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Global variability of daily total suspended solids and their fluxes in rivers

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Abstract

The daily variability of river suspended sediment concentration (Cs) and related yield (*Y*) is studied at 60 global stations. The data set covers natural conditions (e.g. pre-reservoir data), ranging from the humid tropics to subarctic and arid regions, located in all types of relief (yearly runoff q^* from 0.1 to 55 l s^{-1} km^{-2}). Basin area ranges from 64 km^2 to 3.2 million km^2. Survey lengths range from 1 to 20 years with a median of 3 years. Median values (Cs_{50}, q_{50}, Y_{50}) and discharge-weighted averages for Cs* and *Y** range from 5 to 29 000 mg l^{-1} and 10 to 5000 kg km^{-2} day^{-1}, respectively. A set of indicators of variability are proposed for sediment concentration, water and sediment discharges including mean to median ratios (Cs^*/Cs_{50}, Y^*/Y_{50}), the percentage of sediment flux discharged in 2% of time (Ms_2), the percentage of time necessary to carry half of the sediment flux (Ts_{50}), and quantiles of Cs, *q* and *Y* distributions corresponding to the discharge-weighted averages. Since most of the sediment flux is discharged in less than 25% of the time, "truncated rating curves" metrics are proposed between the Cs vs. *q* relationship for periods of high flux.

Temporal variability decreases with increasing basin size, lake abundance, and is higher for basins influenced by glaciermelt and snowmelt. The least variable sediment flux regimes are noted for the Mississippi at its mouth, the Rhone Lacustre, the St. Lawrence and the Somme, a medium-sized French phreatic river. The most variable flux regimes were for small- to medium-sized basins (i.e. < 1000 to 10 000 km^2) such as steep Andean Bolivian basins, Thai basins, the Eel (CA) and Walla Walla (OR) rivers. A proposed global scale typology is based on six classes key variability indicators.
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Keywords: Sediment concentration; Sediment flux; River regimes; Global scale; Time variability

1. Introduction

Since the first detailed studies by agronomists (Mangon, 1869), limnologists (Forel, 1886), geomorphologists (Baeff, 1891; Hjulström, 1935) and river managers (Stabler, 1911; Howard, 1929), concentrations of total suspended solids (Cs) and their associated fluvial fluxes are known to vary enormously over time and space. Many authors (Müller and Förstner, 1968a; Walling, 1977; Meade and Parker, 1985; Syvitski and Morehead, 1999) have noted the quantitative role of rare or extreme events on the long-term average Cs flux, particularly in dry or semiarid conditions (Colombani and Olivry, 1984). These observations

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Table 1
General characteristics of database

River	Code	Rating[a]	Reference	Station	Country	Basin area (km^2)	Latitude	Longitude	Period	Cs nb[b]	Altitude station (m)	altitude max (m)
ADOUR	ADO	A –	25		France	7830					10	3300
ALPENRHEIN	ARH	B –	1	Lustenau	Austria	6100	47 26 N	9 42 E	1965/1966	205	400	3700
ANNAPOLIS	ANN	A –	27	Wilmott (NS)	Canada	546	45 36 N	64 42 W	1980–1982	1096	10	400
ARVE	ARV	B–	2	Geneva	Switzerland	2079	46 13 N	6 09 E	1890	365	400	4807
BANDAMA	BAD	B–	3	Tiassale	Ivory Coast	94 250	15 53 N	4 57 W	1969	200	80	700
BANI	BAN	C +	4	Douna	Mali	102 000	14 44 N	1 38 W		763	300	1000
BERMEJO	BER	A-	5	Bermejo	Bolivia	480	17 45 S[c]	63 14 W		1460	900	2400
CHAUDIERE	CHA	B-	6	St Lambert (PQ)	Canada	5805	46 50 N	71 10 W	1969	365	100	100
CHENA	CHE	B-	7	Fairbanks (Al)	USA	5125	64 50 N	147 50 W	1962–1963	730	170	1800
COLORADO	COL	C +	8	Grand Canyon (Az)	USA	434 000	36 02 N	112 09 W	1926–1928	197	1600	4400
COLUMBIA	CLB	B-	9	Steamboat Rapids (BC)	Canada	26 600	51 03 N	118 13 W	1974	365	1800	3400
EEL	EEL	A +	27	Scotia (Ca)	USA	8063	44 36 N	124 12 W	1960–1977	5930	100	2220
EL ABID	EAB	C +	10		Morocco	2635	32 15 N	6 20 E	1995–1997	275	1200	3277
ELM FORK RED	EFR	C +	11	Magnum (Ok)	USA	1940	34 54 N	99 31 W	1905–1907	514	450	900
ELVIRA	ELV	A –	5	Elvira	Bolivia	64	17 45 S[c]	63 14 W		1460	650	1800
ESPEJOS	ESP	A –	5	Espejos	Bolivia	203	17 45 S[c]	63 14 W		1460	550	1800
FRASER	FRA	B –	9	Hope (BC)	Canada	216 400	49 23 N	121 27 E	1974	365	300	3580
FRASER	FRM	A –	27	Mission (BC)	Canada	228 000	49 06 N	122 18 W	1973–1975	1095	50	3505
FYRIS	FYR	A –	12	Uppsala	Sweden	1200	59 55 N	17 38 E	1924–1934	1460	50	600
GAMBIA	GAM	B –	13	Gouloumbou	Senegal	42 000	13 3 N	13 50 W	1983–1984	365	50	700
GARONNE	GAR	B –	14	La Réole	France	52 000	44 47 N	0 36 W	1994	365	20	3000
GARONNE (2)	GRN	A –	25		France	53 000						
GRAND MORIN	GRM	B +	15	Villier	France	1200	48 52 N	3 00 E	1992–1995	1460	50	250
HUAI MAE YA	HMY	B +	16	Sop Huai Mae Ya	Thailand	84.8	19 44 N	98 29 E	1996–1997	731	510	1350
KHLONG MALA	KLM	B +	16	Hat Som Paem	Thailand	188	10 41 N	98 03 E	1996–1997	731	100	792
KHLONG SOK	KLS	B +	16	Ban Cheo Sai	Thailand	892	8 49 N	98 50 E	1996–1997	731	100	996
LIARD	LIA	A –	27	R2 mouth (NWT)	Canada	275 000	61 42 N	121 12 W	1979–1981	521	150	2792
LITTLE COLORADO	LCA	B –	17	Cameron (Ut) (236 days)	USA	70 600	35 15 N	111 25 W	1964/1965	365	1700	3500
LITTLE COLORADO	LCR	B –	17	Cameron (Ut) (365 days)	USA	70 600	35 15 N	111 25 W	1964/1965	365	1700	3500
LOIRE	LOI	C +	18	Mauves	France	110 000	47 12 N	1 30 W	1999	365	10	1750
LOT	LOT	B –	14	Clairac	France	11 500	44 24 N	0 36 W	1994	365	30	1550
MARNE	MAR	B +	15	Noisiel	France	12 500	48 51 N	2 37 E	1992–1996	540	50	450
MATANUSKA	MAT	B –	7	Palmer (Al)	USA	5345	61 35 N	149 10 W	1961–1963	730	150	4000

MEKONG	MKM	B+	16	Mukdahan	Thailand	391 000	16 32 N	104 44 E	1996–1997	731	124	5500
MEKONG	MKC	B+	16	Chiang Saen	Thailand	189 000	20 16 N	100 05 E	1996–1997	731	357	5500
MELARCHEZ	MEL	A–	15	Mélarchez	France	7	48 49 N	3 05 E	1975–1977	1095	70	80
MISSISSIPPI	MIS	A–	27	Tabert Landing (Lo)	USA	3 221 000	30 36 N	91 18 W	1950–1952	1096	25	3688
NAM MAE PAI	NMS	B+	16	Sop Mae Samat	Thailand	5530	19 14 N	97 56 E	1996–1997	731	169	1950
NAM MAE PAI	NMB	B+	16	Ban Na Chalong	Thailand	369	19 24 N	98 27 E	1996–1997	731	196	1800
NIGER	NIG	C+	4	Banankoro	Mali	71 000	11 59 N	8 22 W		620	300	1000
NIVELLE	NIV	A–	25		France	165						
NZI	NZI	C+	3	Zienoa	Ivory Coast	33 150	6 05 N	4 45 W	1969	200	80	600
PALOUSE	PAL		19	Hooper (Id)	USA	?	46 45 N	118 09 W	1961–1965	1460	350	1900
PEACE	PEA	B–	9	Peace River (Al)	Canada	186 000	56 15 N	117 19 W	1974	365	450	3300
PEACE	PPP	A–	27	Peace Point (Al)	Canada	293 000	59 06 N	112 24 W	1973–1975	1095	250	3952
PECOS	PEC	C+	11	Santa Rosa (NM)	USA	7490	34 56 N	104 42 W	1905–1906	387	800	3900
PIRAY	ANG	A–	5	Angostura	Bolivia	1420	17 45 S[c]	63 14 W		1460	650	2400
PIRAY	LBE	A–	5	La Belgica	Bolivia	2880	17 45 S[c]	63 14 W		1460	350	2400
PIRAY	TAR	A–	5	Taruma	Bolivia	1590	17 45 S[c]	63 14 W		1460	600	2400
RED DEER	RDD	B–	9	Red Deer (Al)	Canada	11 570	52 10 N	113 40 W	1974	365	800	5747
RHINE	RHI	A+	20	Maxau	Germany	50 196	49 00 N	8 20 E	1973–1993	7300	150	3700
RHONE ALPESTRE	RHA	B–	21	Porte du Scex (Vs)	Switzerland	5220	46 21 N	6 53 E	1967–1968 1973–1974	415	380	4500
RHONE LACUSTRE	RHL	B–	21	Geneva (Ge)	Switzerland	7987	46 13 N	6 09 E	1971–1972	207	375	4500
RIO GRANDE	RGR	C+	11	El Paso (Tx)	USA	99 700	31 42 N	106 29 W	1905–1907	247	1800	4400
S SASKATCHEWAN	SSA	B–	9	Lemsford (Al)	Canada	179 000	51 01 N	109 07 W	1969	365	600	3200
S SASKATCHEWAN	SSS	A–	27	Saskatoon (Sas)	Canada	141 000	52 06 N	106 36 W	1969–1971	1095	500	3449
SACRAMENTO	SAC	C+	11	Red Bluff (Ca)	USA	24 000	38 33 N	131 30 W	1905–1907	593	50	3187
SAINT LAWRENCE	STL	B–	26	Quebec	Canada	1 000 000				365	0	500
SALT FORK RED	SFR	C+	11	Mangum (Ok)	USA	3150	34 54 N	99 31 W	1905–1906	249	450	1200
SALWEEN	SLW	B+	16	Ban Mae Sam Laeb	Thailand	260 000	17 59 N	97 44 E	1996–1997	731	400	5000
SEINE	SEI	B+	15	Poses	France	65 000	49 2 N	1 10 E	1983–1985	730	0	500
SOMME	SOM	C+	18	(Somme)	France	5560			1980–97	216		200
STIKINE	STI	A–	27	Butterfly Creek (BC)	Canada	36 000	56 42 N	131 48 W	1980–1982	595	25	3300
TUY	TUY	B–	23	Caracas	Venezuela		10 35 N	66 56 W			100	2700
WALLA WALLA	WAW	A–	24	Touchet (Or)	USA	4279	46 05 N	118 18 W	1962–1965		150	1500

References: (1) Müller and Förstner, 1968b; (2) Baeff, 1891; (3) Monnet, 1972; (4) Picouet, 1999; (5) Guyot, 1993; (6) Ministère de l'Environnement, 1971; (7) Love, 1965; (8) Howard, 1929; (9) M.o.E., 1974; (10) Cherifi, 2001; (11) Stabler, 1911; (12) Hjulström, 1935; (13) Lô, 1984; (14) Latouche, 1995, 1996; (15) Meybeck et al., 1999; (16) DEDP, 1996, 1997; (17) U.S.G.S., 1966; (18) this work, data R.N.B., 2000; (19) Boucher, 1970; (20) B.f.G., 2000; (21) O.F.E.H., 1976; (22) M.o.E., 1969; (23) Ramirez et al., 1988; (24) Mapes, 1969; (25) Maneux et al., 1999; (26) Rondeau, personal communication and Rondeau et al., 2000; (27) Binda et al., 1986 and Water Survey of Canada, 1995.

[a] See text.

[b] Actual number of documented Cs.

[c] Latitude and longitude at Santa Cruz (Bolivia).

are the basis of the magnitude/frequency concept (Wolman and Miller, 1960), now widely used in riverine geomorphology (Nash, 1994). Another major use of Cs studies is to assess land denudation (Tabuteau, 1960; Judson and Ritter, 1964) and the related global sediment flux to the oceans (Fournier, 1960; Walling, 1994). At this scale, only "average" values have been used in computing sediment delivery to ocean (Milliman and Meade, 1983; Milliman and Syvitski, 1992) and its associated organic carbon (Meybeck, 1982; Ludwig et al., 1996). These studies point to a globally skewed distribution of long-term specific fluxes or yields (Y in t km^{-2} year^{-1}): most sediment is carried to the oceans from a small proportion of the land mass, namely South East Asia and the Pacific Islands. However, the temporal variability of daily Cs fluxes has not been addressed, mostly for lack of representative data assembled at the global scale. A unique monthly sediment flux database was developed by Fournier (1969, 1974) under the auspices of UNESCO and the International Association of Hydrological Sciences (IAHS), but has not been revised since. This is unfortunate since river particulates are the key carriers of heavy metals (Horowitz, 1995), or Persistent Organic Pollutants, and discharge of these pollutants is highly dependant on concentration levels and loads (Thomas and Meybeck, 1992).

Our purpose is to:

(1) propose and test a set of indicators designed to characterize flux variability at the dynamic level (daily time steps),
(2) establish the global range of these indicators in terms of concentrations and yields under natural conditions,
(3) compare the temporal patterns of daily sediment flux and water discharge (flux duration) at the global scale, and
(4) study the factors that regulate the spatial distribution of such temporal variability, in terms of annual runoff, basin size, influence of lakes and morphoclimatic conditions.

In addition to classical metrics, such as the flux duration curve for water and Cs (ASCE Task Committee, 1970; Dunne, 1979; Walling, 1977, 1984), we employ new metrics. Our database of daily Cs (Table 1) includes 60 river basins from 64 km^2 to 3.2 million km^2, representing different flow regimes and locations on all continents except Australasia. The survey periods range from 1 to 20 years with a median of 3 years. Data were selected to minimize anthropogenic influence, such as rapid land use changes and reservoir operations. This latter point is critical due to the globally significant retention of particulates in artificial impoundments, arising from the aging of continental runoff and distortion of river hydrograph (Vörösmarty et al., 1997a,b; Vörösmarty and Sahagian, 2000; Vörösmarty et al., 2003-this volume).

2. Data selection and rating

The database covers most river flow regimes, from subarctic (Alaska) to monsoon (Thailand), and most relief types (Meybeck et al., 2001) from plains (France, West Africa) to plateaus (Colorado) and to steep mountain basins (Alps, Rockies, Andes, Upper Mekong). Annual runoff ranges from 4 (Little Colorado) to 1750 mm/year (Thailand). All basins except two were selected for the absence of major impacts such as dams and storage reservoirs, and for limited land use change during the period of record. A few basins are influenced by agriculture and or ranching, i.e., Western Europe (Loire, Seine, Garonne) and the Canadian Prairies (South Saskatchewan), as agriculture is not the key driver of sediment concentration levels or variability. We have largely avoided basins in newly deforested areas. The targeted period of record is 2 years for both daily Cs measurements and daily specific discharge (q in l s^{-1} km^{-2}), with a median value of 2.8 years (Table 1).

In some regions, the selected predamming surveys are historical, such as for the Southwest US from 1905 to 1930. These data are generally incomplete, e.g., only 197 Cs measurements are available for 2 years for the Colorado in 1926–1928 and only 247 Cs data values for 2 years for the Rio Grande in 1905–1907. Due to their prime importance as surveys of basins now regulated by dozens of small to large dams, we consider these records. It is postulated that the documented Cs and Q variations were fully representative of the whole period. Such extrapolation is made for the South Fork and the Elm Fork of the Red River in Oklahoma in 1905–1907, and the Pecos River in New Mexico in 1905–1906. For the Mississippi near its mouth, the record chosen is from 1950 to 1952, i.e., prior to the construction of most dams on the Missouri and other tributaries (Meade and Parker, 1985; Keown et al., 1986). The lacustrine-influenced Rhone, the outlet of Lake Geneva, and the Alpine Rhone, inlet to Lake Geneva, and the El Abid in Morocco are also characterized by incomplete records (e.g. 100 daily samples per year during 4 years for the Rhone) but considered as representative. The Alpine Rhone is partially impounded (ca. 20% of basin), with a 50% sediment retention compared to 1920s values (Loizeau and Dominik, 2000).

Two stations in the Middle Niger River at Banankoro and on its tributary, the Bani River, both in Mali, are also considered on the basis of 7 years of *monthly* averages (Picouet, 1999). We implicitly consider that the monthly variability is close to the daily variability. A comparison with other rivers of similar size (50 000–100 000 km^2) in West Africa (Gambia, Bandama, Nzi), where the daily Cs variability is very moderate over a period of 1 month (Lô, 1984; Monnet, 1972), justifies our assumption. Likewise, the Somme River indicators are based on 18 years of monthly Cs records. This phreatic river drains the Chalk Aquifer north of Paris and is likely characterized by very low daily variability. The maximum Cs measured during high flows is very small (<60 mg l^{-1}) and the daily flow variation is small. We have also reconstituted the daily Cs for unsurveyed periods at very low stage for a few rivers, on the basis of available daily Q as for the winter period of the Matanuska and Chena Rivers (Alaska), Stikine and Liard (Canada), and for the dry season of the Bandama and Nzi (Ivory Coast) rivers.

This study focuses on perennial rivers with one exception, the Little Colorado which is kept in the database for comparison. The river ran dry for 129 days during the year of record, therefore, we have differentiated between its annual characteristics averaged for 365 days (termed LCA) and those related only to the discharging period (LCR). The El Abid in Morocco also ran nearly dry for some days. Both rivers are considered due to their unusually high Cs levels at low flows and as an example of the statistical treatment of a non-perennial river.

Very small basins (<64 km^2) are not considered except for the Melarchez stream (7 km^2), part of a nested basins set of increasing size (Melarchez, Grand Morin, Marne and Seine in France) (Meybeck et al., 1999). The Nam Mae Pai, in Thailand, the Lot-Garonne (France), the Piray (Bolivia) are also nested stations. A few stations show the influence of one or several lakes: Rhone Lacustre, Middle Rhine at Maxau that is influenced by subalpine Swiss lakes, and the St. Lawrence at Quebec.

Two stations illustrative of reservoir influence are included, the Upper Columbia river at Steamboat Rapids, highly influenced by water flow regulation and the South Saskatchewan at Saskatoon, located below the Gardiner Dam. The latter station is compared to the South Saskatchewan at Lemsford located just above the reservoir.

The reproducibility of indicators at similar stations is tested on three rivers with very close stations: the Garonne at La Réole (GAR and GNR), the Peace at Peace River (PEA) and at Peace Point (PPP), and the Fraser at Hope (FRA) and at Mission (FRM). Most indicators show very close values for these station comparisons (Table 2).

The origins of the daily data are variable (see Table 1), ranging from very old values from the Arve River (1890) (a glacial-fed river draining the Mont Blanc massif) and the first U.S.G.S. measurements in the US Southwest (1905–1907), to recent surveys in Thailand (1996–1997). We also use recent data on Bolivian basins (Guyot et al., 1996), Niger River (Picouet, 1999) and El Abid (Cherifi, 2001). Some data are from national yearbooks (Alpine Rhone, Lacustrine Rhone, some Canadian stations, all Thailand stations). Other data come from scientific publications: Fyris in Sweden (Hjulström, 1935), the Walla Walla in Oregon (Mapes, 1969), the Adour, Nivelle and the Garonne in South West France (Maneux et al., 1999), and the Tuy river in Venezuela (Ramirez et al., 1988), and the Alpine Rhine (Müller and Förstner, 1968b). We also utilize data from the U.S.G.S. WATSTOR National Water Data Exchange (see Nash, 1994), and the HYDAT database of Canadian rivers (Binda et al., 1986; Water Survey of Canada, 1995).

We have rated the quality of our data: A^+ for more than 4 years of daily records as for the Middle Rhine (20 years) and the Eel River (for 17 years), A^- for 3–4 years of daily record, B^+ for 2 years of daily record, B^- for 1 full year of daily measurement or 2 years of record with partially reconstituted data as for Matanuska and Chena, C^+ for incomplete measurements for

Table 2
Indicators of Cs and Cs flux variabilities (see text)

River	Code	q^* ($l \cdot s^{-1}$ km^{-2})	q^* (%)	q^*/q_{50}	Cs* ($mg\ l^{-1}$)	Cs* (%)	Cs*/Cs_{50}	Y^* ($kg \cdot km^{-2}$ day^{-1})	Y^* (%)	Y^*/Y_{50}	β_{95-50}	(Cs^*/Cs_{50})/(q^*/q_{50})	(q^*/q_{50})(Cs^*/Cs_{50})	Ms_2 (%)	Ts_{50} (%)	Vw_2 (%)	Tw_{50} (%)
ADOUR	ADO	9.6			67.8									24	5.8	8	17.5
ALPENRHEIN	ARH	47	69	1.78	1236	89.5	18.7	5000	84	32.9	2.3	10.50	33.3	33.5	3.6	7	21.8
ANNAPOLIS	ANN	22.8	95.8	1.69	11	84.0	2.7	20.1	78	3.5	0.98	1.58	4.5	28.2	6.2	11.4	16.9
ARVE	ARV	28	54	1.04	335	91	9.7	820	85	9.8	3.4	9.36	10.1	50.5	1.95	11	24.4
BANDAMA	BAD	2.54	66	2.99	89	66	1.3	19	67	4.0	0.27	0.42	3.8	11.5	13.8	10	15.3
BANI	BAN	2.17	70	4.52	57	74	3.3	10.6	73	9.8		0.72	14.8		9		12
BERMEJO	BER	7.4	75	2.24	3495	96	16.6	2230	92.5	31.9	1.34	7.42	37.3	79	0.23	24.8	10.5
CHAUDIERE	CHA	24.4	76	2.98	74	91	8.2	155	87	23.8	0.9	2.77	24.5	53.3	1.8	17.8	9.6
CHENA	CHE	13	67	2.36	134	90	11.2	150	85	26.3	1.36	4.72	26.4	28	3.9	11.3	14.3
COLORADO	COL	1.44	71	1.95	15760	83	2.6	1970	80	6.2	0.9	1.35	5.1	30.9	6.2	8.2	17.5
COLUMBIA	CLB	21.9	42 ?	0.91	56	91	2.8	108	88	2.6	2.28	3.07	2.6	40.5	3	5	24.8
EEL	EEL	28.2	78.4	5.35	1073	91.4	97.5	2616	88.6	443.4	1.6	18.23	522.0	66.1	0.9	31.2	5.1
EL ABID	EAB	4.34	73	2.19	11600	90	1.2	4380	58	3.4	0.54	0.53	2.5	23.5	7.5	20.9	10
ELM FORK RED	EFR	3.47	78	3.40	6420	92.5	24.7	1920	92.5	89.3	1.16	7.26	84.0	73.8	0.48	26.5	6.81
ELVIRA	ELV	6.61	75	2.13	1995	97	15.3	1140	94.5	42.4	1.5	7.20	32.7	84	0.21	31.1	10.1
ESPEJOS	ESP	12.1	73	2.24	4920	96.6	20.5	5150	95	39.0	1.57	9.15	45.9	84.3	0.21	28.7	10.6
FRASER	FRA	14.7	64	1.73	232	80	3.7	294	72	6.0	1.5	2.16	6.5	15.5	9.6	6.7	20.7
FRASER	FRM	12.2	65	1.56	196	80.4	3.4	206	73.2	6.3	1.49	2.20	5.4	18.9	8.6	6.8	20.8
FYRIS	FYR							12.6	75	2.1							
GAMBIA	GAM	1.49	72	3.82	45	87	3.0	5.8	76	11.6	0.59	0.78	11.4	22	6.6	11.6	11.4
GARONNE	GAR	16.9	63	1.26	139	83	4.6	203	80	5.7	1.65	3.67	5.8	27.6	5.75	7.9	21.4
GARONNE (2)	GRN	8.1			46									30	2.7	6	22
GRAND MORIN	GRM	5.42	79	1.84	91	94.5	15.1	42	91	29.2	1.51	8.23	27.8	68.9	0.89	16	14.4
HUAI MAE YA	HMY	10.3	71.8	1.81	307	94.7	3.5	273	85.1	6.8	0.76	1.93	6.3	52	1.7	22	12.2
KHLONG MALA	KLM	46	73	4.79	129	97.1	12.9	510	90	51.0	0.78	2.69	61.8	70	0.7	26	9.6
KHLONG SOK	KLS	55.5	90	3.26	69	95.2	3.3	329	83.2	11.0	0.46	1.00	10.6	49	2.2	24	8.75
LIARD	LIA	8.3	62.2	1.82	508	89.8	20.3	362	81.8	37.7	2.0	11.14	37.1	32.2	4.4	9.3	16.1
LITTLE COLORADO	LCA	0.125	75	5.95	29000		7.3	313	84	18.7	0.92	1.22	43.2	42	2.8	23	6.3
LITTLE COLORADO	LCR	0.193		2.61	29000		2.6	484		7.2		1.01	6.9	32	4.2	16	9.7
LOIRE	LOI	8.81	62	1.27	50	90.0	1.8	38	79	2.7	0.8	1.41	2.3	27.5	7.3	8	22.4

LOT	LOT	22.1	60.5	1.49	106	87.0	4.8	203	79	8.4	1.49	3.23	7.2	27.8	5.15	13.4	13.45
MARNE	MAR	8.9	70	1.68	33	77.0	1.9	25	75	3.6	1.09	1.16	3.3	28	5.9	8.2	19
MATANUSKA	MAT	22.5	70	2.36	1750	87.0	17.5	3400	79	62.0	1.58	7.42	41.3	27.2	5.4	9.7	14.8
MEKONG	MKM	20.7	69.6	2.59	584	72.6	6.1	1044	75.1	10.4	1.17	2.38	15.9	20	6.7	8.3	16.1
MEKONG	MKC	13.8	62.8	1.53	962	81.9	2.8	1140	70.6	3.8	1.14	1.82	4.3	16.8	10	8.5	21.1
MELARCHEZ	MEL	7.8		13.93	62	95.5	13.0	40	96	210.5	0.82	0.93	180.5	91.5	0.34	42	3.42
MISSISSIPPI	MIS	5.33	53.2	1.03	849	61.6	1.1	391	53.3	1.1	0.92	1.08	1.16	6.3	26.6	4.7	31.4
NAM MAE PAI	NMS	9.7	75	1.76	165	87.0	3.1	136	79.9	4.5	0.97	1.73	5.4	35	4.4	11	17.5
NAM MAE PAI	NMB	12.7	72.2	2.89	209	88.2	5.5	229	82.3	11.5	0.92	1.91	15.9	41	3.6	18	16.1
NIGER	NIG	10.4	63	3.35	24	70.0	1.7	21.7	71	5.2	0.42	0.50	5.6		11.2		13 ()
NIVELLE	NIV	33.2			80									78	0.48	15	16
NZI	NZI	0.935	76	1.73	182	81.0	1.3	14.7	83	4.1	0.27	0.76	2.3	28	4.2	17.5	11.5
PEACE	PEA	11.3	69	1.27	889	87.0	20.2	868	84	31.6	3.57	15.91	25.7	40	3.1	9	27.4
PEACE	PPP	6.6	69.2	1.16	587	84.3	14.3	334	80.8	19.8	4.31	12.36	16.6	38.2	3.55	5.6	33.1
PECOS	PEC	0.58	70	4.83	4730	72.0	14.8	237	82	79.0	1.09	3.06	71.4	30.3	5.1	12.7	11.8
PIRAY	ANG	5.2	77	2.60	4540	96.2	20.6	2040	93	45.3	1.33	7.94	53.7	78.6	0.61	25.4	9.11
PIRAY	LBE	4.01	75	2.88	5761	92.5	4.3	2000	87	13.9	0.69	1.47	12.3	55	1.55	26.9	7.75
PIRAY	TAR	4.65	76	2.64	5932	96.0	18.0	2380	95	55.7	1.17	6.80	47.5	79.9	0.465	27.4	8.35
RED DEER	RDD	4.56	68	2.14	217	90.0	43.4	83	84.5	107.8	2.3	20.27	92.9	33.5	3.8	10	14.7
RHINE	RHI	25.5	63	1.09	29	74.0	1.4	64	69	1.6	1.47	1.27	1.5	15.8	16.7	4.84	34.7
RHONE ALPESTRE	RHA	33.6	65	1.35	302	84.0	4.9	878	78	6.8	2.24	3.61	6.6	30.5	5.7	5.7	27.8
RHONE LACUSTRE	RHL	23.4	62	1.08	5	71.0	1.4	9.7	75	1.5	1.71	1.26	1.5	10.8	19.3	3	35.7
RIO GRANDE	RGR	0.458	77	2.08	8240	63.0	1.1	205	75	3.1	0.45	0.54	2.4	15.3	10.1 ?	18	10.8
S SASKATCHEWAN	SSA	2.72	70	2.31	935	90.5	5.9	220	88	10.6	1.08	2.55	13.6	42.5	2.6	11.3	16.4
S SASKATCHEWAN	SSS	4.6	63.2	1.23	115	71.1	1.6	45.4	67.6	2.2	1.21	1.30	2.0	15.9	12.6	4.9	30.2
SACRAMENTO	SAC	19.1	68	2.12	67	81.0	2.8	112	76	5.3	0.95	1.31	5.9	28.5	4.8	12.4	
SAINT LAWRENCE	STL	12	64	1.08	14	79.5	1.4	14.16	74.5	1.5	2.02	1.27	1.5	16	17	4.1	40.8
SALT FORK RED	SFR	0.933	65	1.76	2610	85.0	5.0	210	79		1.44	2.85	8.8	17.6	6.8	9.8	29.2
SALWEEN	SLW	20	65.5	1.67	994	78.5	5.9	1737	71.4	8.7	1.79	3.55	9.9	14	10	6.75	22.4
SEINE	SEI	7.4	63	1.20	38	79.0	1.8	24	73	2.5	1.2	1.50	2.2	16	11.6	6.6	27.7
SOMME	SOM	6.5	53.3	1.02	23	62.3	1.3	13	61.9	1.3	1.59	1.26	1.3	7.9	23.3	4.5	36.7
STIKINE	STI	8.9	66	1.93	240	91.7	16.0	184.7	82.8	26.0	1.66	8.27	30.9	37.2	3.3	10.1	15
TUY	TUY	17												43	3	8.8	
WALLA WALLA	WAW	3.87	62	1.95	7000	98.0	116.7	2260	95	243.0	1.96	59.69	228.0	92.6	0.14	27.7	9.8

more than 1 year, as Rio Grande and Colorado, Niger, Bani and Somme (Table 1).

Methods for determining Cs vary from simple surface bucket sampling to depth-integrated sampling with multiple verticals. These differences can provide for 100% variation in Cs values. However, since we focus on the time variability of Cs fluxes, which vary across six orders of magnitude, these discrepancies are of secondary importance on the variability indicators.

We focus the study on the suspended solid concentrations, and fluxes or "sediment load". Bed load is not included, as it is rarely measured and generally assumed to be of the order of 10% of particulate load for most erosive rivers.

2.1. Representativeness of the selected data at the global scale

The river basins chosen are located on all continents excepted Australasia: North America ($n = 26$), South America ($n = 7$), Africa ($n = 8$), Europe ($n = 16$) and Asia ($n = 6$). Existing data from river surveys in China and Russia are not considered. We suggest that these data, which cover a wide range of natural environments, should be used as independent sets to validate our findings. Many other documented stations on pristine basins in Canada or Alaska are not used in order to avoid an overrepresentation and to keep a balance between all hydrological types. Other stations in the conterminous USA are not included because they are now influenced by flow regulation and other human impacts. Although the northern temperate zone, between 40°N and 50°N of river station latitude, is probably overrepresented (20 stations out of 60), most latitudinal zones are represented, except for the equatorial regions between 10°S and 10°N, such as Central Amazonia and the Zaire Basin.

The average annual specific discharge ranges from less than 0.12 l s^{-1} km^{-2} for the Little Colorado (Arizona) to 55.5 l s^{-1} km^{-2} for the Khlong Sok in Southern Thailand. Such a range covers practically all perennial runoff conditions including: glacier fed rivers (Matanuska and Chena, Arve, Alpine Rhone, Alpine Rhine), snowmelt rivers (Stikine, Liard, Peace, Saskatchewan, St. Lawrence, Chaudière, Fraser, Annapolis, Mekong at Chiang Saen), pluvial oceanic (Grand Morin, Marne, Seine, Garonne, Lot, Adour, Nivelle), pluvial Mediterranean (Eel), pluvial continental (Columbia, Palouse, Walla Walla), Asian monsoon (Huai Mae Ya, Khlong Sok, Mekong at Mukdahan, Nam Mae Pai), arid and subarid climate (Pecos, Little Colorado, Rio Grande, El Abid), dry and wet tropical (Piray, Bermejo, Elvira, Espejos in Bolivia, Nzi, Bandama, Niger, Gambia, Bani, in West Africa), and mixed regimes for the largest basins (Colorado at Grand Canyon, Mekong at Chiang Saen, Mississippi). In essence, the database covers a wide spectrum of global river flow and relief conditions.

3. Metrics of suspended solids concentrations and fluxes

The following metrics of total suspended solids concentration and fluxes, generally established over a minimum of one hydrologic year, are used (Table 2). Flux indicators normalized to basin area (yields) are preferred to aid intersite comparisons.

Cs* (mg l^{-1}) discharge-weighted total suspended solids $= \Sigma(\mathrm{CsiQi})/\Sigma\mathrm{Qi}$, where Csi and Qi are daily averages.

Cs*% average discharge-weighted suspended solid quantile, i.e., quantile of the daily Cs distribution corresponding to the weighted Cs* value.

Cs_{50}, Cs_{75}, ...Cs_{99} (mg l^{-1}) quantiles of the daily Cs levels ranked in increasing order.

Ms_1%, Ms_2%,... Ms_{50}% percentage of total mass of suspended solids carried during 1%, 2%,... 50% of the observational period; established from the highest daily fluxes, and used to build up the duration curve of solid load.

Ms_{1-10}%, Vw_{1-10}%... percentage of total mass of suspended solids and of water carried between 1% and 10%,... of the time.

q^* (l km^{-2} s^{-1}) average specific water discharge (q^* can also be expressed in milliliter per year, referred to as yearly runoff).

q^*% average runoff quantile, i.e., quantile of the q distribution corresponding to the average q^* value.

q_{50} median daily specific discharge (l km^{-2} s^{-1}); also expressed in millimeter per year for comparison with q^*.

q_{50}, q_{75}, ...q_{99} (l km^{-2} s^{-1}) quantiles of daily specific water discharge ranked in increasing order.

Tw_{50}% percentage of time necessary to carry 50% of the water volume.

Ts_{50}% percentage of time necessary to carry 50% of the suspended solid flux.

Vw_1%, Vw_2%,... Vw_{50}% percentage of total volume of water carried in 1%, 2%...50% of time; established from the highest daily discharges and used to build up the duration curve of water flow.

Y^* (kg km^{-2} day^{-1} or kg km^{-2} $year^{-1}$) weighted average specific flux of Cs (or yield); based on daily measured and/or reconstituted values.

Y^*% average yield quantile, i.e., quantile of the Y distribution corresponding to the Y^* value for the period of record.

Y_{50}, Y_{75}...Y_{99} (kg km^{-2} day^{-1}) quantiles of daily yields ranked in increasing order (daily loads divided by the basin area at station).

The following ratios are also used:

β_{95-50} slope of the "pseudo rating curve" between log Cs and log q, based on medians (Cs_{50}, q_{50}) and 95% quantiles (Cs_{95}, q_{95}).

Cs^*/Cs_{50} weighted suspended solids variability, ratio of discharge-weighted Cs* over median Cs_{50}, a descriptor of weighted Cs variability.

Cs_{99}/Cs_{50} ratio of Cs 99% and median Cs.

$(Cs^*/Cs_{50})/(q^*/q_{50})$ ratio of relative variabilities of Cs and water discharge.

$(Cs^*/Cs_{50})(q^*/q_{50})$ product of relative variabilities of Cs and water discharge.

q^*/q_{50} river discharge variability, ratio of average daily specific discharge to median specific discharge.

$Ts_{50}\%/Tw_{50}\%$ ratio of percentage of time necessary to carry 50% of solid flux over percentage of time necessary to carry 50% of water flux.

Y^*/Y_{50} suspended solid flux variability ratio of average daily sediment flux over median daily flux.

Y_{99}/Y^* ratio of specific daily sediment flux discharged in less than 99% of time over the weighted average daily sediment flux; a descriptor of Cs flux variability.

$Ms_2\%/Vw_2\%$ ratio of percentages of sediment and water discharged during 2% of the time, from sediment flux and flow duration curves.

In many cases, our database does not exceed 3 years of record and cannot be used to determine the "effective sediment-transporting discharge" that results from the magnitude–frequency analysis over a long period (Wolman and Miller, 1960); according to the review of Nash (1994), the return period of such discharge may exceed 2 years in 20% of this data set, essentially in Mediterranean type of climate as in California.

Wherever used in illustrations, all descriptors of duration curves expressed in percentage (Ms_2%, Vw_2%, Ts_{50}%, Tw_{50}%, Cs*%, q*%, Y*%), are plotted using the Henry law probability scale, following the ASCE Task Committee (1970), Dunne (1979) and Walling (1984). Vw% and Ts%, Tw% metrics have already been used by Gunn (1982) for the dissolved load frequency analysis. We believe q*%, Cs*%, Y*% to be new in duration analysis.

4. Global scale range of suspended solids and flux variability

4.1. General distribution of discharge-weighted suspended solids

The discharge-weighted total suspended solid (Cs*) is the ratio of the total amount of suspended load to the total water volume discharged in a given period, here a multiple of one hydrological year. In our documented set, it varies between 5 mg l^{-1} for the Alpine Rhone, the outlet of Lake Geneva, to 29 000 mg l^{-1} for the Little Colorado (Fig. 1).

This range covers the full spectrum of weighted average Cs*. Very few stations have Cs* < 5 mg l^{-1}, and correspond to outlets of oligotrophic lakes, located on hard to erode rock sills. At the other end of this Cs* range are local tributaries of the Huang He in the Loess Plateau (Walling and Webb, 1996; Walling, 2000) and the Little Colorado. Thus, the global Cs range is enormous. We propose to classify world rivers into six Cs* categories (Fig. 1, Table 3): very low (5–20 mg l^{-1}) generally found downstream of major or numerous lakes, (limnic index >10%, Meybeck, 1995), or in very flat and humid regions with wetland

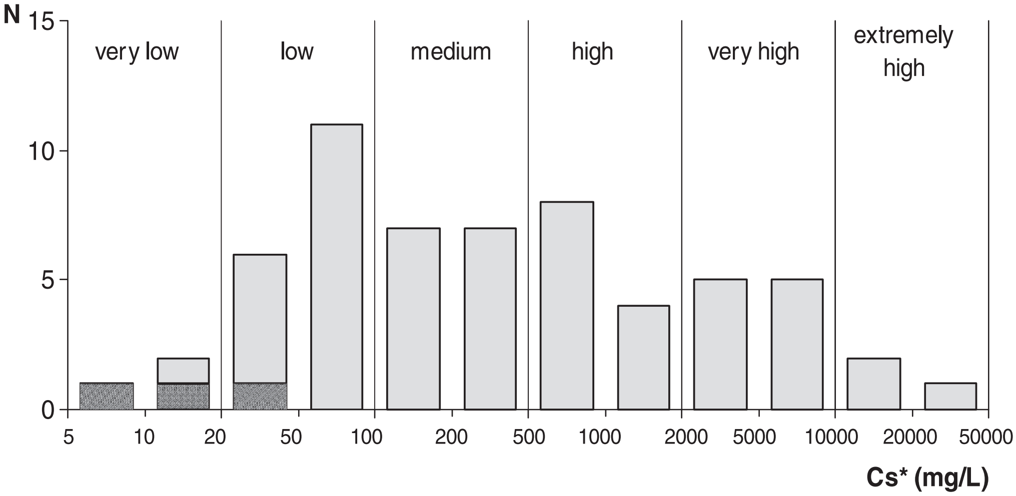

Fig. 1. General distribution of discharge-weighted Cs* (mg l^{-1}) in the documented data (Table 1) (crossed values: lake-influenced stations, RHI, RHL, STL).

predominating as in parts of Central Amazonia; low (20–100 mg l^{-1}) characteristic of plains basins, as defined by Meybeck et al. (2001); medium (100–500 mg l^{-1}) with mountainous headwaters and/or in low-relief basins draining erodible rocks; high (500–2000 mg l^{-1}) in active mountain ranges such as the Alps, Caucasus, Andes (Meybeck et al., 2001); very high (2000–10 000 mg l^{-1}) in active mountain ranges with highly erodible rocks, and in steep volcanic islands and semiarid regions with highly erodible rocks; and extremely high (>10 000 mg l^{-1}) in very specific environments combining absence of vegetative cover, medium to high slopes, erosive seasonal rainfall and highly erodible material like loess and shales. Cs* dependence on basin relief, rock types and climate confirms the findings of Walling (1994, 2000), Walling and Webb (1996) and many others.

Highly turbid mountainous rivers are the major contributor to the global sediment budget (Meybeck, 1982; Milliman and Syvitski, 1992). The present, global-weighted average Cs* is on the order of 500 mg l^{-1}, i.e., 20 Gtons/year discharged to oceans for a water discharge of 40×10^3 km^3/year (Milliman and Syvitski, 1992). This figure is already influenced by human activities in two contradictory ways (Walling, 2003-this volume): (1) the acceleration of soil erosion and (2) the retention of particulates in reservoirs (Vörösmarty et al., 1997a,b, 2003-this volume). The most commonly found Cs* values in world major rivers are less than that around 150 mg l^{-1} due to dominance of flat terrains at the global scale (Meybeck and Helmer, 1989).

4.2. Global range of sediment yields (Y)*

Annual average discharge-weighted specific fluxes (Y^*) are calculated as the ratio of annual suspended load to basin area. These are usually expressed as ton km^{-2} $year^{-1}$ but are also expressed here in kg km^{-2} day^{-1} to permit cross-site comparison using other quantiles of the Y distribution, which cannot be expressed on a yearly basis. They are compared with the medians of daily Cs fluxes (Y_{50}) and with the upper percentiles (Y_{99}) (Fig. 2, Table 3).

Specific suspended fluxes (Y) are extremely variable, from less than 1 kg km^{-2} day^{-1} (0 for the non-perennial rivers) to near 100 000 kg km^{-2} day^{-1} for Y_{99}. High daily fluxes occur in basins combining several factors of erodibility, such as very high runoff during floods, steep relief and occurrence of erodible materials, as found in the Alps, Central Asia mountains (Salween, Upper Mekong) and in Bolivian tributaries of the Amazon (Guyot et al., 1996). Very high fluxes are also observed for the Eel ($Y_{99} = 50\,200$ kg km^{-2} day^{-1}) or the Walla Walla ($Y_{99} = 58\,400$ kg km^{-2} day^{-1}) (Syvitski and Morehead, 1999; Mapes, 1969).

Table 3
Global ranges of suspended solids indicators and examples of related rivers in predammed basins

	Very low	Low	Medium	High	Very high	Extremely high
Discharge-weighted total suspended solids						
Cs* mg l^{-1}	5–20	20–100	100–500	500–2000	2000–10 000	>10 000
		Bandama	Arve	Eel	Pecos	
	Annapolis	Chaudière	Huai Mae Ya	Matanuska	Piray	Colorado
	Rhone Lacustre	Loire	Red Deer	Mekong	Rio Grande	El Abid
	St. Lawrence	Sacramento	Stikine	Mississippi	Walla Walla	Little Colorado
Average daily suspended solids yields						
Y* kg km^{-2} day^{-1}	< 10	10–50	50–200	200–1000	1000–5000	>5000
		Annapolis		Khlong Mala	Colorado	
	Gambia	Nzi	Chaudière	Mississippi	Eel	Alpine Rhine
	Rhone Lacustre	St. Lawrence	Middle Rhine	Peace	El Abid	Espejos
		Somme	Sacramento	Pecos	Matanuska	
					Salween	
Weighted-suspended solids variability						
Cs^*/Cs_{50}	1–2	2–5	5–10	10–20	20–50	>50
	Loire	Annapolis				
	Mississippi	Bani	Arve	Alpine Rhine	Peace	Eel
	Rio Grande	Fraser	Chaudière	Matanuska	Red Deer	Walla Walla
	Seine	Lot	Salween	Stikine		
Suspended solids flux variability						
Y^*/Y_{50}	< 2	2–5	5–10	10–20	20–50	>50
	Mississippi	Bandama	Bani	Gambia	Alpine Rhine	Eel
	Rhone Lacustre	El Abid	Colorado	Khlong Sok	Peace	Matanuska
	Somme	Fyris	Fraser	Peace	Piray	Red Deer
	St. Lawrence	Rio Grande	Rhone Alpestre	South Saskat	Stikine	Walla Walla
Percentage of time needed to carry half of the sediment flux						
$Ts_{50\%}$	Very long	Long	Medium	Short	Very short	Extremely short
	>16.5%	16.5–8%	8–3.4%	3.4–1.4%	1.4–0.4%	< 0.4%
	Middle Rhine	Bani	Adour	Chaudière	Eel	
	Mississippi	Fraser	Gambia	Red Deer	Grand Morin	Bermejo
	St. Lawrence	Middle Mekong	Sacramento	Stikine	Khlong Mala	Elvira
	Somme	Niger	Upper Mekong	Tuy	Nivelle	Walla Walla

Such an enormous range over five orders of magnitude is exceptionally wide for a hydrological descriptor.

It is interesting to note that the general distribution of specific fluxes is shifted by an order of magnitude between Y_{50} and Y*, and by another magnitude between Y* and Y_{99} (Fig. 2). The lowest yields are associated with basins influenced by lakes (Rhone Lacustre, Fyris in Sweden, Middle Rhine, St. Lawrence) and in basins with low relief such as the Seine (Seine, Marne, Grand Morin) and West Africa rivers (Bani, Niger, Bandama, Nzi, Gambia). This pattern holds for river basins characterized by poorly erodible rock types. Global scales of average daily yields (Y*) and of the maximum daily yields as described by Y_{99}, are proposed into six classes from very low to extremely high (Table 3).

4.3. Global range of daily suspended solids variability

To characterize Cs variability at the daily level we use the ratio between discharge weighted Cs* and median Cs_{50}. Cs^*/Cs_{50} ranges from 1.1 to more than 100. As for the previous indicators, we propose a

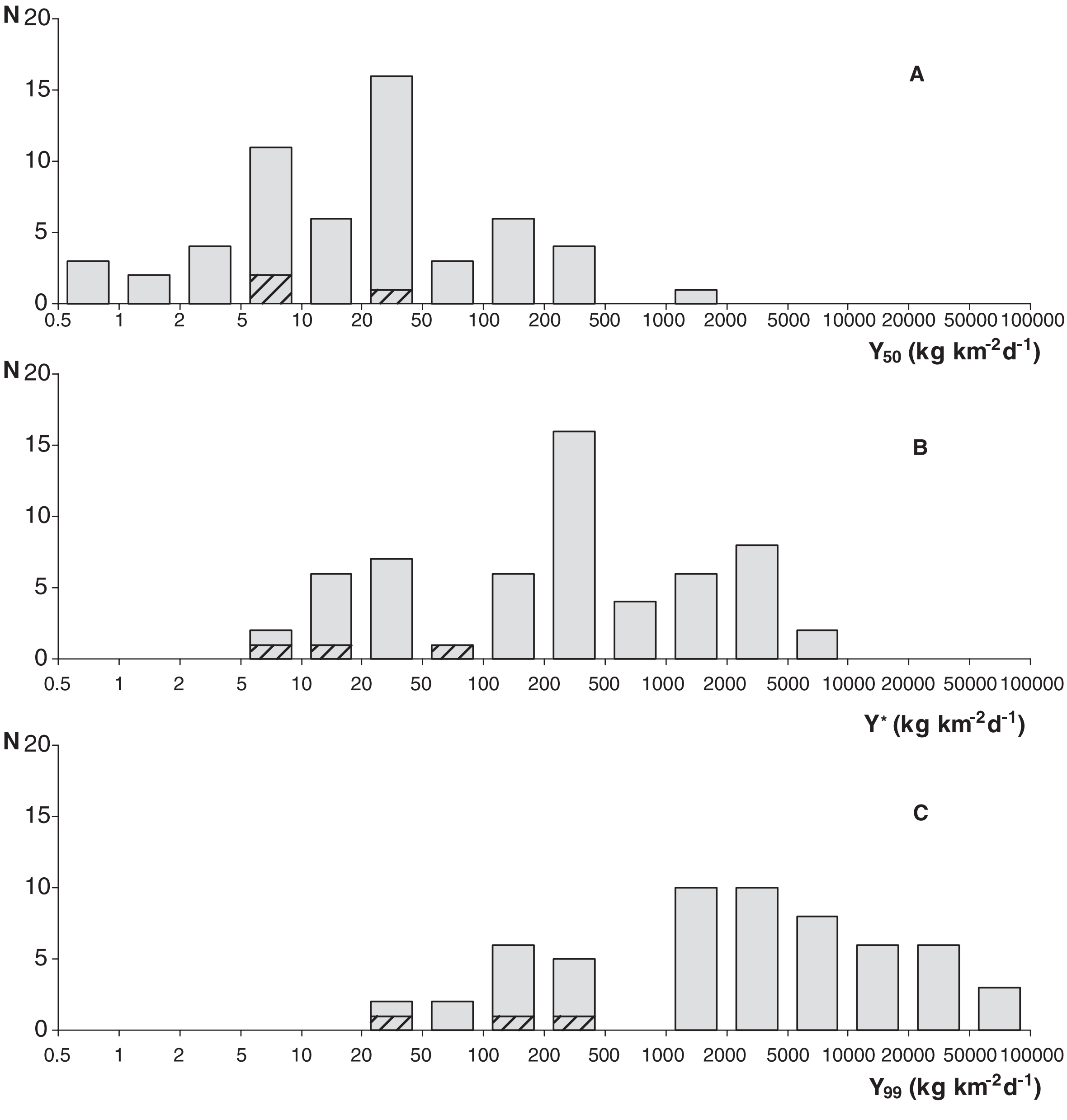

Fig. 2. General distribution of specific daily TSS fluxes (kg km^{-2} day^{-1}) for the documented data set: (A) median (Y_{50}), (B) discharge-weighted average (Y^*), (C) upper percentile (Y_{99}) (crossed values: lake-influenced stations).

scale for this weighted suspended solid variability divided into six classes, from very low to extremely high (Table 3).

Cs_{50} and Cs* are not correlated at the global scale but correlate at the local to regional scale as both decrease with basin size. The weighted Cs* variability decreases with basin area. Driving factors include the presence of lakes that decrease this variability (St. Lawrence, Rhone Lacustre, Middle Rhine), and the dominance of groundwater in the flow regime such as for the phreatic Somme River. Low relief (plains) basins have low Cs^*/Cs_{50} (Loire and Seine or West

African basins). The glacier-fed rivers (Arve, Chena, Matanuska, Alpine Rhine) have relatively higher Cs*/Cs_{50} ratios, from 10 to 20, as do some snowmelt rivers (Peace, Liard, Stikine, Chaudière). Surprisingly, some of the most turbid rivers (El Abid, Little Colorado and Rio Grande) are characterized by very low Cs*/Cs_{50} levels. The highest Cs*/Cs_{50} ratios are for the Walla Walla, a median-sized (4279 km^2) tributary basin of the lower Columbia (Mapes, 1968) and the Eel, a river well studied for its exceptional sediment fluxes (Syvitski and Morehead, 1999).

4.4. Global range of sediment flux variability (Y^*/Y_{50} and Y_{99}/Y^*)

The Cs flux variability at a given station is expressed as the ratio of discharge-weighted average flux to median flux, Y^*/Y_{50}. For the basins exceeding 60 km^2, Y^*/Y_{50} ratio ranges from < 1.5 for the Mississippi, the Somme and lake-influenced stations, to >200 for the Walla Walla and Eel (Table 2). Assuming that this documented set covers the whole range of Cs flux variability, a global scale of sediment flux variability divided into six classes is again proposed (Table 3).

The flux variability (Y^*/Y_{50}) is controlled by factors as climate, vegetation and relief. At the local to regional levels, these factors may be relatively uniform and basin size becomes a key driver. The Seine nested catchments provide a good illustration for this scale dependence: Y^*/Y_{50} is 210 for Melarchez station (7 km^2), 29 for the Grand Morin (1200 km^2), 3.6 for the Marne (12 500 km^2) and 2.5 for the entire Seine basin (65 000 km^2). The flux variability is very low at lake-influenced stations. Basin relief is another important control factor: flux variability is low to medium for plains basins and can be high to very high for small glacier-fed rivers as the Arve, Chena, Matanuska. Extreme variability is encountered in drier catchments, such as Red Deer, Elm Fork Red, Walla Walla, Pecos, or in the smaller, wetter, or mountainous catchments found in South Thailand and in the Bolivian Andes.

The observed flux variability as defined by Y^*/Y_{50} and the variability as obtained by the product (Cs*/Cs_{50})(q^*/q_{50}) are highly correlated. Throughout their range, which covers two orders of magnitude, these two indicators do not differ by more than 20% (Fig. 3). The exceptions include the Nzi and Bani rivers, which are poorly documented (C^+ rating in data quality, Table 1). This correlation reflects the quasi-universal, although complex (Williams, 1989) relationship between Cs and q (Walling and Webb, 1983; Müller and Förstner, 1968a,b; Morehead et al., this volume). Rivers for which there is no Cs vs. q correlation, as for the El Abid (Cherifi, 2001), provide the exception (Fig. 3). The Little Colorado at Cameron (Arizona), the only non-perennial river in the data set, is also an outlier (Fig. 3). When the variability coefficients are computed for the hydrological year, i.e., with non-flowing periods (LCA), the corresponding values are well outside the general relation. When considering the running period only (LCR), the variability is well within the general relationship (Fig. 3).

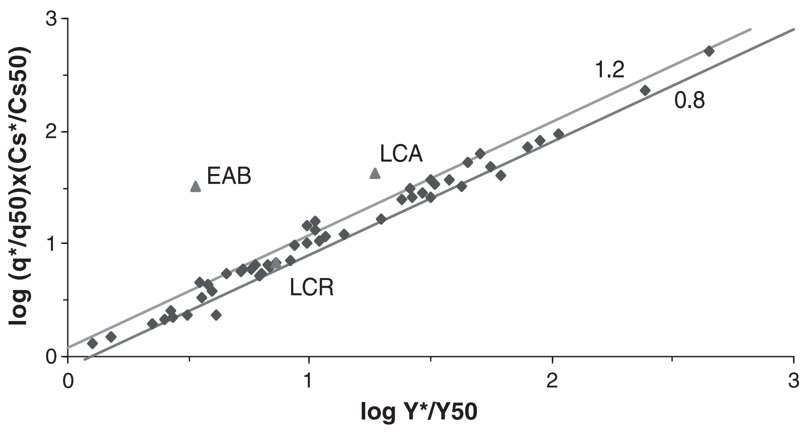

Fig. 3. Log of runoff variability (q^*/q_{50}) times log of TSS variability (Cs*/Cs_{50}) vs. log of suspended sediment flux variability Y^*/Y_{50}. Cs*, q^* and Ys* are discharge-weighted averages, Cs_{50}, q_{50} and Y_{50} are medians (MEL omitted).

Another expression of the variability of Cs fluxes is the ratio between the upper percentile of daily fluxes (Y_{99}) that provides an indicator of the maximum flux over the discharge-weighted average (Y^*). Unlike the Y^*/Y_{50} ratio, the Y_{99}/Y^* ratio is relatively constant (5–20) through the range of annual sediment transport, from 10 to >5000 kg km^{-2} day^{-1} for Y^* (Fig. 4). If long-term Y^* can be determined from sedimentary filling in lakes or coastal basins, then the extreme Y_{99} values can be approximated by this relationship.

4.5. Global range of sediment flux durations

The duration of Cs flux, i.e., the percentage of sediment transport observed during a given period discharged in 1%, 2%... 50% of time, is described first by the percentage of time necessary to carry 50% of the Cs flux (Ts_{50}%), based on daily data. This flux duration is compared to Tw_{50}%, the percentage of time necessary to carry 50% of the water discharge (Fig. 5A). In our data set, Tw_{50}% varies from 5% for the Eel to 40% for the St. Lawrence. The maximum theoretical value of 50% corresponds to a constant flow throughout the hydrological year. The highest values (Tw_{50}%>30%) are observed in highly regulated rivers as the South Saskatchewan (Tables 1 and 2) downstream of the Gardiner reservoir (30.2%) compared to only 16.4% for the same river at Lemsford (Tables 1 and 2), upstream of the reservoir. High Tw_{50}% is also observed at lake-influenced stations as the Lacustrine Rhone, St. Lawrence, Middle Rhine and at groundwater-fed stations such as the Somme where flow regulation is mostly natural.

The duration pattern is somewhat different for the suspended transport, with a range much wider than for the water flow. The duration of the suspended load is always shorter than for the water discharge, this attests the relatively higher "mobility" of sediment relative to runoff generation under predam conditions. Half of the load (Ts_{50}%) is carried over a range from less than 0.4% of time to 26.6% of time (Fig. 5B). The duration time is reported on the Henry law probability scale to characterize the duration patterns in six classes according to Ts_{50}% from very long sediment flux duration (Ts_{50}%>16.5%) to extremely short (Ts_{50}% < 0.4%) (Table 3).

The shortest durations are observed for the smaller basins located in mountainous regions: Eel, Walla Walla or the Piray at Angostura. The longest duration is noted for the Mississippi (Ts_{50}% = 26.6%) as a consequence of its enormous size (3.2 million km^2). This size influence is also noted for the Upper Mekong (MKM; Ts_{50}% = 6.7%) and the Middle Mekong (MKC; Ts_{50}% = 10%).

Relief and water flow regime play an important role: the Somme river, fed by groundwater is characterized by one of the longest Cs flux durations (Ts_{50}% = 23.3%), despite its relative small basin area (5530 km^2). Longer durations are also noted for lake-influenced basins as the Rhone Lacustre (19.3%), St. Lawrence (17%) and the Middle Rhine (16.7%). We hypothesize that Ts_{50}% for the Amazon and Zaire,

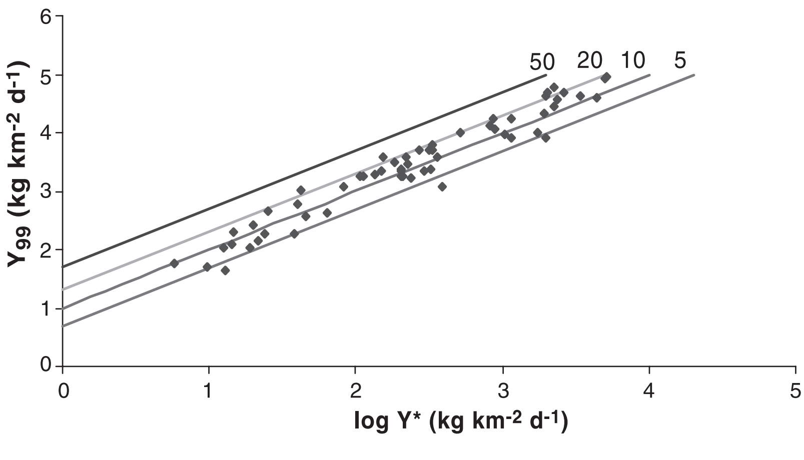

Fig. 4. Upper percentile of daily specific fluxes (Y_{99}) vs. the discharge-weighted average daily flux Y^*. Diagonals represent equal Y_{99}/Y^* ratios.

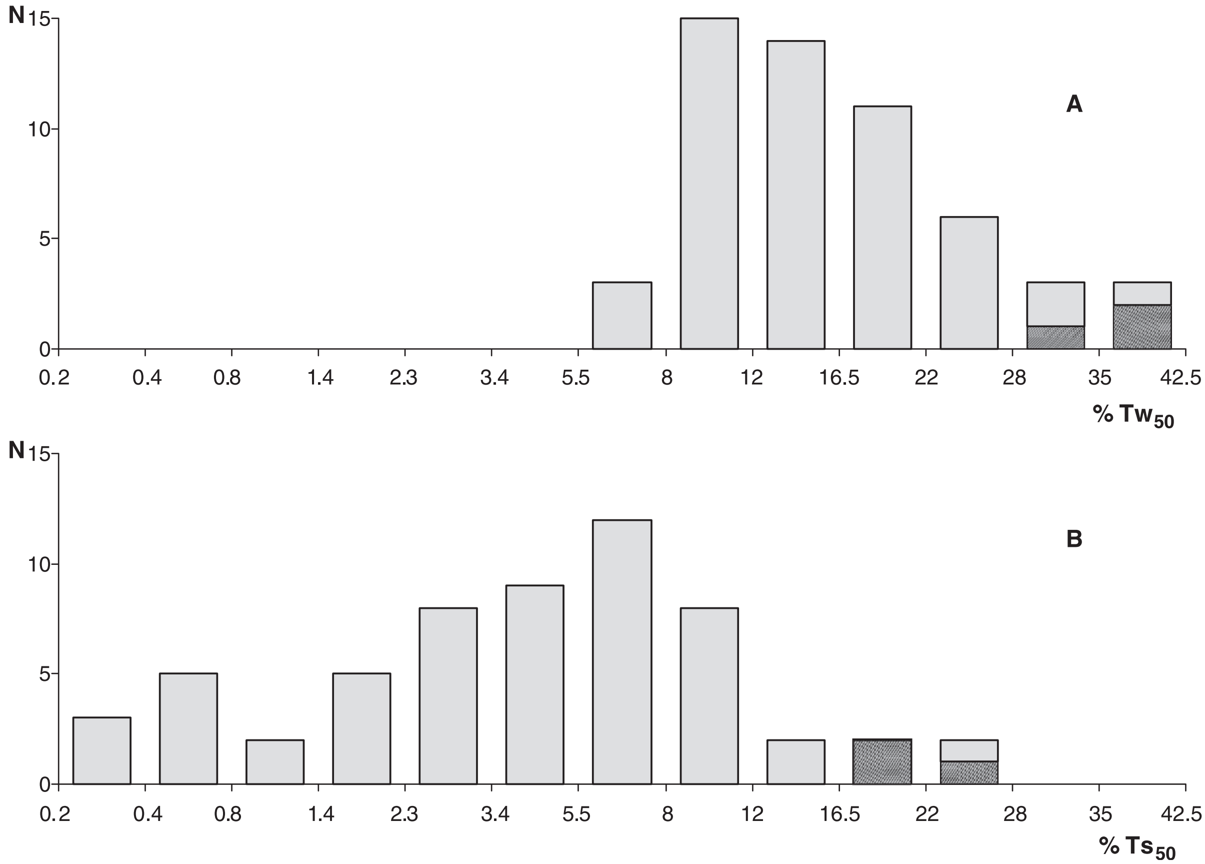

Fig. 5. General distribution of percentage of time necessary to carry: (A) 50% of the water flux (Tw_{50}%), (B) 50% of the TSS flux (Ts_{50}%) in the documented data (omitted data: CLB, MEL, SSS) (crossed values: lake-influenced stations) (Henry law probability scale).

which combine both very regular flow regimes (J.L. Guyot, P. Seyler, D. Orange, personal communication, Laraque et al., 2001) and greatest basin areas, would exceed 30%.

5. Runoff and basin size as controlling factors on sediment flux variability

5.1. Influence of water runoff

The general increase of Cs with q has been observed and quantified over 140 years since the first daily surveys of Mangon (1869) in the Durance and the Marne in France, of Forel (1886) in the Alpine Rhone in Switzerland and confirmed later by hundreds of studies (Müller and Förstner, 1968a,b; Walling and Webb, 1983). This complex relationship (Williams, 1989) is generally termed "rating curve" and is commonly used to extrapolate missing data at given stations. Tabuteau (1960), for Mediterranean regions, tested if such a relation was also observed on yearly Cs* averages and runoff q*. But the Cs* vs. q* relationship is not universal as discussed by Milliman and Syvitski (1992). It is tested here on the median values, Cs_{50} and q_{50} and the discharge-weighted averages, Cs* and q*. Although our documented set of rivers is much smaller than those of Tabuteau (1960), it is more reliable since it is based on daily surveys, yet the dispersion is still very high (Fig. 6).

As observed in previous studies (Tabuteau, 1960), there is no global increase of weighted Cs* with average q* for river basins exceeding 60 km^2 nor of median Cs_{50} with median q_{50}. Erosion is limited by

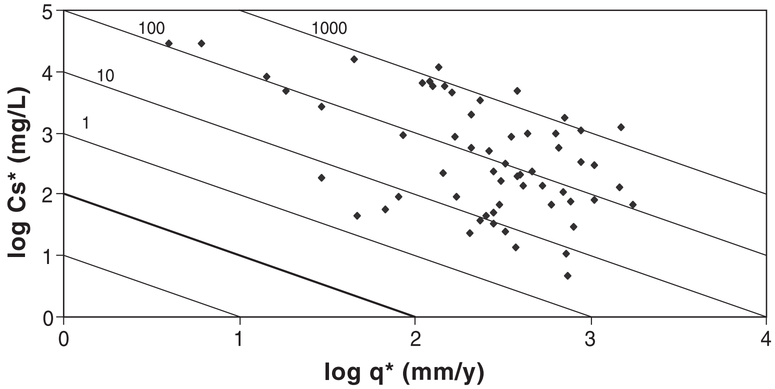

Fig. 6. Relationship between log of discharge-weighted suspended solids (Cs* in mg l^{-1}) vs. log of average specific runoff (q* in mm $year^{-1}$). Diagonals represent lines of equal specific sediment transport (ton km^{-2} $year^{-1}$).

vegetation cover: for the semiarid and dry river basins ($q<30$ mm/year), the vegetation is nearly absent and well developed for the wet basins ($q>500$ mm/year). This remains to be established on a greater documented set of basins—with careful site selection to avoid reservoir influence. On Fig. 6, a decrease of Cs* with q* is possible if the stations markedly influenced by lakes are discarded. If confirmed, it would mean that highest Cs* values (>2 g l^{-1}) are not generally found in very humid conditions. The extreme annual transport rates (Y*>1000 ton km^{-2} $year^{-1}$, Fig. 6) cannot be sustained in medium and large rivers unless very peculiar geological conditions are met (volcanic ash, loess) and/or very high tectonic uplift rates as found in some SE Asia Islands.

The $Y^* - q^*$ relation in the semiarid and arid regions has been debated for decades (Walling and Kleo, 1979; Walling, 1987) and it is essential for the estimate of long-term erosion rates in these environments. Very low runoff basins (< 30 mm/year of annual runoff) are poorly represented in our data set. In arid conditions, below 1 mm/year of runoff (long-term average), river flow is only observed once every few years or less. In such conditions, the increase of Cs* is not balancing the runoff decrease and the corresponding sediment flux is decreasing. Actually, during exceptional floods in arid environments, observed once every 10–50 years, Cs* barely exceeds 100 g l^{-1} as for the Medjerdah prior damming (Claude et al., 1977) or the Oued Zeroud (Colombani and Olivry, 1984), both in Tunisia. For a long-term average q* of 1 mm/year and Cs* ranging from 10 to 100 g l^{-1} during these exceptional floods, the corresponding long-term Y* should be between 10 and 100 tons km^{-2} $year^{-1}$ which probably represents the maximum sediment transport rate possible in such environments.

5.2. Influence of basin size

Basin size is a key factor in controlling suspended sediment transport by rivers (ASCE Task Committee, 1970; Walling, 1983; Milliman and Syvitski, 1992). Suspended load and bedload originating from steeper headwaters tend to settle on hillslopes, floodplains, wetlands and lakes. As a result, the ratio of sediment delivery to the ocean to the supply of sediment from headwaters, known as the sediment delivery ratio (Walling, 1983), is inversely related to the logarithm of basin area. Moreover, the time variability of river runoff generally decreases along the river course: annual hydrographs are also smoother for large basins, with the noted exception of snowmelt runoff regimes.

The Cs variability at a given station, described here by Cs^*/Cs_{50}, decreases markedly with the logarithm of basin size. This relationship is better for the very low to medium Cs* values (Cs*< 800 mg l^{-1}) and for nested basins in homogeneous regions. For example, in the very homogeneous Seine basin (Meybeck et al., 1999), this ratio varies from 15.1 for the Grand Morin (120 km^2) to 1.9 for the Marne (12 500 km^2) and 1.8 for the Seine (65 000 km^2). For the Melarchez stream, a Grand Morin tributary, the Cs^*/Cs_{50} is only 13.0 for

7 km^2, but this value, established on daily means over a period of 4 years, is probably too low and does not reflect the actual Cs variability which should be established for such small stream at a finer time scale, perhaps as short as a few hours (V. Andreassian, personal communication). A similar decrease with basin area is noted for Bolivian rivers, in southern Thailand between the Khlong Mala (188 km^2, $Cs^*/Cs_{50} = 12.9$) and the Khlong Sok (892 km^2, $Cs^*/Cs_{50} = 3.3$), and in Alberta between the Red Deer (11 570 km^2, $Cs^*/Cs_{50} = 43.4$) and the South Saskatchewan (179 000 km^2, $Cs^*/Cs_{50} = 5.9$).

Basin size is a critical factor controlling the riverine fluxes pattern as described by the percentage of load discharged in 2% of time (Ms_2%). Ms_2% provides another descriptor of flux duration: (i) it is robust and corresponds to the seventh highest daily flux observed in one hydrological year and varies less than Ms_1 or $Ms_{0.5}$ from 1 year to another, (ii) at many stations, particularly on larger basins, it can be assessed from long-term surveys with lower frequencies such as weekly or bimonthly. When plotted against log (basin area), Ms_2% shows a marked decrease (Fig. 7). For the smallest documented basins, 64–500 km^2, 50–90% of the suspended flux is discharged in 2% of time, for the greatest basins exceeding 100 000 km^2, this proportion drops from 10 to 30%.

A marked decrease of Ms_2% with basin area is noted for the Tana river tributaries in Kenya (Dunne, 1979), for Turkish rivers and for various US rivers (ASCE Task Committee, 1970; Meade et al., 1990; Hay, 1994) which have also been reported in Fig. 7.

5.3. "Truncated" and "pseudo rating curves" and their description

In the documented data set, 65–99% of the sediment load is discharged in less than 25% of time. The exceptions are (1) the three lake-influenced stations, Middle Rhine, St. Lawrence and Rhone Lacustre, with 57–61% suspended solids discharged; (2) very large basins as the Mississippi (47.8% only); and (3) the phreatic Somme river (53%). The proportion of suspended load discharged in less than 1% of time varies between 3.4% (Mississippi) and 82% (Walla Walla).

Classically, the rating curve is established for all the data points (Nash, 1994 and others) and influenced by the majority of low and medium flows that represent at most stations less than 20% of the suspended solids discharge.

It is therefore proposed here:

(1) to focus rating curves on the highest quantiles of the river flow and of Cs, thus, defining a "truncated rating curve" which at many stations

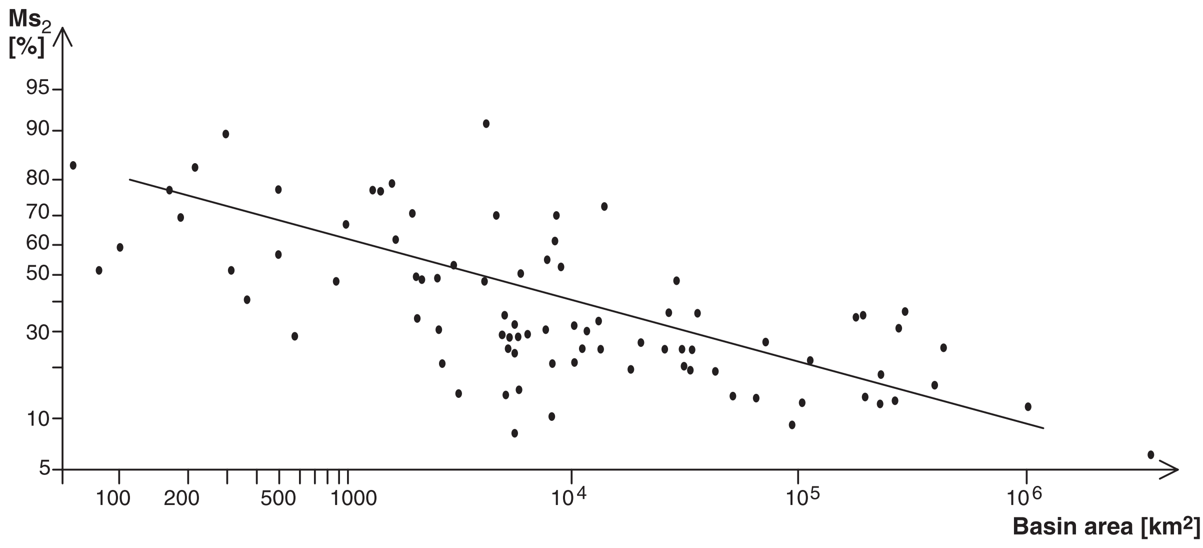

Fig. 7. Percentage of suspended solids flux discharged in 2% of time (Ms_2) vs. log of basin area.

may be significantly different than for the whole rating curve using all individual values.

(2) to test a description of this truncated rating curve by a "pseudo rating curve" on the basis of the 99%, 98%, 95%, 90%, 75% and 50% quantiles ($Cs_{99}...Cs_{50}$; $q_{99}...q_{50}$) instead of using all the data set, i.e., without the lowest half of q and Cs values.

The pseudo rating curve is simple: dozens to hundreds of data points are replaced by few quantiles values (Fig. 8) without a major loss of information. At most analysed stations, the pseudo rating curve is nearly linear in a log Cs – log q scale and can be used: (i) to compare the Cs vs. q patterns between stations (Fig. 8), and (ii) to reconstruct the highest quantiles of Cs from the known quantiles of q, at stations where Cs measurements are less frequent. In both cases, the focus is to determine the highest fluxes. The lower parts of this relationship can be used to investigate the most common conditions (from 25 to 75% of the time) or the low flows (conditions found in less than 25% of the time) which are important descriptors for river ecology.

The enormous ranges of Cs and q at the global scale are well evidenced in such a diagram. The lake influence on the St. Lawrence is very obvious when compared to the Peace River of equivalent size and climate. Size and relief explain the major differences observed between the Khlong Mala and the Mekong, both in Thailand. The pseudo rating curve can only be applied at stations where a general positive relationship exists between Cs and q since both Cs and q are ranked separately for the determination of quantiles. They cannot be used to describe river basins where seasonal Cs vs. q loops (hysteresis) are pronounced as in West Africa, or where there is no correlation between Cs and runoff, as for the El Abid. The use of the pseudo rating curves to reconstruct the missing Cs data from known water discharge data remains to be tested.

5.4. Duration curves of water transport and suspended solids transport

Duration curves give the proportion of water volume (Vw%) or sediment load (Ms%) discharged in a given proportion of elapsed time, ranked from the highest fluxes. Such relationships are established for a multiple of one hydrological year with daily time steps for river basins (>100 km^2). For streams and brooks (< 100 km^2), time scales of hours should be used. The proportions of the highest fluxes reached in 0.5, 1%, 2%, 5%, 10%, 25% and 50% of time ($Ms_{0.5}$%, Ms_1%,... and $Vw_{0.5}$%, Vw_1%,...) are key indicators of sediment and water flux patterns at a given station.

The ASCE Task Committee (1970), Dunne (1979) and Walling (1984) have used the Henry Law diagram

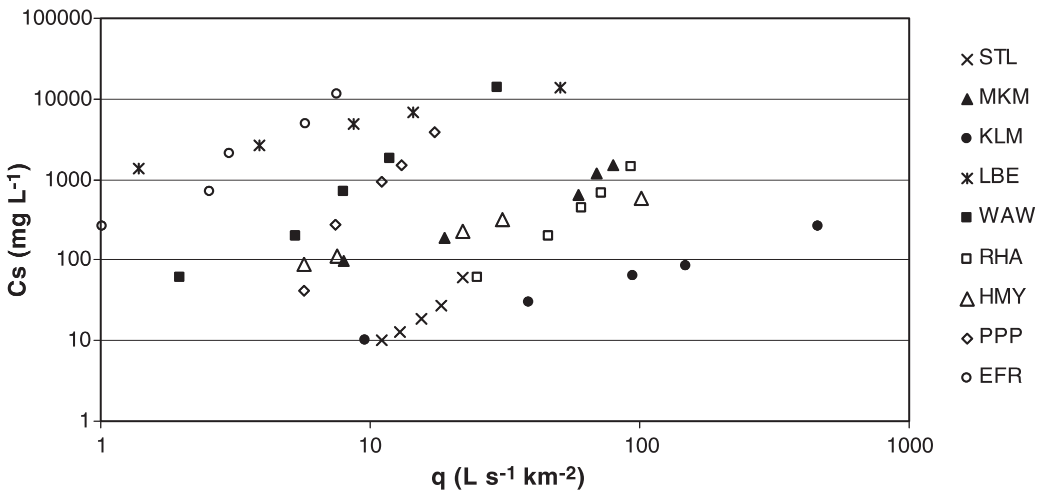

Fig. 8. Examples of pseudo rating curves, Cs vs. q for the quantiles 50%, 75%, 90%, 95%, 99% (ranked daily values for documented periods): STL = Saint Lawrence, MKM = Mekong at Mukdahan, KLM = Khlong Mala, NZI = Nzi, EAB = El Abid, RGR = Rio Grande and HMY = Huai Mae Ya, PPP = Peace at Peace Point.

(based on the Gauss probability law) to represent the duration curves using percentage of fluxes vs. percentage of time (Fig. 9). The proposed flux duration indicators can be tested: (i) the percentage of time necessary to carry 50% water volume (Tw_{50}%) or suspended load (Ts_{50}%) and (ii) the percentage of total water volume (Vw_2%) or of suspended load (Ms_2%) carried in 2% of time.

These indicators are inversely correlated for both water (Fig. 10A) and sediment fluxes (Fig. 10B) and few data previously published also fit this relation (ASCE Task Committee, 1970; Meade et al., 1990; Hay, 1994). The second percentiles Vw_2% and Ms_2% are those that have the best inverse relationship with Tw_{50}% and Ts_{50}%. The duration curves are relatively similar at all stations. The Little Colorado points to the treatment of non-perennial rivers. When statistics are based on the annual record, i.e., including the non-flowing period, the corresponding values clearly lie outside the general regression; when based on the flowing period, the fit is excellent.

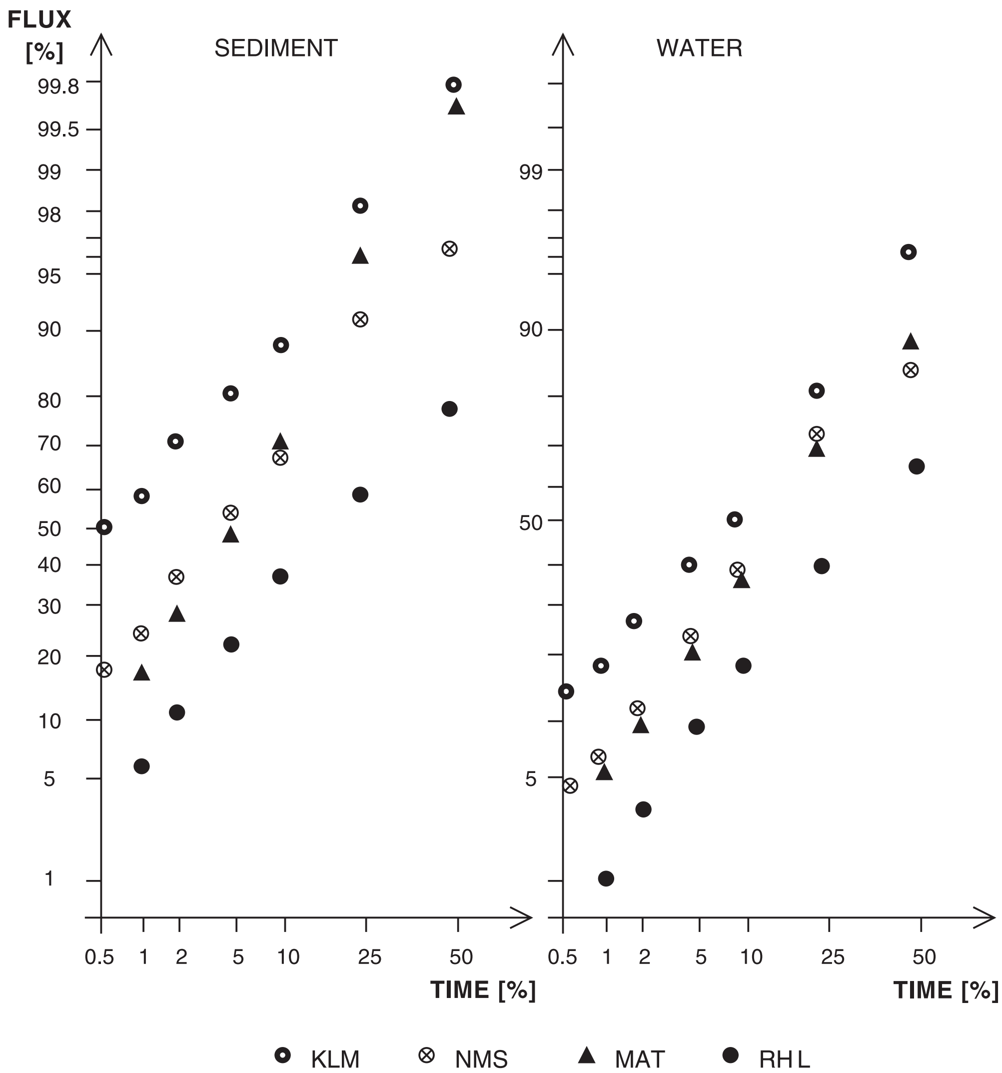

Fig. 9. Duration curves as represented in Henry law probability scales: percentage of sediment fluxes and water fluxes vs. the percentage of time for the Khlong Mala (KLM), Nam Mae Pai at Sop Mae (NMS), Matanuska (MAT) and Rhône lacustre (RHL).

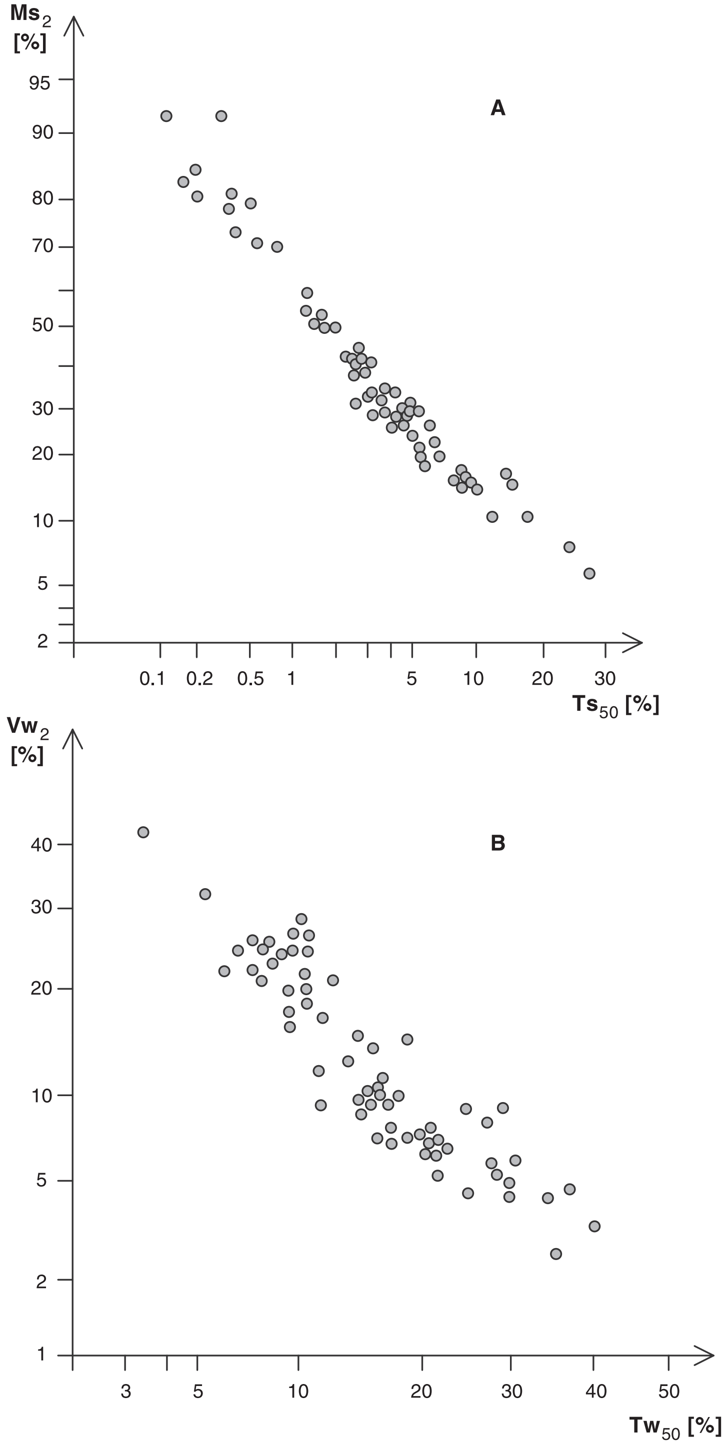

Fig. 10. (A) Sediment load discharged in 2% of time (Ms_2%) vs. the percentage of time needed to carry 50% of the sediment load (Ts_{50}%). (B) Water volume discharged in 2% of time (Vw_2%) vs. the percentage of time needed to carry 50% of the water volume (Tw_{50}%). (Henry law probability scales on both axes).

5.5. Skewness of Cs and Y distributions

The "weighted average quantiles", q*%, Cs*% and Y*%, are the quantiles of daily q_i, Cs_i, Y_i, distributions corresponding to the average runoff (q*), to the discharge-weighted values of suspended solids (Cs*), and to the average sediment yield (Y*). They describe skewness of duration curves and of Cs distribution. Their distribution expressed on a Henry law probability scale provides for a visualization of the extreme quantiles (Fig. 11A–C).

The distribution of the average runoff quantile (q*%) has a relatively narrow range when plotted using a Henry law representation, between 57.5% and 78% for 90% of documented stations. The average sediment flux quantile Y*% range is much wider between 67% and 95%, an expression of additional factors controlling the suspended solid exportation as

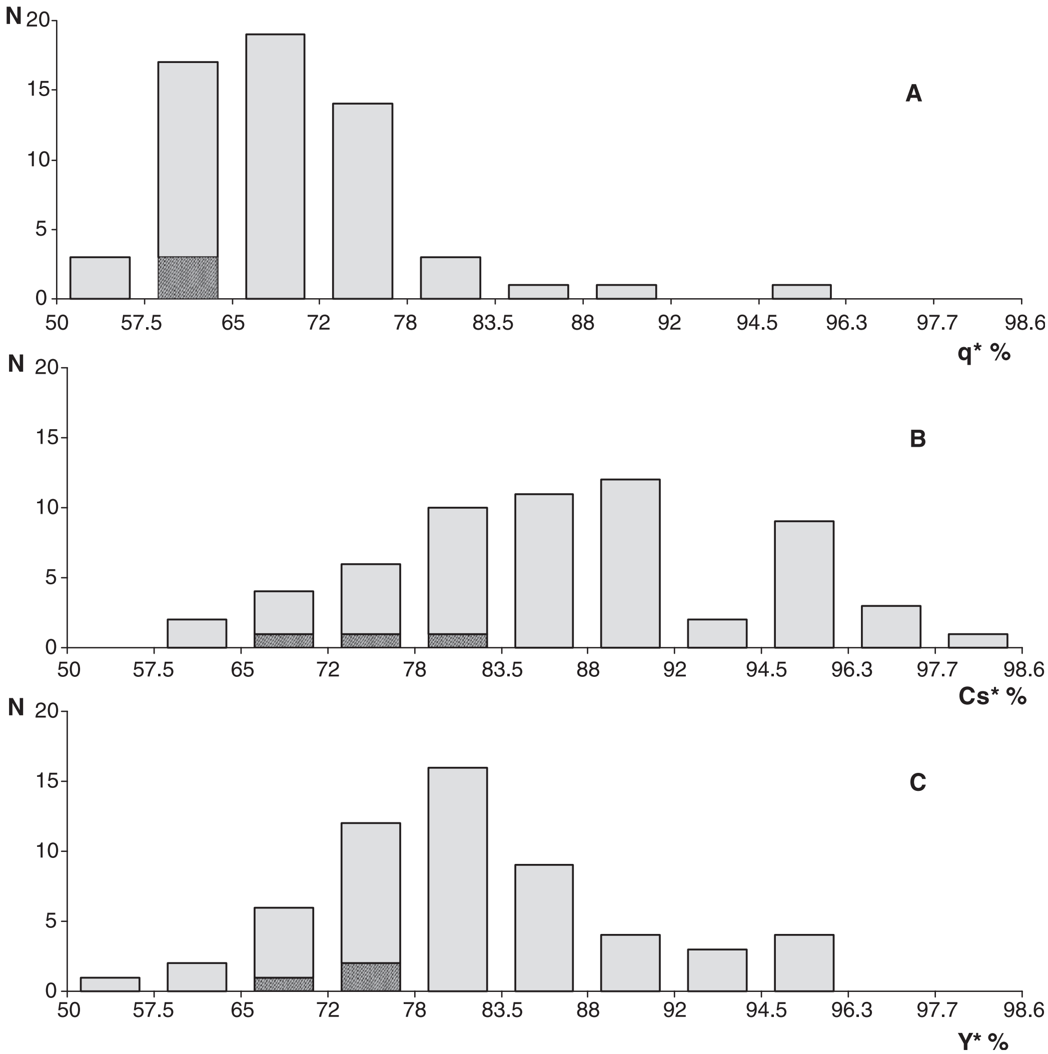

Fig. 11. General distribution of the quantiles corresponding to (A) average discharges (q*%), (B) weighted TSS (Cs*%) and (C) suspended sediment yields (Y*%), in the documented data set expressed in Henry law probability scale (without CLB and MEL) (crossed values: lake-influenced stations).

lithology and relief. The range of the average Cs quantile (Cs*%) is also wider than for q*%: 66% (Bandama) and 98% (Walla Walla).

Cs*% is inversely correlated to basin area and directly correlated to the Cs variability coefficient (Cs^*/Cs_{50}). When Cs^*/Cs_{50} exceeds 10, Cs*% is between 85% and 95%. For the lower Cs^*/Cs_{50} ratios (< 10), Cs*% ranges from 70% to 80%. Cs*% is also inversely correlated to Ts_{50}, the percentage of time needed to carry half of the suspended load (Fig. 12).

Some general patterns in Y*% can also be seen: (1) Y*% is also inversely correlated with basin area; (2) West African low relief basins are characterized by the lowest Y*% quantiles, from 66 to 78%; (3) snowmelt and icemelt fed rivers have middle values from 78 to 88%; (4) erosive and/or high relief basins as Andean rivers in Bolivia, the Walla Walla and the Eel have the highest values from 88% to 96%. As for Cs, a positive correlation between Y*% and the flux variability coefficient, (Y^*/Y_{50}), is noted (Fig. 13). The El Abid, where Cs levels are weakly correlated with q, and the regulated Upper Columbia at Steamboat Rapids are two outliers in this correlation.

5.6. Sediment and water fluxes variability and pseudo rating curves slope

The pseudo rating curves can be described by their slope β_{95-50} where

$$\beta_{95-50} = [\log Cs_{95} - \log Cs_{50}]/[\log q_{95} - \log_{50}]$$

(see Table 2).

β_{95-50} is directly related to the ratio $(Cs^*/Cs_{50})/(q^*/q_{50})$ an expression of the relative magnitude of the two components of sediment flux variability (Fig. 14):

$$\log[(Cs^*/Cs_{50})/(q^*/q_{50})] = 0.39\beta_{95-50} - 0.05 \times (r^2 = 0.44, n = 51)$$

The water discharge variability is given by the ratio q^*/q_{50}, which varies from nearly 1 to more than 4. It is outside the scope of this paper to consider the water discharge variability per se which can be based on records from tens of thousands of stations. The median q^*/q_{50} value is near 2.0 (Table 2). The q^*/q_{50} ratio is controlled by multiple factors such as basin size, runoff origin, lake or groundwater influence. The highest values (>4) are observed for the Khlong Mala in Thailand, the Eel (California) and the

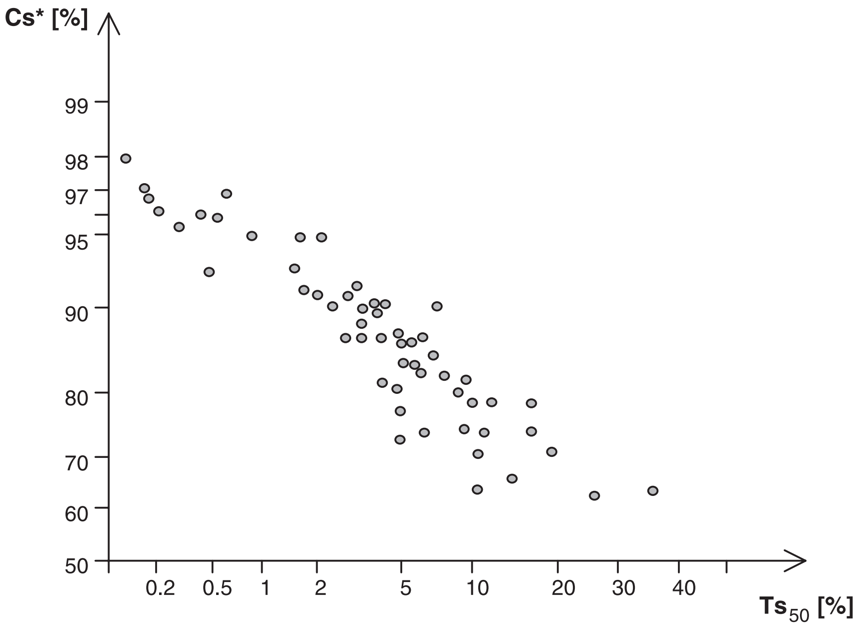

Fig. 12. General relationship between the weighted average total suspended solids quantile (Cs*%) and the percentage of time necessary to carry half of the sediment load (Ts_{50}%). (Henry law probability scale on both axes).

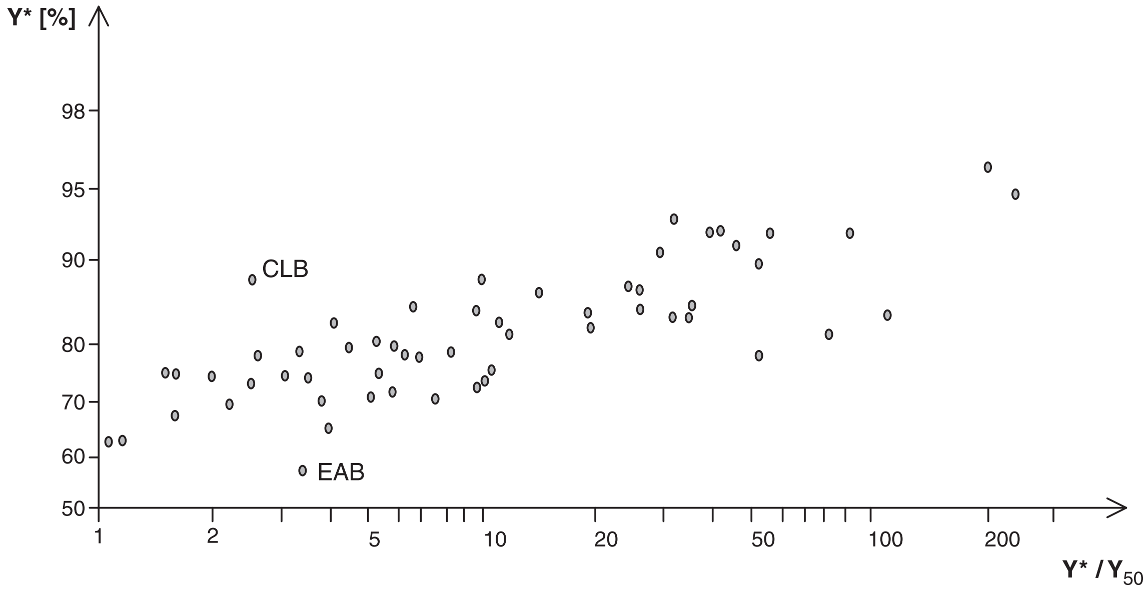

Fig. 13. General relationship between the average specific sediment flux quantiles (Y^*%) and the sediment flux variability as expressed by the average over median flux ratio (Y^*/Y_{50}). CLB = Columbia; EAB = El Abid.

Pecos (New Mexico). The lowest values, below 1.1, are noted for the lake-influenced stations, Rhone Lacustre, Middle Rhine and St. Lawrence, the large Mississippi, ($q^*/q_{50} = 1.03$) and the phreatic Somme River ($q^*/q_{50} = 1.02$).

The exceptional values of 13.9 noted for the Melarchez stream is related to its very small size (7 km^2): it is established here on a daily basis and the value is likely to be even higher if established at a time scale of hours. The only documented q^*/q_{50} ratio smaller than 1

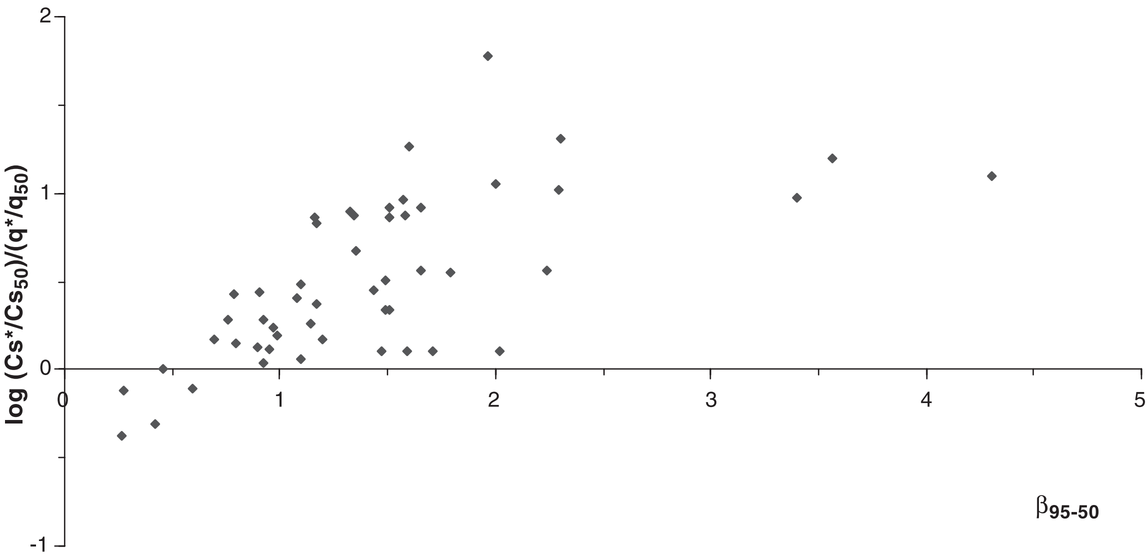

Fig. 14. General relationship between the ratio of TSS variability to water discharge variability, as expressed by the ratio Cs^*/Cs_{50} over q^*/q_{50}, and the pseudo TSS rating curve slope coefficient (β_{95-50}) (without EAB, LCA, RGR, CLB, MEL and SSS).

(0.91) is for the Upper Columbia at Steamboat Rapids. This station was markedly influenced by reservoir operation, with sustained low flows and regulated high flows. Both Melarchez and Upper Columbia stations are provided here only as examples, their values are not included in the statistical or graphical analysis.

As sediment fluxes are directly dependant from water discharges, the proportion of sediment dis-

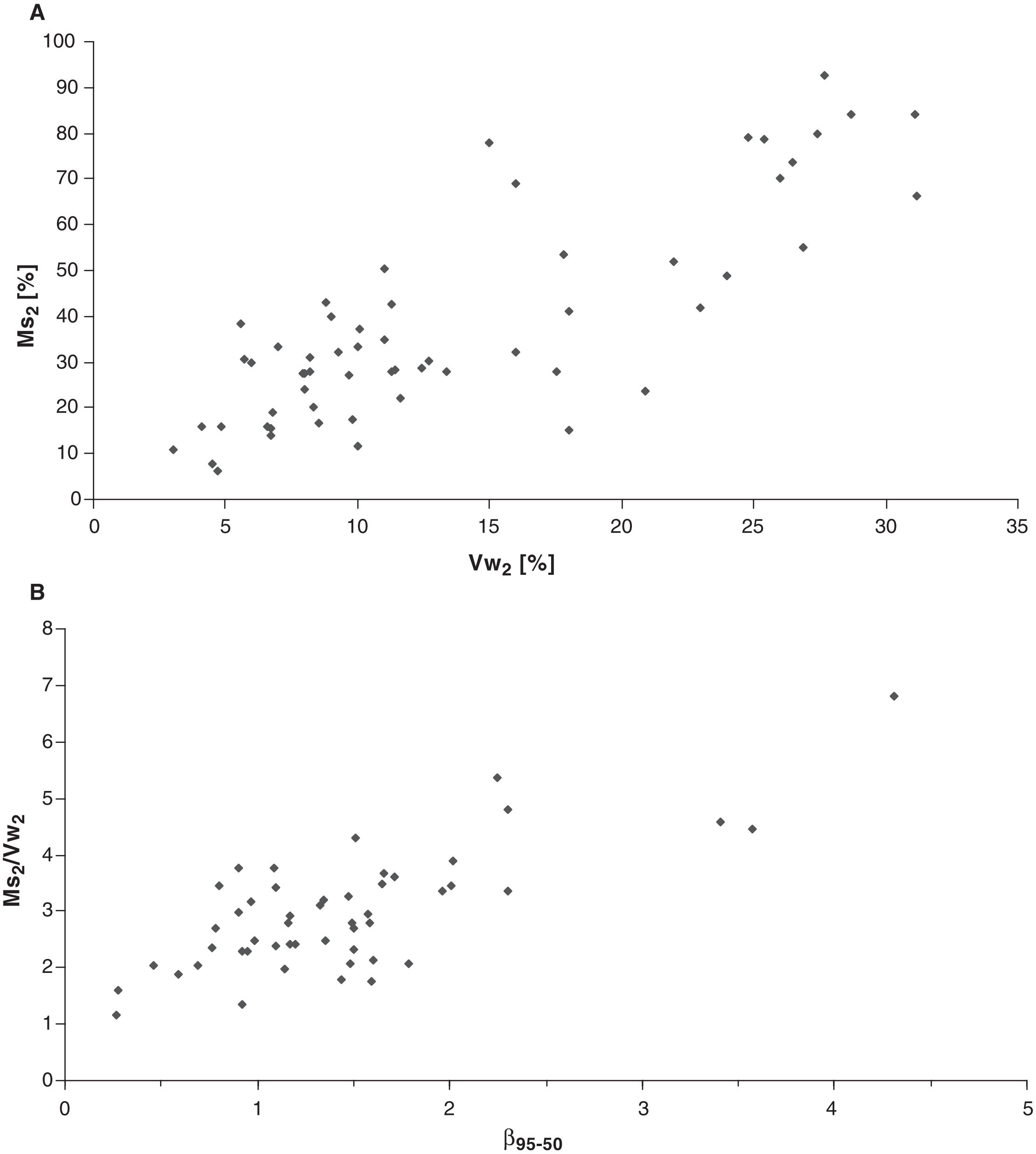

Fig. 15. (A) General relation between the proportions of sediment discharged in 2% of the time (Ms_2) and of water volume discharged in 2% of the time (Vw_2) (omitted data: CLB, MEL, SSS). (B) Relation between the ratio of percentages of sediment and water fluxes discharged during 2% of the time ($Ms_2\%/Vw_2\%$ and the slope of the pseudo TSS rating curve between quantiles 95% and 50% (without EAB, LCA, RGR, CLB, MEL, SSS).

charged in 2% of the time (Ms_2%) is related to the proportion of water volume discharged in the same fraction of time (Vw_2%) (Fig. 15A). However the ratio $Ms_2\%/Vw_2\%$ may vary considerably from 1 to more than 6, an indication of differences in flux duration patterns. This ratio, a measure of relative skewness of sediment and water fluxes, is related to the slope of the pseudo rating curve β_{95-50} as previously defined (Fig. 15B):

$$(Ms_2\%/Vw_2\%) = 1.04\beta_{95-50} + 1.46 \times (r^2 = 0.57; n = 51)$$

This relationship could be used to estimate Ms_2% from Vw_2% values calculated from hydrological records, and from the β_{95-50} coefficient determined at most water quality stations. The influence of the β_{95-50} coefficient is found in the (Cs^*/Cs_{50}) variability: the highest variability rivers are associated with $\beta>2$, the lowest variability rivers ($Cs^*/Cs_{50} < 1.7$) are associated with stations with $\beta < 1$.

6. Perspectives

A set of new metrics describing the variability of river suspended solids concentrations and fluxes has been proposed here and applied to river basins in predam conditions. Our data covers a wide range of environmental conditions but remains limited in its spatial representation. Therefore, the histograms of suspended solids indicators (Figs. 1, 2, 5 and 11) are only illustrative of the enormous range in natural conditions. The histograms suggest a global scale typology (Table 3). The proposed metrics should be tested against river surveys in China (Xu, 1998; Wang et al., 1998), the former USSR (Karaushev, 1977), IAHS-UNESCO surveys conducted in the 1950s and 1960s (Fournier, 1969, 1974) and recent surveys of the Amazon and Zaire basins (P. Seyler and D. Orange personal communication, Olivry et al., 1988).

Multiple factors are shown to regulate the variability of suspended solids transport at the dynamic (daily) level, including runoff, relief, lithology, rainfall pattern, vegetation protection and basin size. Most of these interbasins factors have already been addressed to understand the global scale variation in time-averaged sediment yields (Milliman and Syvitski, 1992; Fournier, 1960; Holeman, 1968; Sundborg and Rapp, 1986; Pinet and Souriau, 1988; Jansen and Painter, 1974; Ludwig and Probst, 1998; Walling and Webb, 1983). Intrabasin factors remain to be addressed, including floodplain and lake retention (Picouet, 1999; Stallard, 1998), and the relative importance of groundwater vs. surface runoff.

Our study confirms the importance of basin size in suspended solids transport. Such dependence has been well established for long-term yields (Walling, 1983; Milliman and Syvitski, 1992). Our indicators of water and sediment fluxes durations can be used to characterize and map the water and sediment flux regimes at the global scale, however, they are also basin-scale dependant. Most hydrological research has involved the study of very small rivers and brooks (hillslope hydrology on basin area less than 100 km^2), which is also the classical scale of many ecological studies. At such scales, the suspended solids may vary from 1 h to the next and the related surveys are therefore extremely tedious. Such scale is not convenient for a worldwide analysis, which is better based on medium-sized representative basins, of a few ten thousand square kilometers.

Our results confirm that arithmetic means and medians commonly obtained from regular water quality surveys worldwide cannot be used to estimate fluxes of particulate material and associated pollutants. The discharge-weighted average may exceed the median by a factor 2–100. The relationships established here between flux duration indicators and basin size provide for an effective way to optimise river surveys for suspended solids, and for dissolved and particulate pollutants for given types of runoff regimes. Sediment rating curves should focus on time spans when most of the sediment flux occurs, particularly in small- and medium-sized basins where sediment is commonly transported during 1–15% of the time. These Cs vs. q relationships should target these periods of high fluxes using "truncated rating curves". The "pseudo rating curves" established with the upper quantiles (50% to 99%) of Cs and q provide for interstation comparison.

The Henry law probability scale allows for a direct linear correlation to be established between duration indicators and their distribution (Figs. 5 and 11). Many of the observed relations between duration indicators (Figs. 10, 12, 13 and 15) are due to intrinsic mathematical properties of the water and sediment duration curves. This includes: (1) the inverse relationship between the suspended flux in 2% of time and the time needed to discharge half of the suspended flux or the water volume; and (2) the relative constancy of the Y_{99}/Y^* ratio, (5–20), across a wide range of sediment yields, as expressed by the Y^*/Y_{50} ratio, and the product of the suspended solid variability (Cs^*/Cs_{50}) by the water runoff variability (q^*/q_{50}).

The proposed metrics allow for multiple anthropogenic impacts on sediment transport and its variability to be evaluated since model data has largely avoided the impacts of land use change, deforestation, intensive agriculture and impoundment. The impact of reservoir construction should be investigated as a major global change to the Earth system: it is now widespread (Avakyan, 1987), has already a major impact on river connectivity and its related biodiversity (Dynesius and Nillson, 1994), on river aging (Vörösmarty et al., 1997b) and hydrograph distortion (Vörösmarty and Sahagian, 2000). The global reservoir development ("neocastorisation", Vörösmarty et al., 1997a) is responsible for a worldwide sediment trapping (Meade et al., 1990; Vörösmarty et al., 1997a, 2003-this volume). Our initial investigation through the station of Upper Columbia at Steamboat Rapids illustrates the hydrograph distortion ($q^*/q_{50} < 1$). Reservoir sediment trapping will increase the natural sediment retention already occurring in lakes, as observed in our data for the St. Lawrence, the Rhone Lacustre and the Middle Rhine. Reservoir trapping may balance the increased soil erosion occurring in headwaters due to land clearing and poor soil conservation practices (see Walling et al., this volume). Also, the natural diversity of suspended solids levels and flux is very likely to be reduced in regulated basins by thus reducing the aquatic biota diversity (Ibanez et al., 1996; Petts and Calow, 1996).

Global hydrological change is a result of climate change, land use change, water transfers and river engineering. These impacts manifest themselves in changes to fluxes of water and related material with global consequences in terms of soil erosion, carbon transfer and storage, nutrients, pollutants and sediments supply to ocean, biodiversity of continental aquatic systems, as well as for the sustainability of human development. The analysis of river basins at the global scale by GIS (Vörösmarty et al., 2000a,b; Meybeck et al., 2001) provides an adapted tool for multifactor studies of river fluxes, provided that preimpacts environmental river archives are collected and studied to understand the natural behaviour of river basins and that present-day river surveys (water runoff, suspended solids, water and particulates quality) are maintained, where threatened as in the former Soviet Union (Kimstach et al., 1998; Zhulidov et al., 2000), or in Africa and parts of other continents (Robarts et al., 2002; Vörösmarty, 2002).

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