Geomorphic/Tectonic Control of Sediment Discharge to the Ocean: The Importance of Small Mountainous Rivers[1]

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ABSTRACT

Analysis of data from 280 rivers discharging to the ocean indicates that sediment loads/yields are a log-linear function of basin area and maximum elevation of the river basin. Other factors controlling sediment discharge (e.g., climate, runoff) appear to have secondary importance. A notable exception is the influence of human activity, climate, and geology on the rivers draining southern Asia and Oceania. Sediment fluxes from small mountainous rivers, many of which discharge directly onto active margins (e.g., western South and North America and most high-standing oceanic islands), have been greatly underestimated in previous global sediment budgets, perhaps by as much as a factor of three. In contrast, sediment fluxes to the ocean from large rivers (nearly all of which discharge onto passive margins or marginal seas) have been overestimated, as some of the sediment load is subaerially sequestered in subsiding deltas. Before the proliferation of dam construction in the latter half of this century, rivers probably discharged about 20 billion tons of sediment annually to the ocean. Prior to widespread farming and deforestation (beginning 2000–2500 yr ago), however, sediment discharge probably was less than half the present level. Sediments discharged by small mountainous rivers are more likely to escape to the deep sea during high stands of sea level by virtue of a greater impact of episodic events (i.e., flash floods and earthquakes) on small drainage basins and because of the narrow shelves associated with active margins. The resulting delta/fan deposits can be distinctly different than the sedimentary deposits derived from larger rivers that discharge onto passive margins.

Introduction

Estimating the flux and fate of fluvial sediments discharged to the ocean has proved to be difficult, as rivers for which we have at least some data account for only about two-thirds of the land area draining into the ocean. Small rivers (drainage basins $<10,000$ km^2) drain only about 20% of the land area, but they number in the many thousands (figure 1) and, as will be seen in this paper, collectively they may contribute much more sediment than previously estimated. Previous attempts (e.g., Holeman 1968; Milliman and Meade 1983) assumed that global sediment flux could be calculated by extrapolating the yield of large and medium-sized rivers over large regions. By failing to take into account adequately smaller rivers, however, this assumption led to mistaken conclusions regarding seaward flux of fluvial sediment.

[1] Manuscript received June 28, 1991; accepted March 18, 1992.

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To predict the sediment load of a small river, we need to understand the interaction of numerous factors, including climate, precipitation (both average and peak), discharge (volume and velocity), basin geology, human impact, and the size of the drainage basin. Many workers have tried relating sediment load (or yield-load normalized for basin area) to net and/or gross precipitation, with varying results (see review by Walling and Webb 1983). For small basins in the western United States, Langbein and Schumm (1958) showed that yields are high with low precipitation (where vegetation is too sparse to retard the erosive capacity of heavy rain and runoff), decrease in areas of medium precipitation, and then increase with higher levels of precipitation. A better relationship was seen between the annual variability of rainfall and sediment transport (Douglas 1967), with basin relief also having an effect (Fournier 1960). Other workers, however, have noted a variety of sediment transport trends relative to precipitation (e.g., Ahnert 1970), leading Walling and Webb (1983, p. 84)

The Journal of Geology, 1992, volume 100, p. 525–544]

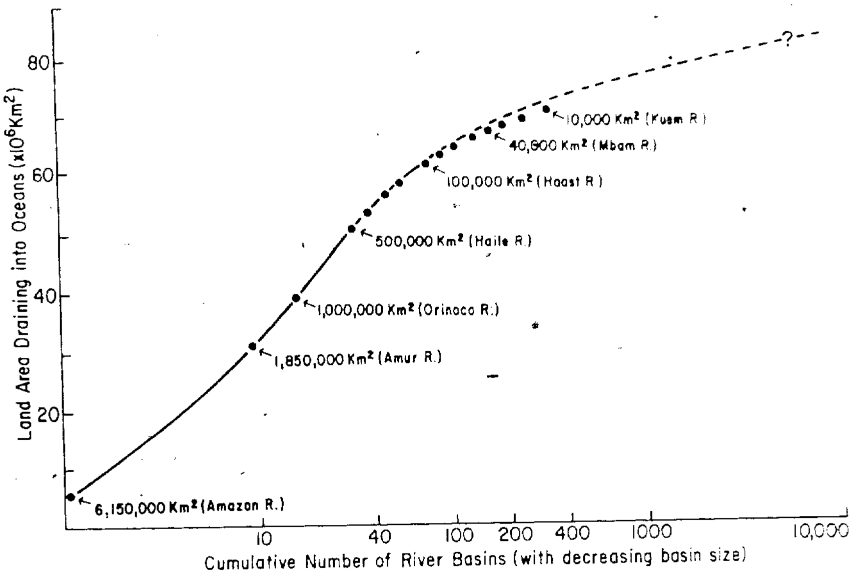

Figure 1. Cumulative drainage basin area of the world's 400 largest rivers with decreasing basin size. Data from Unesco (1978), this paper, and various IAHS publications. The largest river basin (Amazon) accounts for about 6×10^6 km² of the 90×10^6 km² land area (estimated by Milliman and Meade 1983) draining into the oceans; the next nine largest rivers drain an additional 32 $\times 10^6$ km². Because many smaller river basins are not listed in the literature, we can only estimate that the next 390 largest rivers basins drain an additional 40×10^6 km² of land. (Numbers by the dots indicate the drainage basin area of that particular river.) The remaining 20×10^6 km² of the land surface are probably drained more than 10,000 small rivers.

to conclude that, "Current evidence concerning the relationship between climate and sediment yield emphasizes that no simple relationship exists."

In this paper we explore fluvial sediment discharge with respect to basin area and basin elevation. Both of these factors have been analyzed previously, but separately. For example, Ruxton and McDougall (1967) found that denudation rates in the Hydrographers Range (Papua New Guinea) are directly related to local relief. Pinet and Souriau (1988) found that the solid load of a river correlated well with mean basin elevation but not with environmental factors (such as rainfall). Potter (1978), Inman and Nordstrom (1971), and Audley-Charles et al. (1977, 1979) showed that large rivers (and their deltas) drain orogenic belts, but mostly discharge into intracratonic basins and trailing edge margins (see Dickinson 1988, for a detailed review). These latter papers seem to have been overlooked by most geologists and oceanographers.

An inverse relationship between sediment yield and drainage basin area also has been noted (e.g., Schumm and Hadley 1961), and Wilson (1973) suggested that sediment yield depends mainly on land use and basin area (not precipitation). Milliman and Meade (1983) reported that sediment yield increases by about seven-fold for every order of magnitude decrease in drainage basin area, but this correlation considered only rivers with sediment loads >15 million tons (mt)/yr, thereby excluding rivers with smaller sediment loads.

River Data

We began by assuming that the topographic/tectonic character of a river basin plays the major role in determining its sediment load/yield, and that sediment yield was partly determined by basin area. Rather than using mean basin elevation as the topographic parameter, we used maximum headwater elevation, because in many rivers much of the sediment load comes from mountains where the river originates. The Amazon is a widely cited example, in which >80% of the sediment load is derived from the Andes, which constitute only about 10% of the river basin area (Gibbs 1965; Meade et al. 1985). Also, maximum elevations can be estimated quickly from a topographic map. Ahnert (1970) pointed out the strong correlation between local relief and denudation (see review by Summerfield 1991), but such a calculation becomes difficult when dealing with the number and diversity of rivers cited here.

We subdivided river basins into five categories based on the maximum elevation within the hinterland: high mountain (headwaters at elevations >3000 m), mountain (1000–3000 m), highland (500–1000 m), lowland (100–500 m) and coastal plain (<100 m). Based on a preliminary analysis of the yields, mountainous rivers, comprising the largest data set, were subdivided into three categories: Asia and Oceania (generally with very high sediment loads/yields); the high Arctic and nonalpine Europe (with low sediment loads/yields);

and the rest of the world (i.e., North and South America, Africa, the Alps, and Asia Minor, Australia, etc.). Clearly this classification is not without problems. For example, in terms of relief, a small island with elevations of 800–900 m probably should be considered mountainous, not upland. Still, as seen in the following analysis, our elevation-based classification seems valid.

Geomorphologists and hydrologists often use the terms "yield," "sediment yield," or "specific yield" to compare sediment loads between disparate river basins by normalizing sediment load relative to size of the river basin (t/km²/yr). Waythomas and Williams (1988) argue, however, that statistically the comparison of yield vs. basin area can give spurious results, since area is common to both axes; they propose the comparison of sediment load and basin area instead. In this paper, data are presented in terms of both yield and load.

Our data base consists of the loads and yields for 280 rivers (table 1). Collectively these rivers account for $>62 \times 10^6$ km², or about two-thirds of the land surface draining into the ocean (Milliman and Meade 1983). Basin sizes range from <200 km² to >6,000,000 km², and loads vary from <0.02 to >1000 mt/yr. Where discharge values are available, we have converted them to runoff (discharge/basin area). The data come from many sources and from a wide variety of techniques, and therefore the quality is variable. Moreover, many of the data are recycled: for example, some of the data used by Lisitzin (1971) are from Strakov (1961), some of which came from Lopatin (1950) and early IAHS/Unesco compilations.

Modern river sediment loads seldom represent natural loads. Sediment discharge changes as erosion levels change or sediment is stored (i.e., river diversion projects). With the exception of Arctic rivers, where human civilization has had minimal impact, most rivers reflect the results of human activity on the erosional capacity of the rivers, both through deforestation and poor soil conservation (see Milliman et al. 1987) and urbanization (Meade 1982). In contrast, the increased diversion and damming of many rivers has decreased sediment discharge dramatically. The Nile and Colorado deliver no sediment to the ocean, and many other rivers, such as the Mississippi, Zambesi, and Indus, have experienced markedly decreased sediment discharges in recent years. Sediment loads of other rivers have decreased because of other human activities; for example, present-day bed loads of some northeast Italian rivers are 1.5 to 20 times lower than they were in the early 1950s because of legal and illegal riverbed dredging (Idrosser 1983; I. N. McCave written comm. 1991). Often these human impacts work in conflicting ways: dams on the Ganges have decreased sediment discharge, whereas increased erosion in the mountains of Nepal (from deforestation) has increased the load of the confluent Brahmaputra (Hossain 1991). In this paper we cite sediment loads of rivers prior to river diversion (at least, where data are available). However, the values given in this paper still reflect increased soil erosion and thus probably are higher than they would be in natural conditions.

Results

Plots of runoff vs. basin area, load vs. runoff, and load/yield vs. basin area (figure 2) show a variety of trends. Runoff decreases with increased basin area (figure 2*a*), probably because larger river basins tend to include a greater proportion of "lowland," with reduced precipitation and increased evapotranspiration (D. Walling written comm. 1991). Also, our data for smaller rivers are biased toward rivers with high runoff, as small rivers with low runoff are seldom gauged. With respect to sediment load vs. runoff, we find the same random relationship noted by Walling and Webb (1985) for load vs. precipitation (figure 2*b*). In contrast, load/yield vary directly/indirectly with basin area, although the scatter is considerable (figure 2*c*, *d*).

When we divide the rivers into the seven topographic categories, a number of trends show much better correlation. For example, the orographic control of precipitation can be seen from the fact that higher elevation rivers have greater maximum values of runoff vs. basin area (figure 3). The greater scatter of runoff with decreasing basin size reflects the influence of local climate (i.e., precipitation vs. evaporation) in small basins. While the trends of sediment load/yield vs. runoff vary with topography (figure 4), the correlation coefficients (r^2) between load/yield and runoff within any topographic category are not meaningful (table 2).

Log-linear trends within our seven topographic categories were determined from best-fit regression analysis. In accordance with the well-accepted method for not allowing spurious data to influence the slope of the regression, points that fell more than one standard deviation from the determinant (y axis as load or yield) were plotted but not considered in determining the variance accounted for by the best-fit curve (table 2). Our philosophy was simple: we could not be sure of what errors were hidden within sediment load data, we assumed little error in the x-axis (drainage basin area), and we wished to discount as few data points as possible.

Table 1. Tabulation of drainage basin areas, loads and calculated yields for various world rivers.

River	Area ($\times 10^6 km^2$)	Load ($\times 10^6 t/yr$)	Yield ($t/km^2/yr$)	Runoff (mm/yr)	Ref. Citation
A. High Mountain (>3000 m)					
Taan (Tai)	.00077	4.8	6300	2000	WRPC
Lanyang (Tai)	.00098	8.1	8200	2900	WRPC
Tachia (Tai)	.0012	3.6	2900	2050	WRPC
Peinan (Tai)	.0016	24	14,800	2350	WRPC
Tanshui (Tai)	.0027	11	4100	2200	WRPC
Choshui (Tai)	.00315	63	20,000	1900	WRPC
Kaoping (Tai)	.00325	36	11,000	2700	WRPC
Aure (PNG)	.0045	50	11,000		Pickup et al.
Fly (PNG)	.076	115	1500	1300	Harris
Purari (PNG)	.031	80	2600	2500	M/M
Magdalena (Col)	.24	220	920	990	M/M
Irrawaddy (Burma)	.43	260	620	995	M/M
Brahmaputra (Bangl)	.61	540	890		Hossain unp. data
Colorado (USA)	.63	.1(120)	190	32	cf. Meade/Parker
Indus (Pak)	.97	59(250)	260	245	Milliman et al.
Ganges (Bangl)	.98	520	530		Hossain unp. data
Orinoco (Ven)	.99	150	150	1100	Meade pers. comm.
Yangtze (China)	1.9	480	250	460	M/M
Parana (Arg)	2.6	79	30	165	Depetris/Lenardon
Mississippi (USA)	3.3	210(400)	120	150	Meade et al. 1990*b*
Amazon (Braz)	6.1	1200	190	100	Meade et al. 1985
B. Mountain (1000–3000 m)—South Asia/Oceania					
Cleddau (NZ)	.00015	2.0	13,000	6500	Griffiths 1981
Hokitika (NZ)	.00035	6.0	17,000	8900	Griffiths 1981
Cijolang (Ind)	.00038	.73	1900		cf. Walling p.c.
Linpian (Tai)	.00034	1.8	5400	2600	WRPC
Potzu (Tai)	.00043	.8	2000	1300	WRPC
Tungkang (Tai)	.00047	.6	1300	3250	WRPC
Pachang (Tai)	.00047	3.2	6750	1600	WRPC
Houtung (Tai)	.00054	4.3	8000	1650	WRPC
Touchien (Tai)	.00057	2.6	4400	1650	WRPC
Angat (Phil)	.00057	4.6	8000		cf. Walling p.c.
Cimuntur (Ind)	.00058	1.9	3000		cf. Walling p.c.
Cilutung (Ind)	.00060	7.2	12,000		cf. Walling p.c.
Tsengwen (Tai)	.0012	31	26,000	2000	WRPC
Agno (Phil)	.0012	5.0	4350		cf. Walling p.c.
Citanduy (Ind)	.0025	9.5	3700		cf. Walling p.c.
Haast (NZ)	.0010	13	13,000	5970	Griffiths 1981
Huallien (Tai)	.0015	20	13,500	2700	WRPC
Hsiukuluan (Tai)	.0018	20	11,000	2700	WRPC
Waiau (NZ)	.0020	2.6	1300	1400	Griffiths, 1981
Wu (Tai)	.002	6.9	3450	1850	WRPC
Rakaia (NZ)	.0026	4.3	1600	2400	Griffiths 1981
Waimakariri (NZ)	.0032	5.3	1700	1200	Griffiths 1981
Cimanuk (Ind)	.0032	25	7800		cf. Walling p.c.
Kali Brantas (Ind)	.0085	8.1	960		cf. Walling p.c.
Porong (Ind)	.012	20	1700		Hoekstra
Solo (Ind)	.016	19	1200		Hoekstra
Daling (China)	.02	36	1800	50	M/M
Damodar (India)	.020	28	1400	500	Holeman
Huai (China)	.026	14	540		Qian/Dai
Haile (China)	.05	81	1600	40	M/M
Narmada (India)	.089	125	1400		IAHS/Unesco
Hungho (Viet)	.12	130	1100	1000	M/M
Mahandi (India)	.14	60	430	515	Chakrapani/Subramanian
Chao Phya (Thai)	.16	11	68	190	M/M
Liaohe (China)	.17	41	240	35	M/M
Krishna (India)	.25	16(64)	260	140	Ramesh/Subramanian
Godavari (India)	.31	170	550	270	Biksham/Subramanian

Table 1. Continued

River	Area (× 10⁶km²)	Load (× 10⁶t/yr)	Yield (t/km²/yr)	Runoff (mm/yr)	Ref. Citation
Pearl (China)	.44	69	160	690	M/M
Huanghe (China)	.77	1100	1400	77	M/M
Mekong (Viet)	.79	160	200	590	M/M
C. Mountain (1000–3000 m)—N/S America, Africa, Alpine Europe, etc.					
Aso (Italy)	.00028	.18	600		Aquater
Djer (Alg)	.00039	.68	1700	130	cf. Walling p.c.
El Harrach (Alg)	.00039	.63	1600	330	cf. Walling p.c.
Tenna (Italy)	.00049	.45	900		Aquater
Lamone (Italy)	.00052	1.3	2400		IAHS/Unesco
Savio (Italy)	.00060	1.1	1900		IAHS/Unesco
Carmel (NA)	.00063	.40	635		
Foglia (Italy)	.00070	1.0	1200		Aquater
Redwood Cr. (USA)	.00073	1.2	1700	1200	Nolan et al.
Puntenza (Italy)	.00077	.45	600		Aquater
Hii (Japan)	.00092	.90	980	970	IAHS/Unesco
Mad (USA)	.0012	2.4	2000	1070	Janda/Nolan
Tronto (Italy)	.0012	1.1	900		Aquater
Esino (Italy)	.0012	.90	800		Aquater
Biferno (Italy)	.0013	2.2	1700		IAHS/Unesco
Metauro (Italy)	.0014	1.2	870		IAHS/Unesco
Tarsus (Tur)	.0014	.13	93	93	D.J.W. Piper p.c.
Simento (Italy)	.0018	4.0	2000		cf. Holeman
Shkumbini (Alb)	.0019	6.8	3600		IAHS/Unesco
Nagara (Japan)	.0020	.4	210	1800	cf. Walling 1985
Osumi (Alb)	.0020	5.7	2800		IAHS/Unesco
Bou Sellem (Mor)	.0023	.22	100	20	cf. Walling p.c.
Maticora (Ven)	.0025	5.4	2200		IAHS/Unesco
Bradano (Italy)	.0027	2.8	1000		IAHS/Unesco
Pescara (Italy)	.0031	.9	295		IAHS/Unesco
Reno (Italy)	.0034	2.7	800		IAHS/Unesco
Squamish (Can)	.0036	1.8	580	510	Hickin 1989
Isser (Alg)	.0036	6.1	1700	110	cf. Walling 1985
Santa Clara (USA)	.0042	6.0	1400		cf. Meade 1991
Morondava (Mad)	.0042	6.7	1600	430	cf. Walling p.c.
Ord (Austr)	.046	20	630		Kata
Semani (Alb)	.0052	22	4200		cf. Holeman
Lamone (Italy)	.0052	12	2400		IAHS/Unesco
Homathko (Can)	.0057	4.3	750	140	Syvitski/Farrow
Savio (Italy)	.0060	11	1900		IAHS/Unesco
Kliniklim (Can)	.0065	5.0	770	160	Syvitski/Farrow
Tuy (Ven)	.0066	12	1800		IAHS/Unesco
Eel (USA)	.008	14	1700	915	M/M
Arno (Italy)	.0081	2.2	270	400	cf. Holeman
Kuem (Korea)	.010	5.6	560		Chough/Kim
Gøksu (Tur)	.010	2.5	250	400	D.J.W. Piper p.c.
Drini (Alb)	.012	15	1200	325	M/M
Ishikari (Japan)	.013	1.8	150	1000	Jansen et al.
Rioni (USSR)	.013	3.5	630		cf. Hay
Filyos (Tur)	.013	4.2	320	220	Hay p.c.
Tiber (Italy)	.016	6.8	350	450	IAHS/Unesco
Sous (Mor)	.016	1.6	260	200	Snoussi et al.
Churokh (Tur)	.017	15	880		cf. Hay
Stekine (Can)	.018	20	1100	690	Syvitski 1992
Seyhan (Tur)	.019	5.2	270	430	D.J.W. Piper p.c.
Ceyhan (Tur)	.020	5.5	275	470	D.J.W. Piper p.c.
Chira (Peru)	.02	20	1000	250	M/M
Coruh (Tur)	.020	8.1	400	312	Hay unp. data
Meddjerdah (Alg)	.021	13	620		Tixeront
Cheliff (Alg)	.022	3.1	140		Tixeront
Klamath (USA)	.022	2.4	160	340	Janda/Nolan

Table 1. Continued

River	Area (× 10⁶km²)	Load (× 10⁶t/yr)	Yield (t/km²/yr)	Runoff (mm/yr)	Ref. Citation
Colorado (Arg)	.023	6.9	300	190	cf. Holeman
Nakdong (Korea)	.024	10	400	490	Lee/Chough
Han (Korea)	.026	3(>10)	>400	590	Schubel et al.
San Juan (USA)	.031	4.9	160	<100	cf. Holeman
Tana (Kenya)	.032	32	1000	135	M/M
Russian (USA)	.036	24	680	615	Janda/Nolan
Yesil-Irmak (Tur)	.034	0.36(19)	560	150	Hay unp. data
Sebou (Mor)	.040	26	930	130	Snoussi et al.
Skeena (Can)	.042	11	260	690	Binda et al.
Sakarya (Tur)	.046	6.2(8.8)	200	140	Hay unp. data
Kuban (USSR)	.048	7.7	160	270	cf. Lisitzin
Susitna (USA)	.05	25	500	800	cf. Meade/Parker
Moulouya (Mor)	.051	6.6	130	30	cf. Walling p.c.
Copper (USA)	.06	70	1200	650	cf. Meade/Parker
Po (Italy)	.054	13	280	670	IAHS/Unesco
Kizil-Irmak (Tur)	.074	0.46(23)	310	82	Hay unp. data
Ebro (Spain)	.085	1.5(18)	210	220	Palanques et al.
Rhone (Fra)	.09	31	340	530	M/M
Negro (Arg)	.10	13	140	300	cf. Holeman
Brazos (USA)	.11	16	140	65	Judson/Ritter
Rhine (Ger)	.17	0.72	4	190	Lisitzin
Rufiji (Tanz)	.18	17	95	50	M/M
Kura (USSR)	.18	37	200	100	Lisitzin
Fraser (Can)	.22	20	91	510	M/M
Limpopo (Mozam)	.41	33	80	13	M/M
Columbia (USA)	.67	10(15)	22	375	Meade et al. 1990*b*
Rio Grande (USA)	.67	0.8(20)	>30		Meade/Parker
Danube (Rom)	.81	67	83	250	M/M
Orange (SA)	.89	17(89)	100	100	Rooseboom/Harmse
Yukon (USA)	.84	60	71	230	Meade/Parker
Tigris-Euphrates (Iraq)	1.05	>53(?)	>52(?)	45	M/M
Murray (Austr)	1.06	30	29	21	M/M
Zambesi (Mozam)	1.4	20(48)	35	390	M/M
MacKenzie (Can)	1.8	42	23	170	Syvitski 1992
Amur (USSR)	1.8	52	28	180	M/M
Nile (Egypt)	3.0	0(120)	40	30	Sestini
Zaire (Zaire)	3.8	43	11	340	M/M
D. Mountain (1000–3000 m)—Non-Alp Europe and High Arctic					
Lewis (Can)	.00020	.01	730		Church
Ekalvgad Fjord (Can)					
South	.0009	.05	590		Church
Middle	.00011	.064	600		Church
North	.00019	.14	720		Church
Ardour (Fra)	.016	.24	18	670	Snoussi et al.
Colville (USA)	.05	6	120		M/M
Babbage (Can)	.05	3.5	70		Forbes
Garonne (Fra)	.055	2.2	44	320	cf. Probst
Kuskokwim (USA)	.08	5–10(?)	100	510	cf. Syvitski
Loire (Fra)	.115	1.5	13	245	Manikam et al.
E. Upland (500–1000 m)					
Arzilla (Italy)	.00010	.13	1300		Aquater
Tesino (Italy)	.00011	.12	1100		Aquater
Gurabo (PR)	.00016	.26	1700		Simon/Guzman-Rios
Ete Vivo (Italy)	.00018	.29	1600		Aquater
Grande (PR)	.00023	.42	1800		Simon/Guzman-Rios
Esk (NZ)	.00025	.27	1100		Griffiths 1982
Erhian (Tai)	.00035	12.5	36,000	1400	WRPC Taiwan 1988
Misa (Italy)	.00038	.47	1300		Aquater
Waioeka (NZ)	.00064	.38	590		Griffiths 1982
Ruamahanga (NZ)	.00064	.23	360		Griffiths 1982

Table 1. Continued

River	Area (× 10^6 km^2)	Load (× 10^6 t/yr)	Yield (t/km^2/yr)	Runoff (mm/yr)	Ref. Citation
Peikang (Tai)	.00064	2.4	3700	1600	WRPC
Musone (Italy)	.00064	1.1	1700		Aquater
Pamanga (Phil)	.00083	1.0	1300	1800	cf. Walling p.c.
Tutaekuri (NZ)	.00079	.33	420		Griffiths 1982
Usk (UK)	.00091	.44	46	1100	cf. Walling p.c.
Neveri (Ven)	.00098	.29	300		IAHA/Unesco
Karamea (NZ)	.0012	.39	320	2900	Griffiths 1981
Chienti (Italy)	.0013	1.3	1000		Aquater
Motu (NZ)	.0014	2.7	2000		Griffiths 1982
Waiapu (NZ)	.0014	28	20,000		Griffiths 1982
Waipaoa (NZ)	.0016	9.3	5800		Griffiths 1982
Whakatane (NZ)	.0016	.38	2400		Griffiths 1982
Ngaruroro (NZ)	.0019	.88	470		Griffiths 1982
Skykomish (USA)	.0022	.24	110		IAHS/Unesco
Tukituki (NZ)	.0024	1.1	440		Griffiths 1982
Mohaka (NZ)	.0024	.89	370		Griffiths 1982
Chishui (Tai)	.0037	2.0	5300	1400	WRPC
Buller (NZ)	.0063	1.7	270	1660	Griffiths 1981
Wanganui (NZ)	.0066	2.2	330		Griffiths 1982
Yodo (Japan)	.0071	1.9	270		cf. Jansen
Sabine (USA)	.013	.75	58		cf. Jansen
Romaine (Can)	.014	.16	11		Long et al.
Tone (Japan)	.012	3	250	1250	cf. Jansen et al.
Ishikari (AS)	.013	1.7	140		cf. Holeman
Saguanay (Can)	.078	.4	5		Syvitski
Skagit (USA)	.080	.33	41		Curtis et al.
Hudson (NA)	.02	1	50	600	M/M
Muonio Ålv (Swe)	.024	.36	15	500	cf. Kempe et al.
Savannah (NA)	.025	<1(2.8)	110		cf. Meade/Parker
Dnester (USSR)	.062	2.5	40	135	cf. Hay
Oder (Ger)	.11	.13	1.2	150	cf. Lisitzin
Colorado (USA)	.11	1.9	18		Curtis et al.
Burdekin (Austr)	.13	3.0	23		Belperio
Elbe (Ger)	.13	.84	6	160	cf. Kempe et al.
Vistula (Pol)	.20	2.5	13	165	Lisitzin
Uruguay (Urg)	.24	11(?)	45(?)		Deptris/Paolini
Pechora (USSR)	.25	6.1	25	425	Lisitzin
Hai (China)	.26	14	55		Qian/Dai
Indagirka (USSR)	.36	14	39	150	M/M
Volta (Ghana)	.40	0(19)	48	91	UNEP
Don (Ukr)	.42	.77	18		Strakov
Sao Francisco (Braz)	.63	6	10		Depetris/Paolini
Niger (Nig)	1.2	40	33	160	M/M
Volga (Rus/Ukr)	1.4	19	15	400	Lisitzin
Ob (USSR)	2.5	16	6	130	M/M
Lena (Rus)	2.5	12	5	205	M/M
Yenisei (Rus)	2.6	13	5	220	M/M
F. Lowland (100–500 m)					
Ystwyth (UK)	.00017		164	1100	cf. Walling p.c.
Yanchui (Tai)	.00022	2.3	10,000		WRPC
Rangitaiki (NZ)	.00023	.02	83		Griffiths 1982
Avon (UK)	.00026	.042	161		Collins
Esk (UK)	.00031	.018	58		Collins
Urama (Ven)	.00043	.02	47		IAHS/Unesco
Manzanares (Ven)	.00083	.2	250		IAHS/Unesco
Clyde (UK)	.0019	.11	60	430	cf. Walling p.c.
Tyne (UK)	.0022	.13	61	680	cf. Walling p.c.
S. Pedro (IC)	.0033	.07	22		cf. Walling p.c.
Chehalis (USA)	.0034	.11	34		Curtis et al.
Wye (UK)	.0040	.20	51	630	cf. Walling p.c.

Table 1. Continued

River	Area (× 10⁶km²)	Load (× 10⁶t/yr)	Yield (t/km²/yr)	Runoff (mm/yr)	Ref. Citation
St. Jean (Can)	.0056	.25	48		Syvitski
Severn (UK)	.0068	.44	65	380	cf. Walling p.c.
Cape Fear (USA)	.013	.29	21		Simmons
Rappahannock (USA)	.0016	.09	56		Meade et al. 1990a
Tano (Ghana)	.016	.35	22		Akrasi/Ayibotele
Delaware (USA)	.017	.68	39	190	Judson/Ritter
Pearl (USA)	.017	.8	46		Curtis et al.
Scheldt (Bel)	.022	1	45		Salomons/Mook
Abitibi (Can)	.024	.14	6		Syvitski
Potomac (USA)	.025	.72	28	310	Judson/Ritter
Roanoke (USA)	.025	<1(2.0)	80		cf. Meade/Parker
Santee (USA)	.027	tr(1.0)	37		cf. Meade/Parker
Meuse (Neth)	.029	0.70	24		IAHS/Unesco
Altamaha (USA)	.035	<1(2.5)	71		cf. Meade/Parker
Attawapiskat (Can)	.036	0.2	6	320	Syvitski
Weser (Ger)	.038	0.33	8	230	cf. Kempe et al.
Mbam (Ghana)	.042	3.6	85		Akrasi/Ayibotele
Tombigbee (USA)	.05	2.2	45		Curtis et al.
Y. Bug (USSR)	.034	0.53	15		cf. Hay
Alabama (USA)	.057	2.3	40		Curtis et al.
Susquehanna (USA)	.062	1.8	29		cf. Meade/Parker
Moose (Can)	.06	0.4	7	410	Syvitski
Seine (Fra)	.065	1.1	18	130	cf. Manickam et al.
Nottaway (Can)	.066	1.0	15	270	Kranck/Rufman
Sanaga (Cam)	.13	2.8	20	500	UNEP
Yana (USSR)	.22	3	14	130	cf. Lisitzin
Senegal (Sen)	.27	1.9	8	48	Martins/Probst
Severnay Dvina (USSR)	.35	4.5	13	330	cf. Lisitzin
Dnieper (USSR)	.38	2.1	5.2	86	cf. Hay
Kolyma (USSR)	.64	6	9	140	cf. Lisitzin
Sao Francisco (Braz)	.64	6	9	150	M/M
St. Lawrence (Can)	1.1	4	4	435	M/M
G. Coastal Plain (<100 m)					
Creedy (UK)	.00026	.01	53	500	cf. Walling p.c.
Welland (UK)	.00053	.01	14	200	Wilmot/Collins
Exe (UK)	.00060	.01	24	860	cf. Walling p.c.
Bristol Avon (UK)	.00067	.02	27	400	cf. Walling p.c.
Swale (UK)	.0014	.034	24		Collins
Nene (UK)	.0015	.01	11	160	Wilmot/Collins
Ely Ouse (UK)	.0036	.03	8		Wilmot/Collins
Neuse (USA)	.0069	.084	12		Simmons
Ogeechee (USA)	.0067	.06	9		Curtis et al.
Pamlico (USA)	.011	.21	19		Curtis et al.
Peedee (USA)	.023	.4	17		Curtis et al.
Kalkkinen (Fin)	.025	.006	0.26	250	cf. Kempe et al.
Kymi joki (Fin)	.037	.15	0.40	80	cf. Kempe et al.
Apalachicola (USA)	.044	.17	4	470	Judson/Ritter
Tar (USA)	.057	.11	2		Meade et al. 1990b

Note. In most cases loads and yields have been rounded to the second digit. Load value in parentheses indicates pre-dam values which have been used in compiling the load/yield vs. basin area trends (figures 4–8). Y and L designate rivers whose yields (Y) or loads (L) are >1 s.d. from the computed mean; therefore they have not been used in calculating the equations and correlation coefficients in table 2.

Alb = Albania; Alg = Algeria; Arg = Argentina; Austr = Australia; Bangl = Bangladesh; Belg = Belgium; Braz = Brazil; Can = Canada; Col = Colombia; Fin = Finland; Fran = France; Ger = Germany; IC = Ivory Coast; Ind = Indonesia; Mad = Madagascar; Mor = Morocco; Mozam = Mozambique; NZ = New Zealand; Nig = Nigeria; Pak = Pakistan; PNG = Papua New Guinea; Phil = Philippines; Pol = Poland; PR = Puerto Rico; Rom = Romania; SAf = South Africa; Sen = Senegal; Swe = Sweden; Tai = Taiwan; Tanz = Tanzania; Thai = Thailand; Tun = Tunisia; Tur = Turkey; Urg = Uruguay; Ven = Venezuela; Viet = Viet Nam.

MM: cf. Milliman/Meade

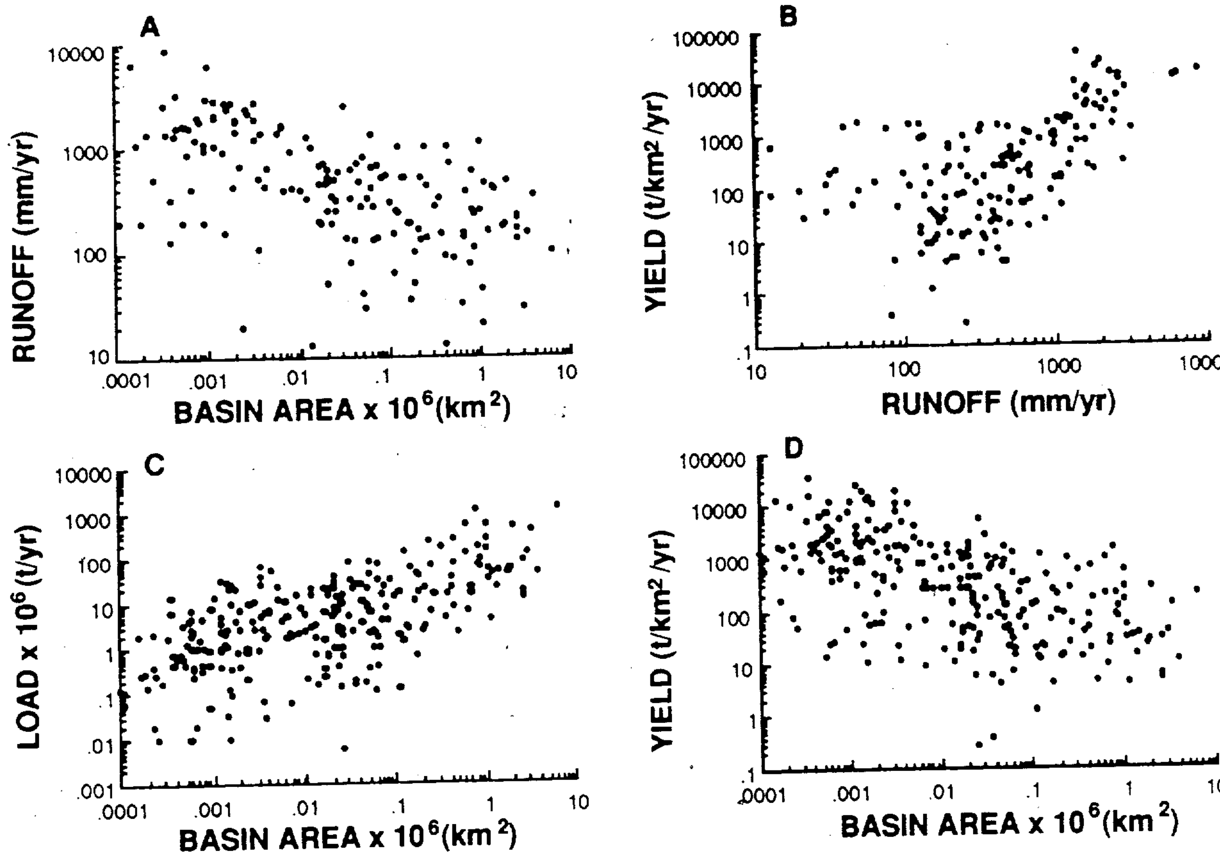

Figure 2. Runoff vs. basin area (A); sediment yield vs. runoff (B); and load (C); and yield (D) vs. basin area for the rivers listed in table 2. Note the generally inverse relationship between runoff and yield with basin area, the strongly positive correlation between load and basin area, and the great amount of scatter for yield vs. runoff.

As can be seen in table 2, <10% of the rivers were discounted on the basis of having either load or yield values more than 1 standard deviation from the mean. In fact, deviations from the predicted norm often reflect either unique fluvial/drainage basin conditions or possible erroneous data bases; various examples are discussed below.

For load/yield vs. basin area, the correlations with the various topographic categories are generally good, ranging from 0.70 to 0.82 (load vs. area) and 0.62 to 0.89 (yield vs. area) (figures 5 and 6; table 2). The relatively poor correlation coefficients (r^2 = 0.81 for load, but 0.32 for yield) for coastal plain rivers, however, suggest that basin area plays little or no role in determining sediment discharge from these low-lying rivers.

Mountainous rivers have greater loads and yields than do upland rivers, which in turn have greater loads and yields than lowland rivers (figures 5 and 6), although there is some overlap in values. For example, mountainous rivers with basin areas of about 10,000 km^2 have sediment yields between 140 and 1700 $t/km^2/yr$ (e.g., Negro, Porong), whereas yields for similar-sized upland rivers are 60–250 (e.g., Sabine, Tone), and lowland rivers 20–60 (e.g., Cape Fear River). With the exception of two rivers (Waiapu and Niger), no upland, lowland or coastal plain river has a sediment load >20 mt, even though more than 25 upland and lowland rivers have drainage basin areas >100,000 km^2. In contrast, nearly 60 mountainous rivers have loads ≥20 mt (table 1). Mountainous rivers draining South Asia and Oceania have much greater yields (2–3 fold) than rivers draining other mountainous areas of the world, and an order of magnitude greater than rivers draining high-Arctic and non-alpine European mountains (figure 5).

The trend of increasing sediment yield with decreasing size of mountainous rivers becomes less pronounced in river basins less than about 4000 km^2 in area, as seen by the relative number of rivers that fall >1 standard deviation from the mean

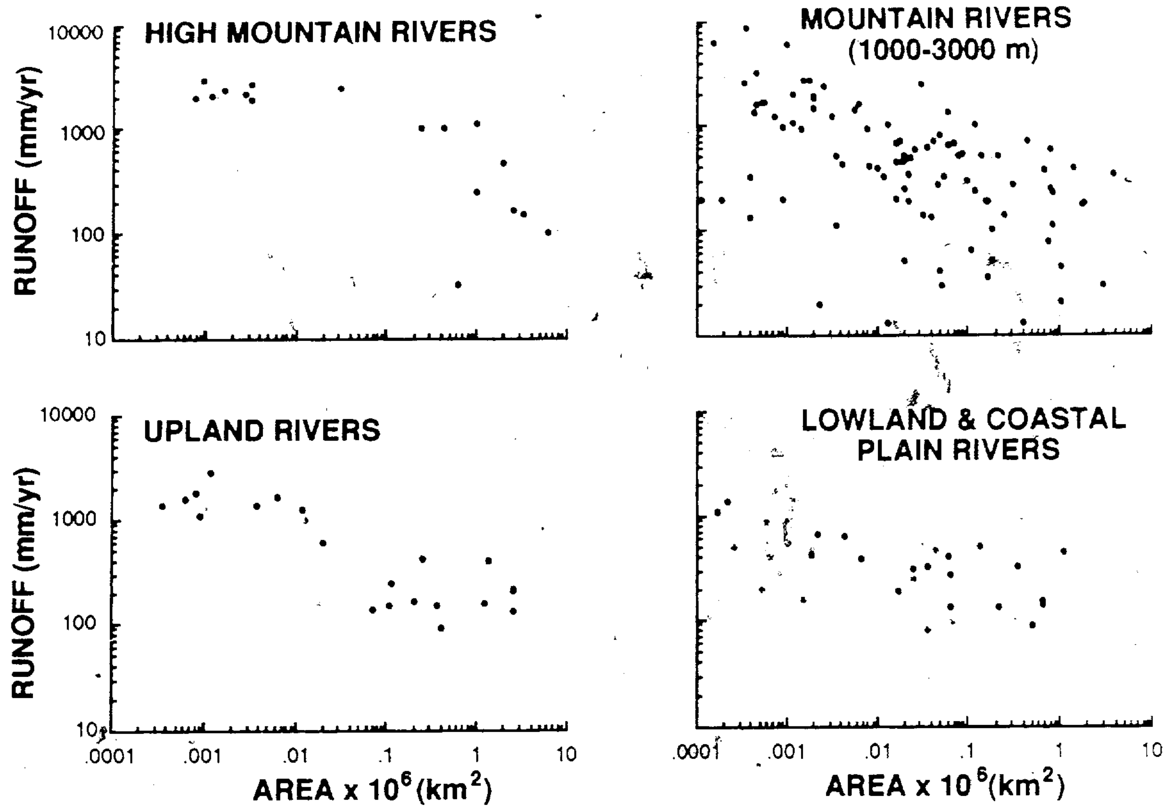

Figure 3. Variation of runoff vs. basin area for rivers within four topographic categories. Note the decreasing maximum runoff values with increased river basin area and with lower elevations.

(table 1). Some very small rivers in New Zealand and Taiwan, for example, have yields much lower than expected, while others have much higher yields; together they account for one-third of the deviating rivers designated in table 1. Slaymaker (1987) noted a decreased sediment yield in rivers <1000 km in western Canada. This variance of sediment yield in very small river basins probably reflects the dominance of single types of geology or microclimate in small basins, whereas larger river basins are modulated by a greater range of conditions.

With the exception of the high Arctic, latitude does not appear important. Equatorial rivers (e.g., the Tana in Kenya) do not have significantly higher yields than rivers of similar size in higher latitudes e.g., the Susitna in Alaska). High-Arctic mountainous rivers whose headwaters rise in the Arctic (e.g., Colville, Babbage), however, have much lower yields than Arctic rivers whose headwaters are in lower latitudes (e.g., Copper, Yukon, MacKenzie). The reason is not clear, but it may be related to lower levels of precipitation and shorter periods during which the rivers can transport sediment (Milliman and Syvitski, unpub. data).

Discharge of Sediment by World Rivers

North America. Most rivers draining eastern North America are upland, lowland, or coastal plain rivers, with correspondingly low sediment loads. Much of the sediment leaving the contiguous United States and Canada comes from three large rivers—the Mississippi, MacKenzie, and Colorado (now dammed)—and smaller west coast rivers (e.g., Eel, Columbia, Fraser), most of which drain mountains. Large discharges of sediment also come from rivers draining western Canada and Alaska; the Susitna, Cooper, and Stekine rivers for example, collectively drain an area <4% that of the Mississippi, but discharge nearly a third as much sediment (table 1); the many other rivers along this coast also must contribute large amounts of sediment: the average thickness of Holocene sediment on the southeast Alaskan Shelf is 55 m (Molnia et al. 1978) and fiords into which

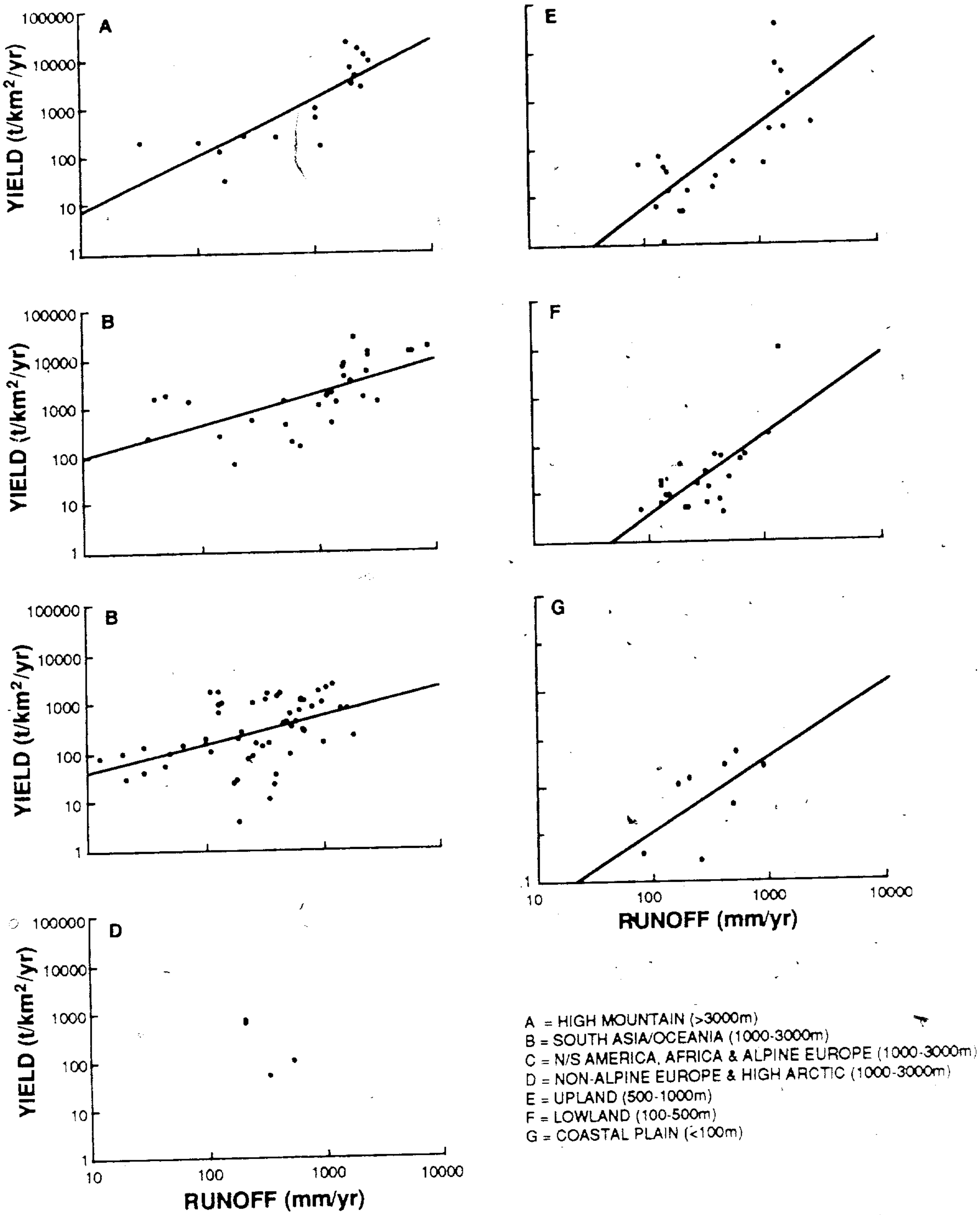

Figure 4. Relation of sediment yield and runoff for the seven topographic categories of river basins listed in table 1. The equations for the slope plus the correlation coefficients are given in table 2. In nearly all instances the correlation coefficients are poor and the deviations from the trend are numerous.

Table 2. Equations and Correlation Coefficients (R^2) for Load/Yield versus Runoff and Basin Area.

	$Y = aR^b$			$Q_s = cA^d$			$Y = cA^f$			
River System (m)	a	b	r^2	c	d	r^2	c	f	r^2	N[d]
>3000	.5	1.16	.66	280	.46	.80	280	−.54	.84	21
1000–3000										
area 1[a]	20	.65	.40	170	.52	.70	210	−.46	.76	41
area 2[b]	10	.56	.19	65	.56	.74	65	−.46	.70	90
area 3[c]	. . .	. . .	. . .	50	.73	.78	25	−.39	.89	10
500–1000	.002	1.74	.56	12	.42	.82	12	−.59	.89	55
100–500	.002	1.67	.49	8	.66	.81	8	−.34	.62	43
<100	.001	1.57	.36	1	.64	.81	5	−.20	.32	15

Note. R = runoff (mm/a); A = area ($km^2 \times 10^6$); Q_s = load ($t/a \times 10^6$); Y yield (t/km^2a). a, b, c, d, e, f = regression coefficients.
r^2 = data variance accounted.
[a] Area 1 = N/S America, Africa, Alpine Europe.
[b] Area 2 = South Asia and Oc[...]ia.
[c] Area 3 = Non-alpine Europe[...]High Arctic.
[d] N = number of rivers.

many of these rivers discharge have Quaternary sediment thicknesses >500 m (Syvitski et al. 1987).

South America. Eastern South America is drained by four major rivers (Magdalena, Orinoco, Amazon, Parana) all having their headwaters in the Andes Mountains. Collectively they drain more than half the continent (10 of 17 million km^2). In contrast, rivers draining the western Andes are less known, but collectively their sediment discharge may be of the same magnitude as the larger rivers draining eastward (smaller area but higher yields). If the average river draining the western sides of the mountains is 15,000 km^2, then the average sediment yield would be about 1200 $t/km^2/yr$ (figure 6c), equaling a sediment discharge of 2.4 bt/yr (1200 multiplied by an area of 2×10^6 km^2). This calculated sediment flux may be unrealistically high, as the arid parts of the western slope may contribute little sediment to the sea; nevertheless, the total sediment discharge from western South American rivers probably is much higher than the 168 mt estimated by Milliman and Meade (1983). At present we can cite only one west coast river, the Chira (Peru), and the data represent only two years of measurement, for one of which, however, the load was 75 mt (yield 3700 t/km^2: Burz 1977).

Europe. Europe is generally regarded as having the lowest sediment flux to the sea (e.g., Holeman 1969; Milliman and Meade 1983). However, the Alps (a collision orogen) are a major sediment source, and the short rivers draining south into the Mediterranean have high to very high yields, generally 500 to >1000 $t/km^2/yr$ (table 2). For example, the little known Semani River (Albania) has more than twice the annual discharge (22 mt') of the collective sediment discharges of the well-known north-flowing rivers Garonne, Loire, Seine, Rhine, Weser, Elbe, Oder, and Vistula, most of which drain upland or lowland terrain. Many rivers draining north from the Alps are tributaries to the Danube, the largest river in Europe. The Rhine is the only large alpine river that drains north to the sea, but most of its sediment load is trapped in Lake Constance; upstream of Lake Constance, the river has a sediment yield consistent with other alpine rivers, but downstream of the lake, its yield is similar to a lowland/coastal plain river (Holeman 1968).

USSR and Asia Minor. The large rivers of the former Soviet Union draining north to the Arctic Sea (Ob, Lena, and Yenesi) are generally considered to have anomalously low sediment yields (see Milliman and Meade 1983). However, their sediment yields and those of other Russian rivers correlate well with other upland and lowland rivers throughout the world (table 1; figure 6). Russian and Ukrainian rivers draining south into the Black Sea are considered lowland rivers, with correspondingly low sediment loads.

Although poorly documented in western literature, the rivers draining the Caucasus Mountains and the Anatolian and Taurus mountains in Turkey have high sediment yields, which is to be expected from rivers draining the same collision orogen as the Alps. Before dam construction in the 1950s, the three largest Turkish rivers emptying into the Black Sea discharged an estimated 50 mt of sediment annually (Hay 1992'. Collectively, in fact, the rivers draining northern Turkey and the

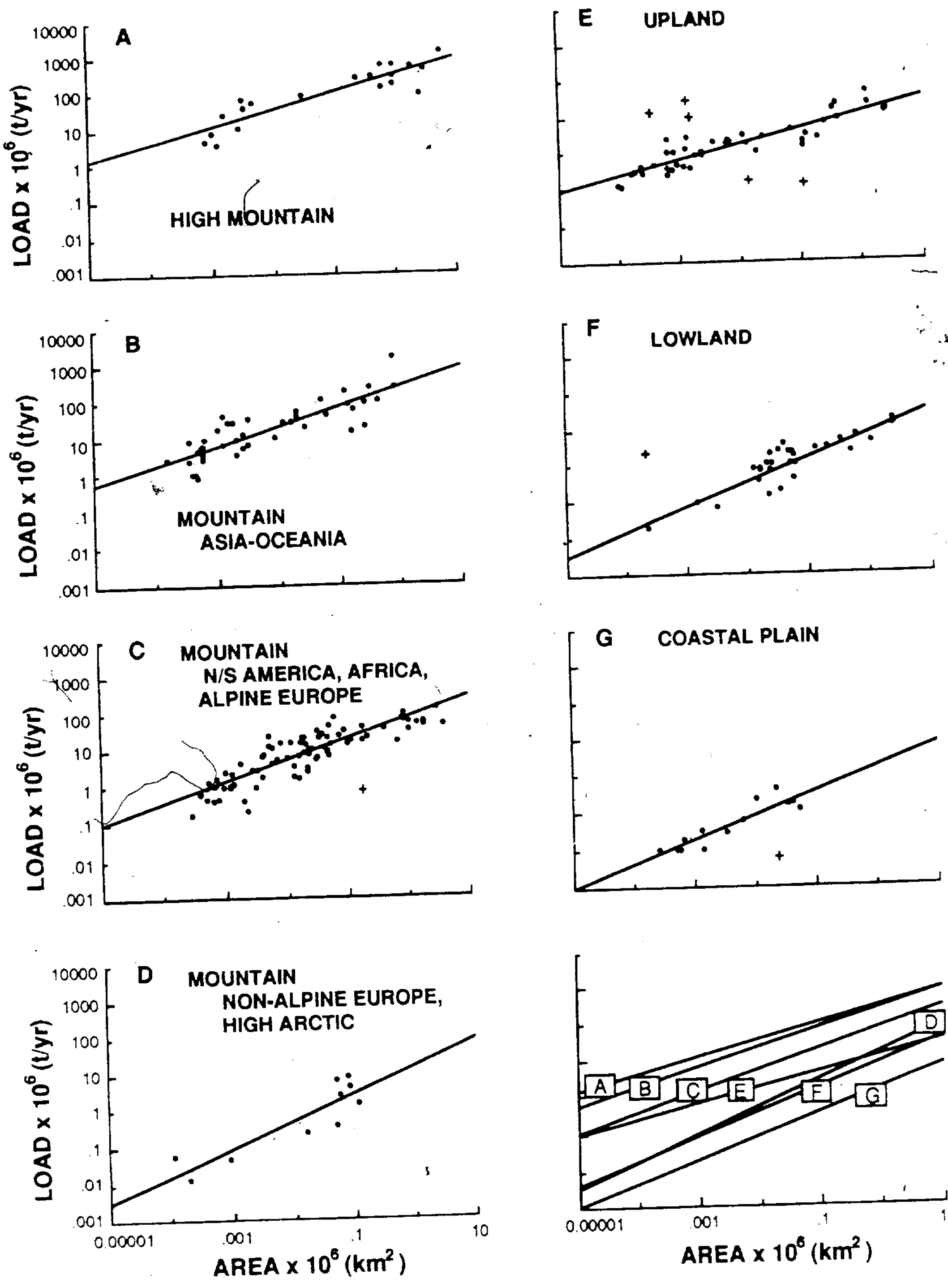

Figure 5. Variation of sediment load with basin area for the seven topographic categories of river basins listed in table 1. For all river types the correlation is strong (r^2 ranging from 0.70 to 0.82). Note that only 13 rivers deviate by more than one standard deviation from the computed means.

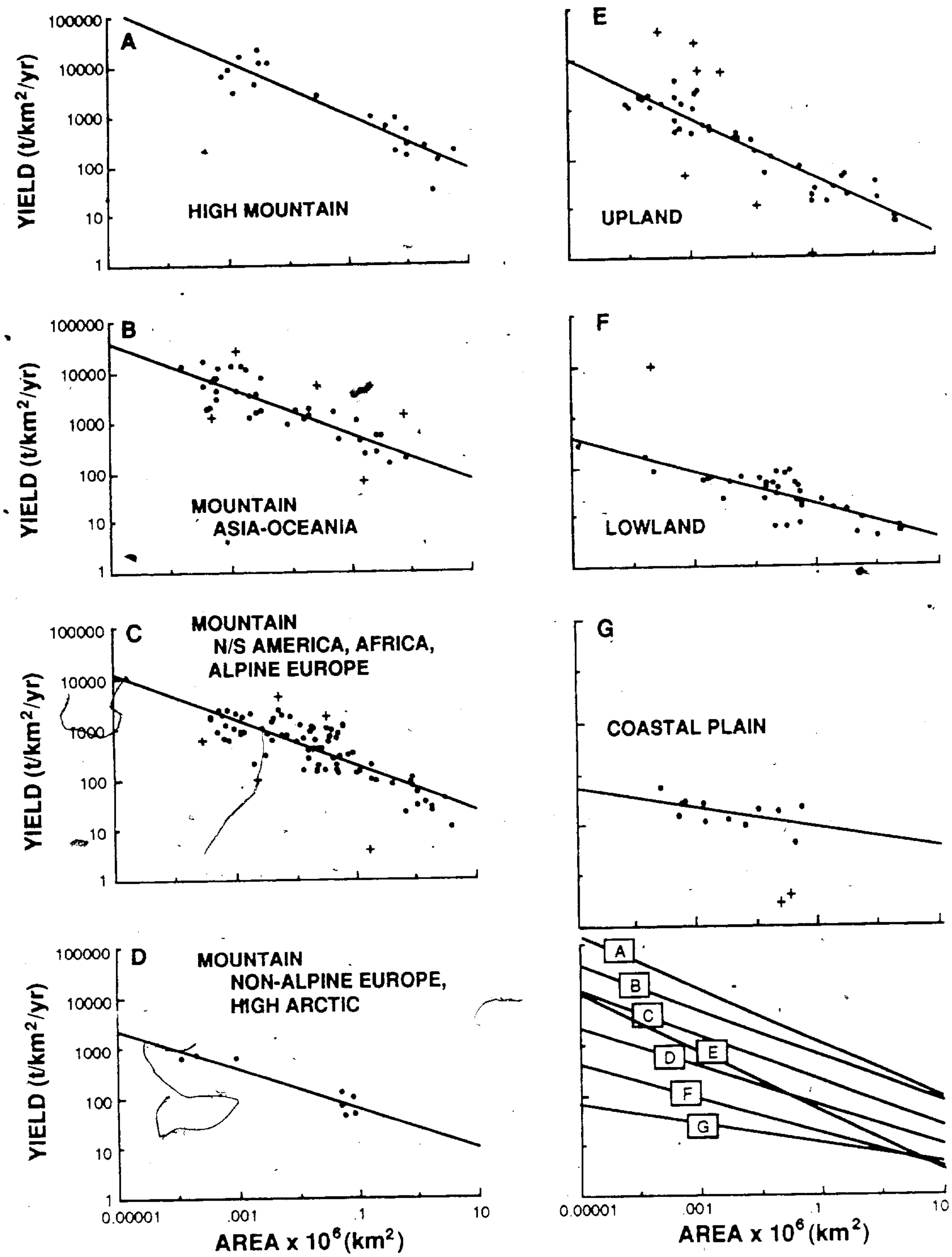

Figure 6. Variation of sediment yield with basin area for the seven topographic categories of river basins listed in table 1. For all river types, except lowland and coastal plain rivers, the correlation is strong (r^2 ranging from 0.70 to 0.89).

western Caucasus Mountains may contribute more sediment to the Black Sea than the Danube and southwestern Russian and Ukranian rivers.

Africa. Rivers draining Africa discharge a disproportionately small amount of sediment to the sea, although the discharge calculated by Milliman and Meade (1983) is probably low (Walling 1985). At first it seems incongruous that Africa, one of the highest-standing continents (in terms of average elevation), has a low sediment flux. Only when viewed in terms of drainage basin morphology does the discharge pattern make sense; some large rivers with low loads (e.g., Senegal, Niger) are nonmountainous, and many small rivers in western Africa are lowland rivers, with correspondingly low sediment loads/yields. The major sediment discharge comes from rivers draining the rift mountains in eastern Africa (Nile, Zambesi, Limpopo, Rufiji) or rivers draining the mountains in Morocco, Algeria, and Tunisia (e.g., Mouloura, Sebou, Cheliff). The loads and yields of these rivers compare well with other mountainous rivers of similar size. The lack of rainfall throughout most of central Africa contributes to the low discharge rates (Walling 1985).

Asia and Oceania. With the notable exception of the loess-imparted Yellow River basin, the high sediment yield in Asia is restricted to rivers draining the Himalayan Mountains in southern Asia. These loads and yields are substantially higher than all other mountainous rivers of the world (save Oceania). Rivers draining eastern Asia have normal (Korea) or low (Japan) sediment loads relative to other mountainous rivers; dams in Japan may be important in these values. The Chao Phya has a much smaller load (11 mt) and yield (68 t/km^2/yr) than other south Asian rivers of similar size; one wonders if the river basin has anomalous erosion patterns or if the data are erroneous.

Milliman and Meade (1983) used data from Taiwan and New Zealand to suggest that rivers draining the high-standing islands between Australia and Asia have unusually high sediment yields. Assuming a sediment yield of 1000 t/km^2/yr, they calculated that these high-standing islands may account for 20% of the global sediment flux to the oceans. In fact, new data from New Guinea, the Philippines, Java, New Zealand and Taiwan (table 1) suggest average yields closer to 3000!

Australia. While Australia is nearly as large in area (2.2×10^6 km^2) as the islands in Oceania, the continent is generally low standing. Only rivers draining mountainous areas in the north (e.g., Ord) and east (e.g., Murray) appear to have high loads. The fact that much of Australia has an arid climate accentuates the low discharge from rivers, although the yields from the Ord, Murray, and Burdekin compare favorably with other rivers of similar size (table 1).

Implications

Factors Controlling Sediment Discharge. The data presented in tables 1 and 2 and figures 5 and 6 clearly show the importance of basin size and topography in terms of sediment discharge. Because sediment yields are strongly dependent upon the size of the drainage basin, they cannot be portrayed accurately on a map; global displays of sediment yields (e.g., Milliman and Meade 1983; Walling 1987) essentially reflect topography (as well as basin size)—high yields equate to mountainous areas, low yields to lowlands.

While many of our data need to be re-evaluated and updated, we suggest that topography and basin area have order-of-magnitude control over sediment discharge of most rivers. In contrast, average net precipitation and runoff generally affect sediment discharge to a lesser extent. For example, the Orange, Sous, and Isser rivers, which drain arid basins, have similar or slightly lower sediment yields than mountainous rivers with moderate rainfall, whereas rivers draining areas with very heavy precipitation (e.g., Solo, Purari, Cooper) have slightly higher yields (see table 1).

The role of sediment erodability (mainly a function of geology, vegetation cover and human activity) clearly cannot be discounted. High erosion rates throughout much of southern Asia partly reflect poor soil conservation, the result of deforestation and over-farming. Milliman et al. (1987) concluded that the Huanghe's sediment load was an order of magnitude lower before humans began farming the loess hills of northern China. (Saunders and Young [1983] suggested that moderate land use can increase sediment yield by a factor of 2–3, while intensive land use can increase it an order of magnitude.) In contrast, the anomalously low sediment yields of rivers northern European and English rivers at least partly reflect river channel management (see Petts et al. 1989) combined with extensive vegetation cover and relatively low soil erodibility (D. Walling 1991 written comm.). The Oder, for example, has the lowest yield (1.2) of any river cited in this paper.

We should emphasize that elevation or relief is, in some ways at least, only a surrogate variable for tectonism. This paper and others (e.g., Hay et al. 1989) that have emphasized the correlation between topography and sediment yield, relief or elevation is used, because it is easily expressed numerically and therefore can be manipulated as a statistical variable. However, the strong correlation between sediment and topographic relief may not indicate that the second is the cause of the first, but rather that both are caused by another factor less susceptible to numerical description—namely, tectonism. It is probably the entire tectonic milieu of fractured and brecciated rocks, oversteepened slopes, seismic and volcanic activity, rather than simple elevation/relief, that promotes the large sediment yields from active orogenic belts.

What Is the Sediment Flux to the Sea? This question really has two parts: how much sediment is carried by rivers, and how much escapes the present-day land/estuarine environment? The answer to both is more or less the same—we don't know. The sediment discharged, however, may be more than previously estimated. Milliman and Meade (1983) calculated an annual global discharge of 13.5 bt by extrapolating average sediment yields for documented rivers over large regions with similar topography. However, since the data used by Milliman and Meade came mostly from large rivers, the yields were necessarily lower than if they also had included smaller rivers. In addition, constrained by the lack of data, Milliman and Meade conservatively estimated the yields for mountainous coastal rivers to be 1000 t/km^2/yr. The new data presented in this paper suggest that the yields for rivers draining Oceania are probably ≥3000/km^2/yr, meaning that the high-standing islands of Oceania (approximate area of 3×10^6 km^2) may be closer to 9 bt than the 3 bt estimated by Milliman and Meade! Similar percentage increases might hold for southeastern Alaska, western South America, the southern Alps-Caucasus orogen and NW Africa (e.g., Walling 1985).

There is another way to calculate the flux: The rivers listed in table 1 >10,000 km^2 account for a combined 62×10^6 km^2 in drainage basin area, and collectively they discharge (before dam construction) slightly more than 8 bt of sediment annually. River basins <10,000 km^2 account for slightly >20% of the total drainage area to the ocean (20×10^6 km^2; figure 1). Assuming that the mean drainage basin area of these rivers is 1000 km^2, an additional 20,000 rivers would be required to account for the entire 20×10^6 km^2. If we assume that 10% of these rivers (i.e., 2000) are mountainous and that of these half drain high mountains and or Asia/Oceania and the other half drain mountains exclusive of the Arctic and non-alpine European, the combined loads of these rivers would be (8mt/river/yr × 1000 rivers) + (1.5 mt/river/yr × 1000 rivers) (see figure 5), or a total of 9.5 bt/yr. This number is surprisingly close to our estimate for the rivers (mostly small) draining Oceania, but since it does not include southern Asia or western North and South America, our calculation may be too conservative. Although the yields for similar-sized upland and lowland rivers are significantly lower (900 and 90 t/km^2/yr, respectively), there are more of them, and the combined small upland and lowland rivers might contribute another 1–2 bt annually. Adding undocumented rivers larger than 10,000 km^2 probably would add another 1–2 bt. The combined total suspended discharge conservatively might be 20 bt.

A regional example of the influence of small mountainous rivers in sediment discharge can be seen in southern Europe. Milliman and Meade (1983) pointed out that the rivers draining south from the Alps have much higher yields than those rivers draining northern Europe. Assuming a yield of 120 t/km^2/yr and a combined drainage area of 0.55×10^6 km^2, Milliman and Meade calculated that the southern rivers discharge 66 mt/yr to the Mediterranean Sea. In fact, the sediment loads of southern alpine rivers are much greater: the 24 mountainous rivers listed in table 1 drain only 0.22×10^6 km^2, but collectively they discharge more than 140 mt of sediment annually. If the values are similar for the remainder of the combined drainage area, total sediment discharge would be 350 mt/yr, five times the value calculated by Milliman and Meade.

Unfortunately, calculating world-wide discharge is more complicated, because not all sediment carried by large rivers reaches the sea: some is stored along the lower reaches of rivers and adjoining deltas. If subsidence rates in the Bengal Delta are 1–2 cm/yr (cf. Milliman et al. 1989; J.R. Curray oral communication 1991), for example, 40–80% of the sediment load carried by the Ganges/Brahmaputra may be sequestered in the subaerial portion of the delta, perhaps explaining the relative lack of Holocene sediment accumulating on the adjacent shelf (Kuehl et al. 1989) and the lack of net progradation of the delta front (Alam 1987). As a result, it is entirely possible that the present sediment discharge of large rivers has been overestimated.

Because rivers are being dammed at an increasing rate, many of the numbers given in this paper are probably out of date. Pearce (1991) states that 13% of all fluvial discharge is presently dammed. Ironically, with their high sediment yields and therefore (at least relatively) high sediment loads

Asian rivers can fill their dammed reservoirs quickly, thereby shortening the lives of these dams more quickly than calculated by the engineers who designed them. But since pre-dam sediment loads for most rivers were artificially high due to human activities in the drainage basins, dam construction, for example on the southeastern US rivers, probably has offset anthropogenically enhanced erosion, and post-dam discharges may not be too different from those prior to European colonization (Meade and Parker 1985).

Even if the present global flux of river sediment could be calculated, the significance of such a number to either future or past river discharge is questionable. Mid-twentieth century river discharge (to the sea) may have been about 20 bt/yr, nearly half of this amount coming from Oceania and another third from southern Asia. But because sediment loads may have increased by a factor of 2–10 since humans began farming (see Saunders and Young 1983; Berner and Berner 1987), the annual sediment discharge 2000–2500 yr ago may have been considerably <10 bt. Extensive human influence in Oceania and southern Asia suggests that sediment loads in this area are disproportionately elevated.

Active vs. Passive Margin Rivers. All rivers with large sediment loads originate in mountains. Most large rivers discharge to the sea along passive continental margins, and they act as point-sources for sediment influx; as a result, large deltas (e.g., Mississippi, Nile, Amazon, Ganges, Indus, Yangtze) form on passive margins or in marginal seas (Audley-Charles et al. 1977; Inman and Nordstrom 1971; Potter 1978).

In contrast, rivers that drain mountainous islands and the active edges of continental margins (e.g., western North and South America) or collision margins (southern Europe, southern Asia) are generally much smaller, but collectively they may transport similar amounts of sediment as do passive margin rivers. In most instances, however, classic deltas do not form, although coalescing deltaic/fan deposits may form along the outer continental margins (e.g., Thornberg et al. 1990). Because these small rivers empty onto active margins, the deposits may be subducted, such that the sedimentary sequences are neither thick nor old. The sedimentary sequences also should experience an accelerated thermal history, thus complicating petroleum maturation.

These calculated trends still may underestimate the relative importance of small rivers in terms of sediment delivery to the sea: smaller rivers often have no estuaries, are more susceptible to periodic floods and (because of their steeper gradients and proximity to source material) have larger contributions from bedload material, which seldom is included in the sediment load values reported in the literature (e.g., Syvitski and Farrow 1983). In addition, along active margins earthquakes and volcanic eruptions can result in mudslides and floods that can increase the sediment loads of adjacent rivers. In the four months following the eruption of Mount St. Helens (Washington State), for example, the sediment load of the Cowlitz River (a tributary of the Columbia) was 140 mt, compared to a normal annual load for the Columbia of 10 mt (Hubbell et al. 1983); for the few years after the eruption, the Columbia River discharged an estimated 35 mt/yr (Meade and Parker 1985).

Smaller mountainous rivers are therefore more likely to discharge larger percentages of their sediment loads directly to the sea than do larger rivers. Moreover, the sediment is more likely to escape the narrow shelves to deeper basins during both high and low stands of sea level.

The Santa Clara River (southern California) serves as an example of both the episodicity and shelf-escape possible with small rivers. During 18 yr of monitoring, more than half the total sediment transported by the Santa Clara was carried in three floods, lasting a total of seven days (Milliman 1991, after Meade 1992). Following a major flood in 1969, Drake et al. (1972) traced the fate of the discharged sediment as it entered the Santa Barbara Basin and ultimately was dispersed there by a series of slumps and turbidity currents.

If sediment discharged from small mountainous rivers can by-pass active margins during high stands of sea level, then standard models of sequence stratigraphy, which have been so successful in determining the position of eustatic sea level in older sedimentary deposits (e.g., Haq et al. 1987), may have less application off active margins. On the other hand, active margin deposits appear to be far less common in the geological record, probably because about of them are subducted back into the arc/orogens that border the active margins (von Huene and Scholl 1991).

ACKNOWLEDGMENTS

We thank G. A. Griffiths, D. Walling, R. H. Meade, B. J. Hay, M. B. Collins, and I. N. McCave for supplying unpublished data and pointing out published sources. Meade, McCave, and Walling, as well as M. G. Gross, B. U. Haq, and S. A. Schumm, helped considerably with their comments on earlier versions of this paper. A special thanks to

K. W. G. LeBlanc of the Geological Survey of Canada for his liaison and data manipulation. JDM acknowledges the National Science Foundation and the Office of Naval Research for long-term support through which many of the data and insights regarding rivers were collected.

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