	Code	Period	Area (km^2)	q* (l s^{-1} km^{-2})	Cs* (mg l^{-1})	Cs_{99} (mg l^{-1})	C_{90} (mg l^{-1})	Cs_{50} (mg l^{-1})	Y* (t $year^{-1}$ km^{-2})	Ms_2 (%)	Ts_{50} (%)	Vw_2 (%)	Tw_{50} (%)
1E	Gaves @ Peyrehorade, France	gve	1999–2002	5030	31.9	50	248	52	7	75	49.3	2.1	9.2	24.3
2E	Isere @ St Martin d'Heres, France	ise	1994–1999	5700	29.8	501	4244	514	99	471	50.4	1.9	5.5	32.5
3E	Isle @ Guîtres, France	isl	1999–2002	6568	10.0	30	102	38	14	14	23.6	7.2	12.2	17.5
4E	Charente @ Taillebourg, France	chr	1999–2002	7600	9.0	90	269	141	72	38	18.4	12.3	10.5	17.7
5E	Adour @ Port de Lanne, France	adr	1999–2002	8900	14.8	98	554	131	37	68	26.8	6.6	11.1	16.7
6E	Dordogne @ Pessac/ Dordogne, France	dor	1999–2002	14925	26.5	46	221	56	9	58	34.5	3.8	8.4	21.6
7E	Rhin @ Maxau, Ge	rhi	1973–1993	50196	25.7	29	97	42	20	23	15.8	16.6	4.8	34.5
8E	Garonne @ La Reole, France	gar	1999–2002	51500	11.2	71	408	105	14	38	35.0	4.2	8.2	23.4
9E	Seine @ Poses, France	sei	1983–1985	65000	7.39	38	121	50	21	9	15.7	11.5	6.6	27.1

2.2. Data treatment (steps 1–9, Fig. 1)

2.2.1. Step 1A: SPM flux indicators

They resulted from a general data analysis of daily suspended particulate matter concentration (Cs) and their related annual yield (*Y*) for the American (step 1A) and European rivers (step 1E). The representativeness of selected data for different SPM transport regimes was assessed from metrics of Cs level and flux variability as proposed by Meybeck et al. (2003):

- q^*, average specific runoff (l s^{-1} km^{-2});
- Y^*, sediment yield, inter-annual mean value (t km^{-2} $year^{-1}$ or kg km^{-2} day^{-1});
- Cs*, suspended sediment concentration, inter-annual mean discharge-weighted value (mg l^{-1});
- Cs_{99}, Cs_{50}, 99 and 50 percentiles of suspended sediment concentration (mg l^{-1}) (whole period of record);
- Vw_2, Ms_2, percentages of water volume (Vw_2) and sediment load (Ms_2) discharged in 2% of time; both Vw_2 and Ms_2 are here determined on the whole record period;
- Tw_{50}, Ts_{50}, percentages of time needed to carry 50% of the water volume (Tw_{50}) and 50% of the sediment load (Ts_{50}) for the whole period of record.

2.2.2. Step 2A: Reference annual SPM fluxes

Annual SPM fluxes at all stations were calculated by summing the series of daily fluxes for each year. These values were assumed to represent the most accurate available estimates and were considered as annual reference fluxes (Eq. (1)).

$$F_{\mathrm{ref}}{}_i^j = \sum_{l}^{365} (Q\mathrm{Cs}0.0864) \tag{1}$$

where $F_{\mathrm{ref}\,i}{}^j$ = annual reference SPM fluxes (t $year^{-1}$) for j year at station i,

- Q = daily water discharge (m^3 s^{-1}),
- Cs = daily SPM concentration (mg l^{-1}),
- i = station rank (Table 1) (i = 1A to 27A for the USGS database and i = 1E to 9E for the European database),
- j = survey year for station i, j = 1 to k, with k = total length of survey years at station i.

2.2.3. Step 3A: Monte Carlo simulated surveys

In order to test the effect of sampling frequency on SPM flux estimates, 28 different sampling intervals (from 2 to 30 days) were simulated for all stations (A and E) using Monte Carlo techniques. This interval was not absolutely regular in order to simulate actual SPM sampling strategies used in current water quality surveys (pseudo-equidistant sampling, e.g. no sampling on Sundays). For example, for monthly sampling, the first day of sampling was generated in the first month by a uniform law. Then, for the following months, the sampling interval was generated by a normal law (mean 30 days, standard deviation 4 days) resulting in simulated intervals ranging from 18 to 41 days. For the average sampling interval of 2 days (standard deviation of 2 days) the simulated intervals ranged from 1 to 4 days. 50 replicates (p = 1–50) of m samples (Cs_m, Q_m) were simulated for each sampling frequency.

2.2.4. Step 4A: Estimation of annual fluxes by method M18

Annual SPM fluxes were calculated by the most frequently used method for research or environmental management studies, the discharge-weighted mean concentration method (Littlewood, 1995; Philipps et al., 1999, method M18). In this way, for a given station and survey year, (i, j), a given sampling interval, d, and a given replicate, p, the yearly flux $F_i^j(d,p)$ (t $year^{-1}$) could be estimated through the product of discharge-weighted mean concentration and mean annual discharge by Eq. (2):

$$F_i^j(d,p,) = 0.0864 \frac{\sum_{m=1}^{m(d,p)} \mathrm{Cs}_{mi}^j Q_{mi}^j}{\sum_{m=1}^{m=f(d,p)} Q_{mi}^j} Q_i^j \tag{2}$$

- Cs_{mi}^j (mg l^{-1}) and Q_{mi}^j (m^3 s^{-1}) are suspended sediment concentration and discharge for the sample rank m, for j year at station i.
- m is the number of samples per year according to the average sampling interval (d) and the replicate (p); for instance for a monthly sampling, m varies from 10 to 14 with an average of 12.
- Q_i^j = mean annual discharge of j year at station i, evaluated from daily discharge data.

2.2.5. Step 5A: Determination of SPM flux errors

The annual SPM flux errors, $e_i^j(d, p)$ for each j year and sampling interval (d) were evaluated for each replicate (p), using Eq. (3):

$$e_i^j(d,p) = 100\left(\frac{F_i^j(d,p) - F_{\mathrm{ref}\ i}^j}{F_{\mathrm{ref}\ i}^j}\right) \tag{3}$$

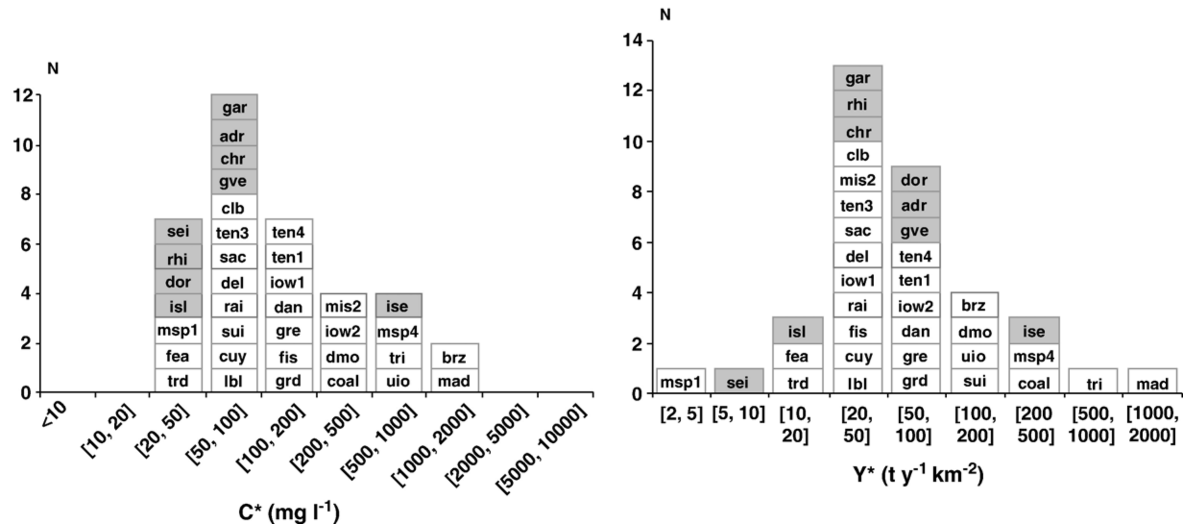

Fig. 2. Distribution of discharge-weighted mean concentration C^* (mg l^{-1}) and specific flux Y^*(t year^{-1} km^{-2}) in databases (US stations, white boxes; European stations, grey boxes). For river codes, see Tables 1 and 2.

For one station and a specific sampling interval (d), the distribution of these relative errors for all years and replicates, $e_i^j(d, p)$, provided a measure of bias and imprecision. Bias indicates the degree of systematic errors while imprecision reflects the random error. The median of the relative errors, $e50_i(d)$, was taken as a measure of bias. The imprecision of the estimation method is generally considered as the 2-standard deviation interval around the mean values of the errors (95% confidence interval for a normal distribution) (Moatar and Meybeck, 2005). In the case of SPM flux estimates, the distribution of relative errors is highly skewed, most of the flux being underestimated. Thus, imprecision is considered as the difference between the upper and lower deciles of the relative errors ($e90_i(d)$ and $e10_i(d)$) for the set of j years and p replicates. Bias and imprecision of the estimation method M18 were analysed for each station in relation to sampling frequency.

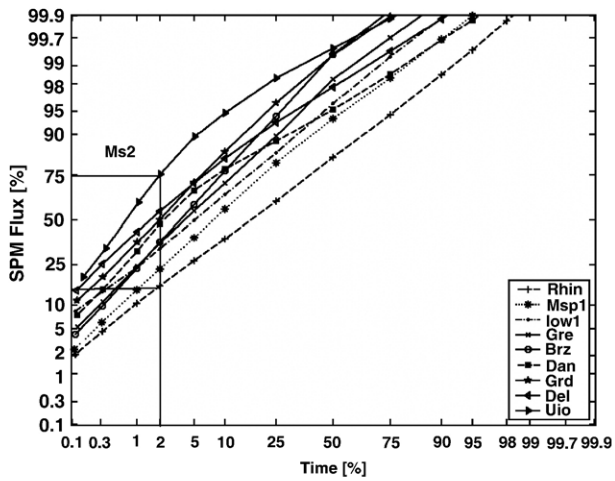

Fig. 3. Daily SPM flux duration vs. time duration for rivers with long-term records (>10 years, except the Upper Iowa River, 5 years), which present the greatest Ms_2 in our data base. Codes: the Rhine at Maxau (Rhi, 7E), the Mississippi at Anoka (Msp1, 19A), the Iowa at Iowa City (Iow1, 14A), the Green at Munfordville (Gre, 11A), the Brazos at Richmond (Brz, 24A), the Dan at Paces (Dan, 12A), the Grand at Painesville (Grd, 6A), the Delaware at Trenton (Del, 17A), the Upper Iowa at Dorchester (Uio, 7A). Duration curve metrics are expressed with both axes on a normal probability scale. The Ms_2 duration indicator corresponds to 2% of time.

2.2.6. Step 6A: Relationship between errors and flux indicators

A regression analysis was carried out between biases and imprecisions of the M18 estimation method and the metrics of flux variability (Ms_2, Ts_{50}) or discharge variability (Vw_2, Tw_{50}) for each station and different sampling intervals.

2.2.7. Step 7A: Flux error nomographs constructed from the US river data set

The performance of regressions (r^2) was tested to explain flux errors from these metrics. From all the tested metrics, the Ms_2 indicator showed the best correlation with flux errors and was retained for the construction of an error nomograph for annual flux biases and imprecisions.

2.2.8. Steps 1E–5E: Data processing for the European data set

The same steps were then followed to process the European data set.

2.2.9. Step 8: Prediction of flux errors for the European set

The Ms2 indicator determined from the European data at step 1E was used to predict biases and imprecision of annual flux estimates from the error nomograph constructed from the US rivers data.

2.2.10. Step 9: Validation of error nomographs with European data

The SPM flux errors predicted for the European rivers at step 8 were compared with those observed from our simulated surveys at step 5E. The objective of this step

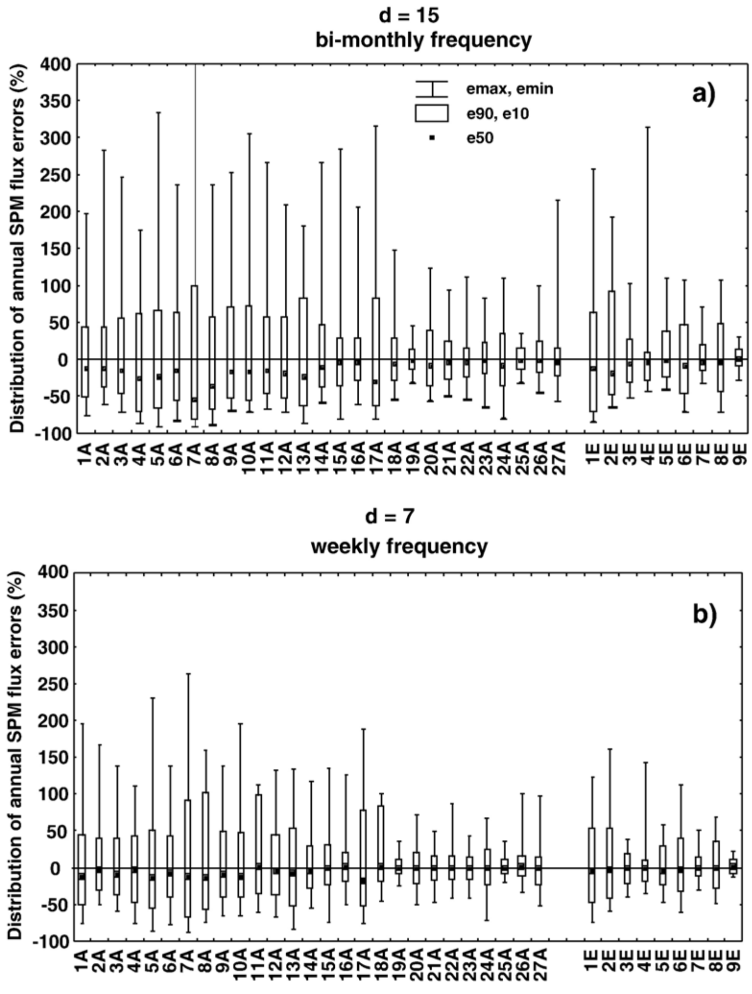

Fig. 4. Distribution of annual SPM flux estimates with (a) bimonthly sampling frequency, (b) weekly sampling. Rivers are sorted in increasing order of basin size: first set US rivers (1A to 27A), second set European rivers (1E to 9E).

was therefore to validate the error nomograph drawn up at step 8.

3. Results

3.1. General representativity of the temperate rivers data set

The data set represents most of the natural conditions encountered in the temperate zone (e.g. runoff and SPM variability) and encompasses a large proportion of the global scale range observed for catchments exceeding 1000 km^2, with the exception of very dry, very turbid and very clear rivers (e.g. lake outlets). Twenty-seven USGS (Table 1) and 9 European (Table 2) stations were selected. These stations exhibit a broad range of basin sizes, discharge and SPM characteristics as well as discharge-weighted mean concentrations (C*) and yields (Y*) (Fig. 2). Basin drainage areas range between 3 orders of magnitude (660–600,000 km^2). Specific discharge, q*, is representative of the range observed in the dry to humid temperate zone (1.3–35 l s^{-1} km^{-2} for US rivers, 7–32 l s^{-1} km^{-2} for European rivers). Cs* concentrations range from 28 to 1600 mg l^{-1} for US stations, and from 29 to 500 mg l^{-1} for European stations, with only very low and very high ranges missing (<20 mg l^{-1} and>2000 mg l^{-1}) from the global classification proposed by Meybeck et al. (2003) (Fig. 2a). The upper percentile of SPM (Cs_{99}) is highly indicative of SPM variability. Some very high concentrations are found in the data sets: around 4 g l^{-1} for the Mad and the Brazos (American rivers) and the Isère (a French river). Also, specific SPM fluxes (Y*) cover most of the global range (5–2000 t year^{-1} km^{-2}).

The four indicators of daily SPM flux variability (Ms_2, Ts_{50}, Vw_2, Tw_{50}), based on duration curves and calculated for the database, also cover most of the global range. Duration curves give the proportion of sediment flux discharged in a given proportion of elapsed time, calculated from the highest fluxes. Fig. 3a presents the duration curves for rivers with long-term records (>10 years) using percent of SPM fluxes vs. percent of time, with both axes on a normal probability scale. This double Henry law representation enables these curves to be linearised (Meybeck et al., 2003). In 2% of time (approx. 7 days), rivers with very variable flux regimes carry between 50% and 75% of the annual flux (Ms_2 between 50% and 75% for the Mad, Siuslaw, Grand, Upper Iowa, Coal, Fisher, Trinity, Feather, and Isère), whereas rivers with regular flux regimes, such as the Rhine and the Mississipi, carry only 15% of annual flux. Ms_2 for documented rivers in this database ranges from 15% to 75%. This database, which differs from that used

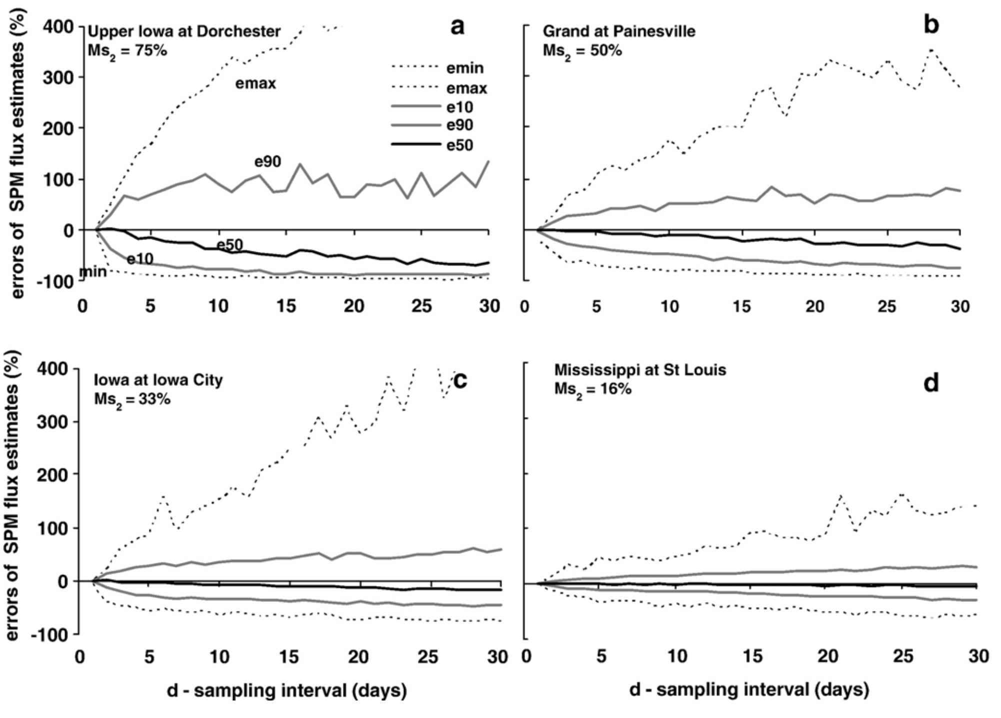

Fig. 5. Indicative growth curves of imprecision (Littlewood et al., 1998) of annual SPM flux estimates with sampling intervals (d) for 4 rivers with contrasting SPM transport regimes; (a) the Upper Iowa at Dorchester, IA (Ms_2 = 75%), (b) the Grand at Painesville, OH (Ms_2 = 50%), (c) the Iowa at Iowa City, IA (Ms_2 = 33%), (d) the Mississippi at St. Louis, MO (Ms_2 = 16%). Flux estimates by Method M18 (Philipps et al., 1999).

by Meybeck et al. (2003) except for two European rivers (7E and 9E, Table 1), is representative of the Ms_2 distribution for catchments between 600 and 600,000 km^2. Ms_2 exceeds 75% at only 3 stations in the database selected by Meybeck et al. (2003), 2 stations on the Piray in Bolivia (Ms_2 = 80%) and the Walla Walla (Oregon) (Ms_2 = 93%). The present database also contains no rivers with very regular SPM transport regimes (Ms_2 between 5% and 15%), such as some lake-influenced basins (e.g. Lake Geneva outlet) or for rivers fed by phreatic aquifers (the Somme, France). In such catchments, flux estimate errors are the lowest and their absence in the database set does not affect our conclusions. The percent of time necessary to carry 50% of SPM fluxes (Ts_{50}) ranges from less than 1% to 20% of time (Tables 1 and 2). These two indicators cover a very wide range of global variability for basins between 600 and 600,000 km^2.

3.2. *Performance of method M18 for bimonthly and weekly surveys in US and European rivers*

Different annual load estimates were obtained by applying the same calculation method to the same station, taking 50 different bimonthly and weekly sampling sub-sets for each documented year representing the most common frequencies in current monitoring programmes. Fig. 4 shows the dispersion of relative errors for each river studied and all recorded years, using a box-whisker plot, representing median (e50), lower deciles (e10) and upper deciles (e90) and the maximum and minimum extreme errors. Rivers are sorted in increasing order of basin size: first set US rivers (1A to 27A), second set European rivers (1E to 9E).

At these sampling frequencies, the reliability of load estimates varies considerably. For most of the rivers, annual fluxes are underestimated, medians of sorted fluxes being systematically lower than the reference fluxes. Due to the episodic nature of suspended matter transport, which is dominated by flood events, these events are easily missed with bimonthly equidistant sampling, resulting in an underestimation of the annual load. The skewed distribution of errors reflects the combination of a high probability of underestimation and a low probability of a large overestimation of the annual load.

The maximum inter-annual biases were attained for the Upper Iowa River: −55% and −24% for a 15-day and 7-day sampling interval respectively. For a few

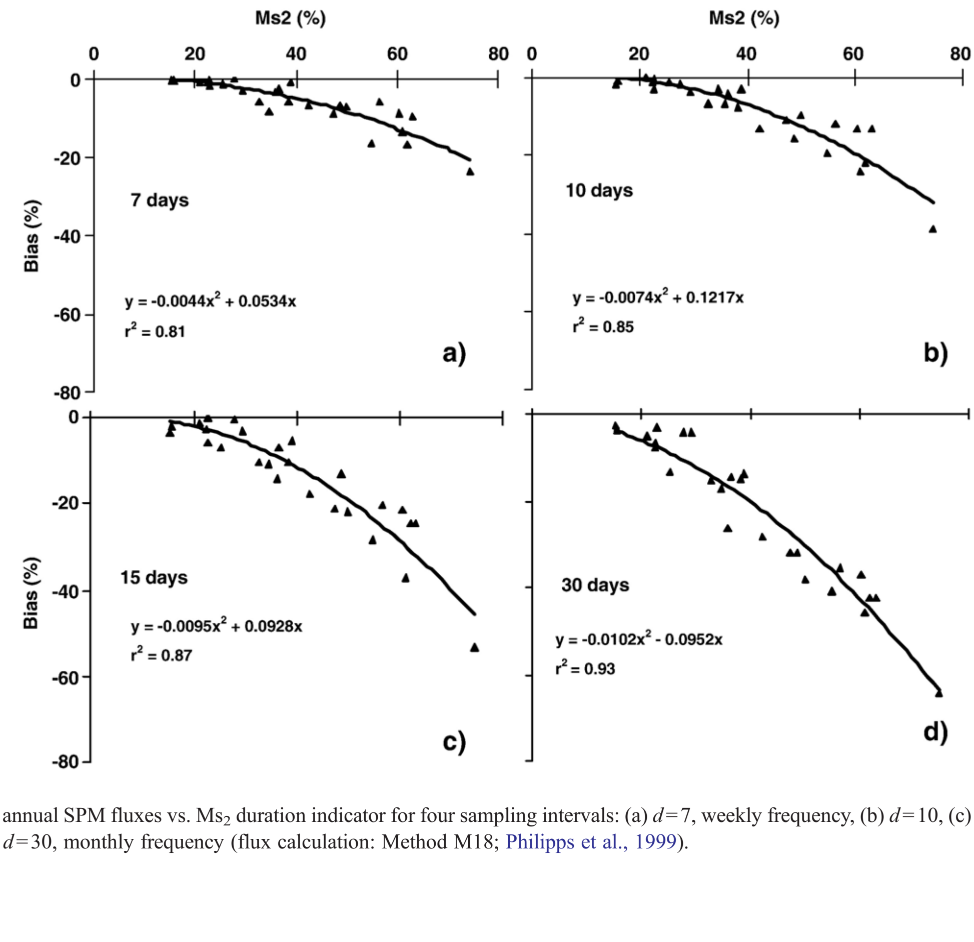

Fig. 6. Bias of annual SPM fluxes vs. Ms_2 duration indicator for four sampling intervals: (a) d = 7, weekly frequency, (b) d = 10, (c) d = 15, bimonthly frequency, (d) d = 30, monthly frequency (flux calculation: Method M18; Philipps et al., 1999).

rivers, the inter-annual bias was negligible (less than 2% for the Mississippi, the Missouri and the Seine).

If a deviation of simulated flux estimates from the reference fluxes lower than ±20% is taken as acceptable, the results presented in Fig. 4a and b show considerable unreliability. When looking at the whole range of flux estimates, bimonthly and weekly sampling are not appropriate to obtain reliable annual SPM flux estimates for any of the rivers studied (Max > 20% and Min < −20%). However, maximum errors represent "worst case" scenarios and could be considered as extreme results. For rivers with low Ms_2, such as the Missouri, Mississippi, Rhine and Seine, a 15-day sampling interval is sufficient to monitor fluxes ±20%. For a weekly-sampling interval, errors for the Tennessee and Sacramento rivers also come within this range.

The imprecision of estimates varies substantially and is correlated with bias. Estimates for rivers for which annual SPM flux estimates are biased are also fairly imprecise. The basin size also exerts some influence, underestimation and lack of precision seeming to be greater for smaller than for larger rivers. Coefficients of determination (r^2) between the two measures of errors (bias and imprecision) and the logarithm of basin drainage area ranged between 0.31 (7-day sampling interval) and 0.53 (15-day sampling interval) for bias, and between 0.45 (7-day sampling interval) and 0.56 (15-day sampling interval) for imprecision.

3.3. Influence of sampling interval for selected rivers (Upper Iowa, Iowa, Grand and Mississippi)

The influence of the sampling interval can be seen in Fig. 5 for four rivers which present a wide range of Ms_2. The indicative growth curves of imprecision, as set up by Littlewood et al. (1998), exhibit a number of consistent differences, which can be related to the contrasting discharge and suspended sediment transport regime of the four rivers. Bias and imprecision increase for rivers with high Ms_2, such as the Upper Iowa (Ms_2 = 75%) at Dorchester (IA) and the Grand (Ms_2 = 50%) at Painesville (OH). For these rivers, the discharge-weighted mean concentration method (Method M18, Philipps et al., 1999) allows annual SPM fluxes to be estimated with less than 20% deviation from the reference values, but only when the sampling interval is less than 2 days for the Grand and less than one day for the Upper Iowa. To achieve the same reliability, the

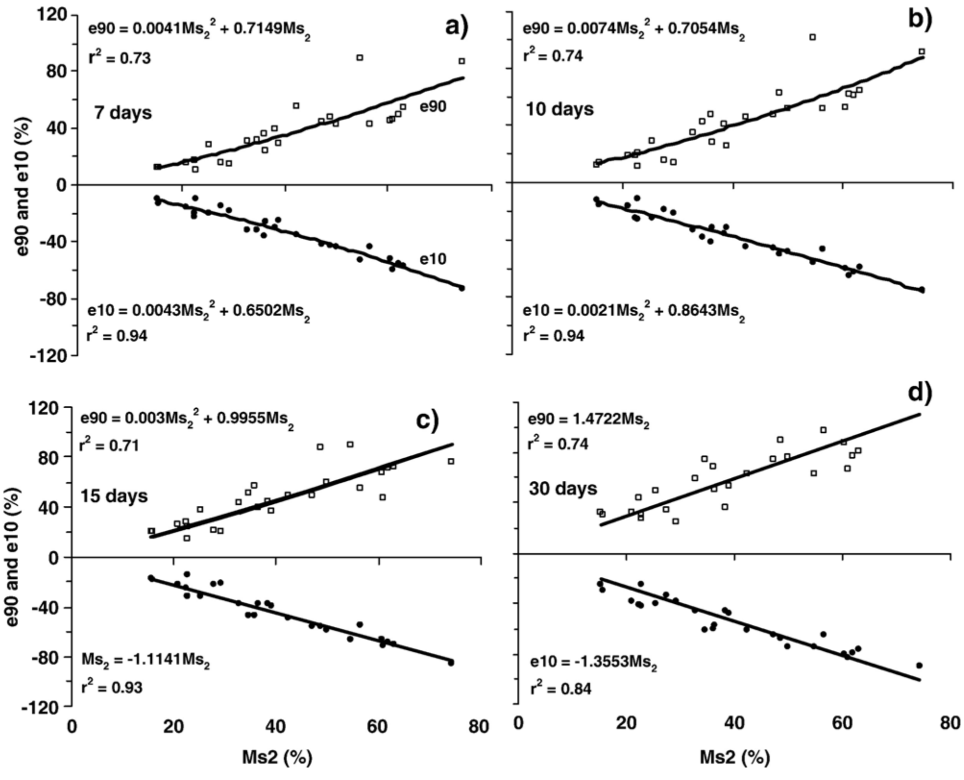

Fig. 7. Upper (e90) and lower deciles (e10) of annual SPM flux errors vs. Ms_2 duration indicator for four sampling intervals: (a) d=7, weekly frequency, (b) d=10, (c) d=15, bimonthly frequency, (d) d=30, monthly frequency (flux calculation: Method M18, Philipps et al., 1999).

Table 3
Error nomograph parameters for different sampling intervals ($y=ax^2+bx$, where $x=Ms_2$ and y=e50, e10, e90, imprecision=e90−e10)

Interval (days)	Bias (e50)			e10			e90			Imprecision (%)		
	a	b	r^2	*a*	b	r^2	*a*	b	r^2	*a*	b	r^2
30	−0.010	−0.095	0.93	0.000	−1.36	0.84	0.000	1.50	0.74	0	2.83	0.84
25	−0.010	0.005	0.90	0.000	−1.29	0.89	0.000	1.40	0.76	0	2.70	0.86
20	−0.010	0.041	0.92	0.000	−1.22	0.92	0.000	1.30	0.67	0	2.38	0.86
15	−0.010	0.093	0.87	0.000	−1.11	0.93	0.003	1.00	0.71	0	2.27	0.86
10	−0.007	0.122	0.85	−0.002	−0.86	0.94	0.005	0.78	0.77	0.007	1.64	0.88
7	−0.004	0.053	0.81	−0.004	−0.65	0.94	0.004	0.71	0.73	0.009	1.37	0.87
5	−0.002	0.029	0.63	−0.005	−0.50	0.93	0.004	0.56	0.77	0.008	1.07	0.87
3	−0.001	0.000	0.31	−0.005	−0.30	0.88	0.006	0.24	0.82	0.011	0.54	0.86

Iowa River at Iowa City (IA) must be sampled every 3 days. The Mississippi (Ms=16%) can be sampled every 15 days, bimonthly sampling being sufficient to achieve the same reliability.

3.4. Relationship between flux bias and the Ms_2 duration indicator

Sets of annual flux estimate biases obtained from Monte-Carlo simulations were constructed for all sampling intervals tested (from 2 to 30 days). Fig. 6 presents the relationships between biases and Ms_2 duration indicators for four sampling intervals (7 days, 10 days, 15 days and 30 days). Linear and polynomial regression functions (2nd degree), with and without a constant term, were tested to fit the data. Polynomial functions provide a better fit between biases of annual SPM flux estimates and the Ms_2 indicator than with the linear regression. For example, for bimonthly and weekly sampling frequencies, the r^2 determination coefficients for linear regression are only 0.64 and 0.58, respectively, whereas r^2 for polynomial functions

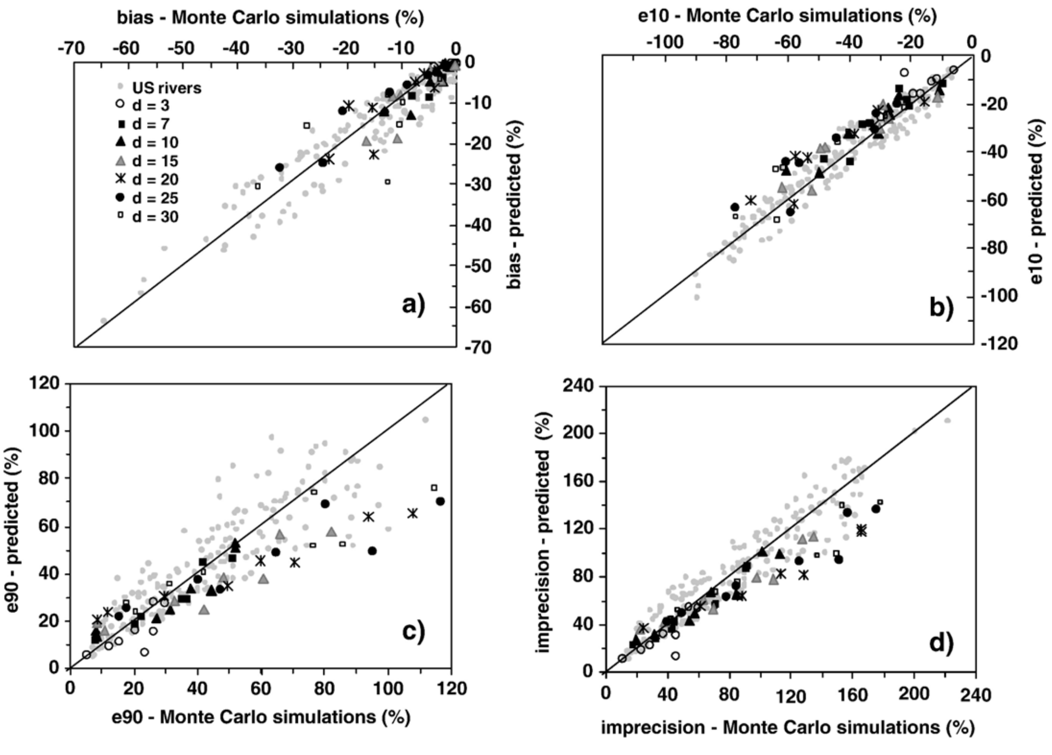

Fig. 8. Comparison between SPM flux errors predicted by the Ms_2-based error nomograph constructed from the US data set and those simulated by the Monte Carlo technique from the European data set: (a) bias=e50, (b) e10, (c) e90, (d) imprecision (e90−e10). Different sampling intervals are considered: d=3, 7, 10, 15, 20, 25, 30 days.

range between 0.81 and 0.87. For a given sampling frequency, flux estimate biases increase with the Ms_2. For low sampling frequencies (lower than bimonthly) the bias can be considered to increase linearly for $Ms_2 < 40\%$, increasing more sharply above this value.

3.5. Relationship between flux imprecision and the Ms_2 duration indicator

The influence of the SPM transport regime, described by the Ms_2 indicator, on the imprecision of SPM fluxes, defined by the upper and lower deciles of the annual flux errors (Method M18) can be seen in Fig. 7 for four different sampling intervals ($d=7$, $d=10$, $d=15$, $d=30$). Polynomial regression functions (2nd degree) and linear regressions (without a constant term) were fitted for both the upper and lower deciles of errors. Polynomial functions fit the data better for lower sampling intervals ($d=3$ to $d=15$; Fig. 7a–c), while for more than 15 days ($d>15$), the parameter of power term tends towards zero. Consequently, for monthly sampling (Fig 7d), linear regression gives better results in terms of r^2. Fig. 7a–d also show that under-estimations are better predicted (r^2 for e10 range from 0.84 to 0.94) than over-estimations (r^2 for e90 range from 0.67 to 0.82). The set of regressions presented in Figs. 6 and 7 is used as a nomograph to determine the errors from the Ms_2 duration metric.

3.6. Validation of Ms_2-based error nomographs for the European rivers set

The curves (see Figs. 6 and 7) were evaluated as 2nd order polynomial functions (without constant): $y=ax^2+bx$, where $x=Ms_2$ and $y=$e50 (bias), e10 (lower deciles), e90 (upper deciles), and $\Delta e=$e90−e10 (imprecision). For high sampling intervals, parameters "a" are zero, errors being linear functions of Ms_2 (Table 3). The parameters of the error curves for given sampling-intervals are presented in Table 3.

These nomographs were used for the European rivers set to predict annual SPM flux uncertainties from the Ms_2 indicator (Table 2). The errors predicted by Ms_2 compared to errors obtained from Monte Carlo Simulations

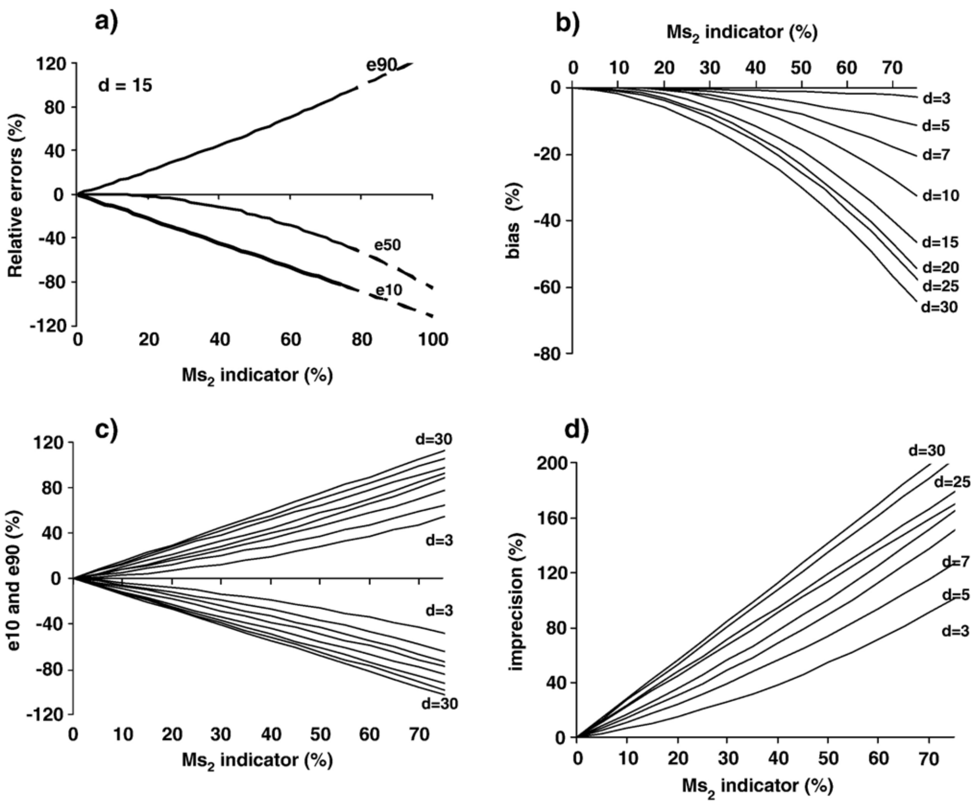

Fig. 9. Error nomographs for annual SPM fluxes: (a) Bias (e50) and imprecision (e10, e90) for bimonthly survey, (b) bias for different sampling intervals ($d=3$, 5, 7, 10, 15, 20, 25, 30 days), (c) under- and over-estimation intervals (e10 and e90), (d) imprecision (e90−e10) of annual SPM fluxes (flux calculation: Method M18, Philipps et al., 1999).

(Fig. 8a–d) show similar performances to the US rivers set, used as calibration.

For example, for bimonthly sampling, standard deviations of residuals, i.e. the difference between biases determined by Monte Carlo simulations and predicted from Ms_2 curves, show similar values: 4.7% for US Rivers (3.4% when taking only rivers with $Ms_2 < 50\%$), and 3.8% for European rivers.

However, the scatter plot for the upper deciles of relative errors (e90) and imprecision ($\Delta e = e90 - e10$) shows a slight trend as uncertainty increases. Predicted errors for the European rivers are systematically inferior to the values determined by the Monte Carlo simulations. This could be due to the nature of the European database, as the time series for the rivers of South West France only cover 3 years, and the Ms_2 evaluated by these time series could be under-estimated.

3.7. Using the Ms_2-based error nomograph to optimize SPM sampling frequency

Error nomographs for different sampling intervals are presented in Fig. 9 for all ranges of documented Ms_2 in our database ($Ms_2 < 75\%$).

These nomographs can be used principally in two ways. Firstly, they can indicate the associated threshold error values, when infrequent long-term SPM concentration data have been obtained by monitoring networks such as those used for water quality surveys. Fig. 9a represents an imprecision and bias nomograph for a bimonthly sampling interval. For example, for a river characterized by an $Ms_2 = 30\%$, the discharge weighted-mean concentration method (M18) produces annual flux errors between −35% and 32% (in 80% of 50 simulated sub-sets), but 50% of estimates are lower than −9%. Secondly, they can be used to predict the sampling effort required to achieve a specified level of precision for a case study. For example, to obtain estimates within 20% of the true load and a bias less than 1% or 2%, these nomographs can indicate the required frequency, provided the Ms_2 is known (Fig. 10):

- sampling-interval lower than 3 days for rivers with Ms_2 greater than 40%,
- sampling-interval between 3 and 5 days for rivers with Ms_2 between 30% and 40%,
- sampling-interval between 12 and 5 days for rivers with Ms_2 between 20% and 30%,
- sampling-interval between 20 and 12 days for rivers with Ms_2 between 15% and 20%.

4. Discussion

The duration indicator (Ms_2) used here is the basis of estimating the flux errors. However it requires a daily survey over a long period, 3–10 years depending on stations. When larger data sets are available, Ms_2 will probably be estimated from other more readily available river basin characteristics, such as basin size, river water regimes, SPM vs. q relationship. Some of these relationships have been tested here.

4.1. Ms_2 versus Vw_2

In an earlier paper on SPM flux duration on a global scale, Meybeck et al. (2003) showed that the proportion

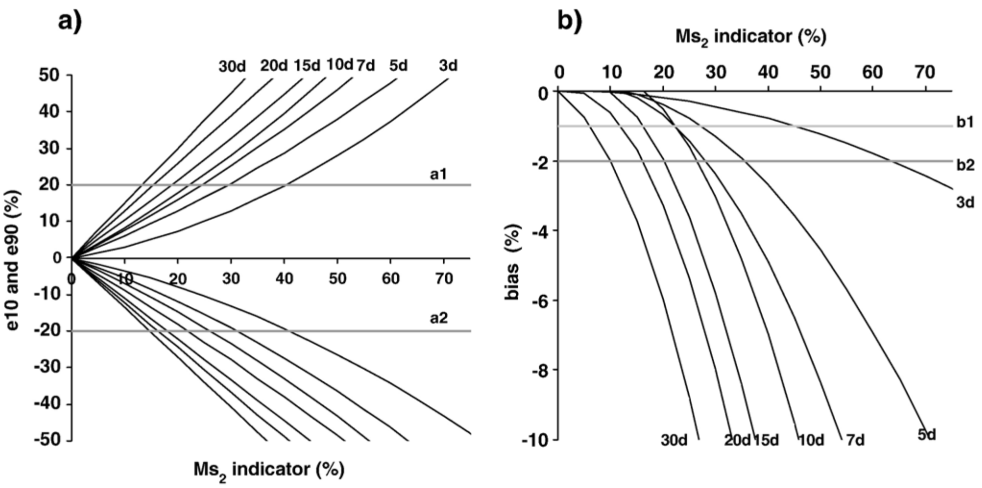

Fig. 10. Sampling-interval required to achieve certain acceptable errors as a function of Ms_2 duration indicator: (a) Imprecision; target a1–a2 (±20%); (b) Bias; targets: b1 (bias < 1%), b2 (bias < 2%).

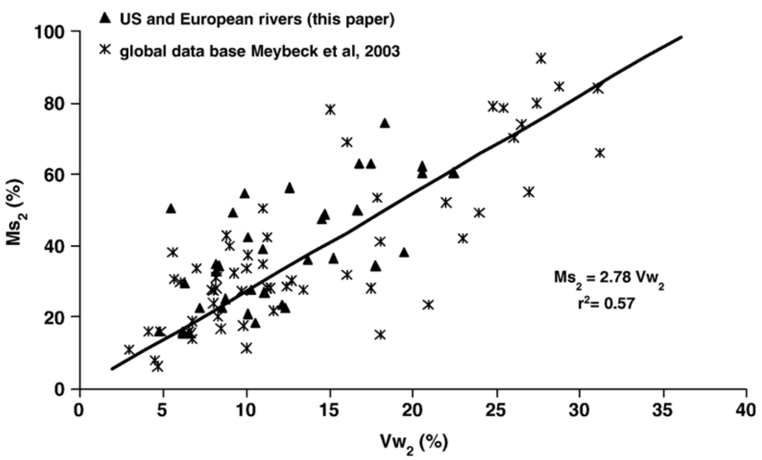

Fig. 11. Relationship between the proportion of SPM flux discharged in 2% of the time (Ms_2) and of water volume discharged in 2% of the time (Vw_2).

of sediment discharged in 2% of time (Ms_2) is related to the proportion of water volume discharged in the same fraction of time (Vw_2). The relationship between Ms_2 and Vw_2, for their database and the present one is shown in Fig. 11. When linear regressions are applied separately to the two databases ($Ms_2 = a Vw_2$), the parameter "a" varies between 2.6 (±0.11) and 3.06 (±0.16), which seems relatively consistent, in spite of a certain scatter around the regression lines. When all data are considered ($N=96$), the Vw_2 indicator explains 57% of Ms_2 variance by the regression $Ms_2 = 2.7(\pm 0.09) Vw_2$. As a consequence, estimates of accuracy and imprecision could be predicted by error nomographs and Ms_2 vs. Vw_2 relationship, when long-term daily discharge data are available but not daily SPM concentrations.

4.2. Ms_2 vs. basin size and SPM sampling effort

The database used in this study also confirms that basin size is one of the key factors controlling the daily water and SPM transport regime, as observed previously. The percent of annual water volume and SPM transport fluxes carried in 2% of time (Vw_2 and Ms_2) shows a marked decrease with the logarithm of basin size (Fig. 12). For both indicators, Vw_2 and Ms_2, there is no significant difference between the US and European data sets and the database used by Meybeck et al. (2003) on a more global scale.

Using the relationship between Ms_2 and the catchment area, the sampling effort required to achieve annual SPM fluxes in the range ±20% and a bias lower than 1%

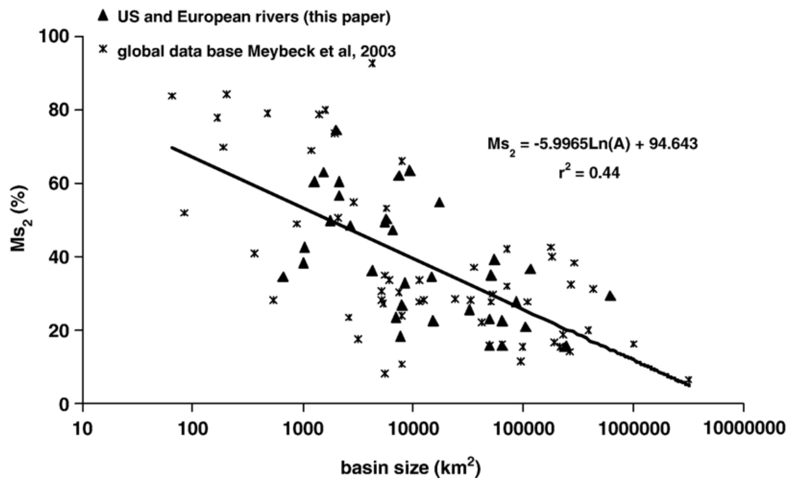

Fig. 12. Percentage of SPM flux discharged in 2% of time (Ms_2) versus ln of basin size (A).

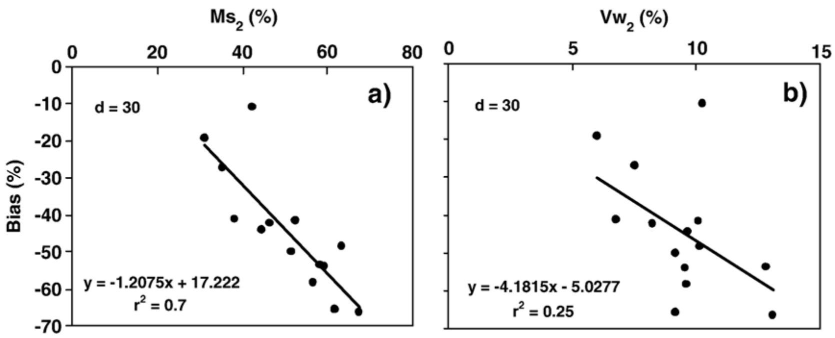

Fig. 13. Biases of annual SPM flux estimates for the Delaware River at Trenton (1968–1981) for monthly sampling: (a) Bias vs. Ms_2, (b) Bias vs. Vw_2.

or 2% could be expressed, as an initial approximation, as a function of the following information:

– <3 days for rivers with basin size <10,000 km^2 (Ms_2 greater than 40%);
– 3–5 days for rivers with basin size between 10,000 and 50,000 km^2 (Ms_2 between 30% and 40%);
– 5–12 days for rivers with basin size between 50,000 and 200,000 km^2 (Ms_2 from 20% to 30%);
– 12–20 days for rivers with basin size between 200,000 and 500,000 km^2 (Ms_2 from 15% to 20%).

4.3. Inter-annual variability of annual flux errors

Annual SPM flux errors evaluated from the Ms_2 error nomographs are constructed on several years of records, including contrasting hydrological situations such as wet, dry and medium years. For a river with daily records of more than 10 years, e.g. the Delaware River at Trenton, errors of annual flux estimates using monthly sampling show considerable year-to-year variation. Biases range from −11% to −66% (median bias −44% for the 1968–1981 period). They are not related to the nature of the hydrological year (wet or dry) but to flux indicators defined on a yearly basis as Vw_2 (Fig. 13a, $r^2=0.25$) and Ms_2 (Fig. 13b, $r^2=0.7$): Imprecisions are high at this frequency, ranging from 66% to 181% with an inter-annual value of 149%. They do not seem to be related to Ms_2 ($r^2=0.0$) or Vw_2 ($r^2=0.1$) at this sampling interval. For shorter sampling intervals, Ms_2 and Vw_2 indicators explain imprecisions in annual flux estimates better: $r^2=0.3$ (Vw_2) and $r^2=0.2$ (Ms_2) for bimonthly sampling.

5. Conclusions

The bias and imprecision of annual SPM flux estimates using the discharge-weighted mean concentration method (Method M18, Philipps et al., 1999) were assessed using Monte Carlo simulations for 28 sampling intervals (from 2 to 30 days) and from 36 basins with different transport regimes and a wide basin area range. As already observed by different authors, both bias and imprecision decrease when sampling intervals between measurements decrease. Moreover, all the biases are negative, i.e. Method M18 under-estimates the reference flux, except for very short sampling intervals (<1–5 days depending on Ms_2) when biases tend to zero.

As many SPM fluxes are based on bimonthly samplings, the related annual fluxes using M18 method show considerable imprecision: > to 80% for catchments between 1000 and 10,000 km^2, 40–80% for catchments between 10,000 and 100,000 km^2, and <40% for catchments exceeding 100,000 km^2. If annual fluxes have to be reported, as in some International Conventions, the sampling intervals should be reduced at most stations in order to reach a ±20% precision and 2% bias, and/or other calculation methods should be considered.

This paper demonstrates that the SPM transport regime of rivers affects the accuracy and precision of flux estimates for given sampling frequencies. The percentage of SPM carried in 2% of time (Ms_2 duration indicator) can be used as a descriptor of the SPM flux regime and is related to both accuracy and precision.

The SPM flux errors graph, linking bias and imprecision with the Ms_2 indicator, constructed on a set of US rivers ($n=27$), was successfully tested on an independent set of European rivers ($n=9$).

For most rivers, preliminary records of daily SPM concentrations are not available to optimise the long-term sampling required by Monte Carlo simulation or the Ms_2 duration indicator. Further development of this approach will determine whether the Ms_2 indicator could be replaced by another set of indicators, for instance combining known daily water discharge and statistics of discrete inter-annual SPM concentrations, particularly from long-term water quality surveys (>20 years).

Future research should now extend this approach to (i) the estimate of flux errors for various reporting periods (e.g. 5, 10 years), (ii) to other load calculation methods, such as those based on rating curves, and (iii) to the solute fluxes.

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