VOLUME 91 NUMBER 1

THE JOURNAL OF GEOLOGY

January 1983

WORLD-WIDE DELIVERY OF RIVER SEDIMENT TO THE OCEANS[1]

JOHN D. MILLIMAN[2] AND ROBERT H. MEADE
Woods Hole Oceanographic Institution, Woods Hole, MA 02543
U.S. Geological Survey, Denver, CO 80225

ABSTRACT

New data and new estimates from old data show that rivers with large sediment loads (annual discharges greater than about 15×10^6 tons) contribute about 7×10^9 tons of suspended sediment to the ocean yearly. Extrapolating available data for all drainage basins, the total suspended sediment delivered by all rivers to the oceans is about 13.5×10^9 tons annually; bedload and flood discharges may account for an additional 1–2 $\times 10^9$ tons. About 70% of this total is derived from southern Asia and the larger islands in the Pacific and Indian Oceans, where sediment yields are much greater than for other drainage basins.

INTRODUCTION

The major source of both solid and dissolved material transported to the oceans is the rivers draining the continents. Two distinct methods have been used to estimate the mass of riverine sediment entering the oceans: one estimates the mass being carried oceanward by rivers (e.g., Kuenen 1950; Lopatin 1950; Holeman 1968), while the other method estimates denudation of the continents (e.g., Gilluly 1955; Fournier 1960; Schumm 1963). Sediment loads based on this latter method are significantly greater than those based on the former because they include a large amount of eroded sediment that never reaches the ocean. Lopatin's and Holeman's estimates, for example, are 12.7 and 18.3×10^9 t yr^{-1} whereas those by Gilluly and Fournier are 32 and 51×10^9 t yr^{-1} (see Holeman 1968, for a comparison).

Access to new data concerning major world rivers, many of which previously were unavailable, now allows us to compute new sediment load budgets. Since the publication of Holeman's paper, for example, new data have become available for the MacKenzie, Amazon, Orinoco, Limpopo, and Zaire Rivers and for several Alaskan rivers, as well as more than 25 years of recent records for the Yellow (Huangho) and Yangtze Rivers (and smaller Chinese rivers).

In this paper the data are presented in two ways. First, discussion is limited (with a few notable exceptions) to rivers with annual sediment discharges in excess of 15×10^6 t. As a basis for comparison with earlier published data, the values given by Holeman (1968) and Lopatin (later updated by Strakhov 1961, and Lisitzin 1972) are listed. Also listed are the drainage basin areas and water discharges, which (with the exception of North American and Chinese rivers) have been obtained from the compilation by UNESCO (1969, 1974, 1978, 1979). In the second part of the paper, these data are combined with other measurements and estimates to derive the average sediment discharges for the various continents. For most of the largest drainage basins, one or more of the listed rivers are

[1] Manuscript received July 14, 1982; revised September 14, 1982.

[2] Contribution number *5127* from the Woods Hole Oceanographic Institution.

[JOURNAL OF GEOLOGY, 1983, vol. 91, p. 1–21]

0022-1376/83/9101-002$1.00

TABLE 1

QUALITY OF DATA BASE FOR 21 LARGEST RIVER-SEDIMENT DISCHARGES TO THE OCEAN

River	Average Sediment Discharge (10^6t/yr)	Adequacy of Data Base
1. Ganges/Brahmaputra	1670	Inadequate
2. Yellow (Huangho)	1080	Good
3. Amazon	900	Inadequate
4. Yangtze	478	Good
5. Irrawaddy	285	Inadequate(?)
6. Magdalena	220	Inadequate
7. Mississippi	210	Good
8. Orinoco	210	Sufficient
9. Hungho (Red)	160	Inadequate
10. Mekong	160	Sufficient
11. Indus	100	Sufficient
12. MacKenzie	100	Poor to fair
13. Godavari	96	Inadequate
14. La Plata	92	Inadequate to Sufficient
15. Haiho	81	Good
16. Purari	80	Inadequate
17. Zhu Jiang (Pearl)	69	Sufficient to good
18. Copper	70	Sufficient
19. Danube	67	Good
20. Choshui	66	Sufficient
21. Yukon	60	Sufficient

used to derive the sediment yield (sediment load per square kilometer of drainage basin area per year).

POTENTIAL ERRORS IN ESTIMATES

The data upon which our estimates are based have a number of serious potential errors, which need to be taken into account when considering either local or world-wide budgets. The most important factor is the widely variable quality of the data, which is a result of differences in measurement techniques, in lengths of observation, and in sampling procedures. Inadequate sampling with depth, for example, can only underestimate the sediment load, particularly the coarser fraction. Moreover, many rivers are poorly studied or unmeasured during large floods, when sediment discharge may be particularly important. Rivers in the more developed countries tend to be well documented, while data from less developed countries commonly are less adequate. Unfortunately, these latter rivers are the ones that discharge the most sediment to the ocean. Of the 21 largest rivers that contribute nearly 50% of the total sediment discharge to the oceans, only five (Yellow, Yangtze, Mississippi, Haiho, and Danube) can be considered adequately documented (table 1).

Compounding the problem still further is our inability to gain access to original data; quoting published reports results in recycled data. Perhaps the ultimate example of recycling is the estimate for the Irrawaddy quoted by Lopatin/Strahkov/Lisitzin and by Holeman (300×10^6 t^{-1} yr), which in fact is based on measurements made by the British in the 1870's (Gordon 1885). Where possible, we have quoted the source for our data and discussed those data that appear to be extensively recycled. If the estimates are new, we present brief discussions of the measurements and assumptions used in calculating the estimates.

In addition to the sampling problems, many of the available river data have been collected at gaging stations upstream from the river mouth, commonly at distances far enough upstream so that some of the load may deposit between the station and the river mouth or, conversely, downstream tributaries may contribute additional sediment. Judging from the number and prominence of subaerial deltas, we suspect that a considerable mass of the sediment estimated to be transported by riv-

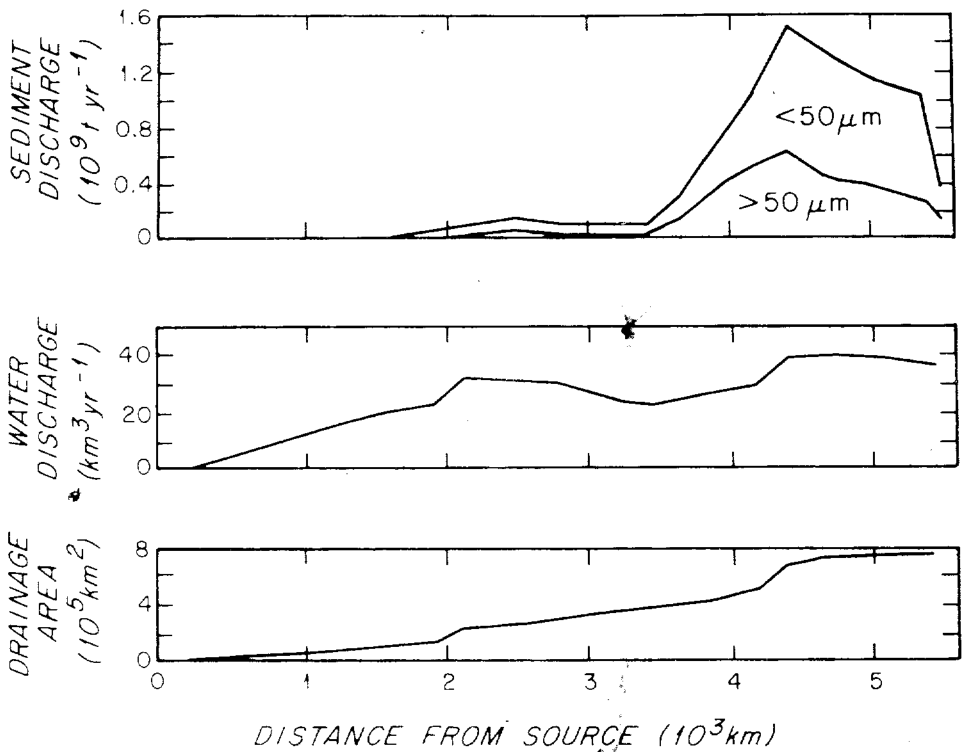

FIG. 1.—Graphs showing sediment discharge, water discharge, and drainage area along the Yellow River (Huangho) of China. Modified after Long and Xiong (1981), and based on continuous daily measurements at a number of gaging stations during 1965–1974. Sediment discharge (top graph) increases markedly as the river enters the loess region (about 3500 km from source), decreases as the river flows across the alluvial plain (4500–5350 km), and decreases most markedly in the delta region (5350–5500 km). Last downstream gaging station is at Lijin, about 5350 km from the source of the river.

ers never reaches the ocean. Perhaps the best documented example is the Yellow River (Huangho) of China (fig. 1) where 33% of the sediment is deposited on an alluvial plain and another 43% in the delta region. Only 24% of the sediment that flows out of the Sanmen Gorge and into the lower Yellow River actually reaches the ocean (Long and Xiong 1981).

Even if our data were uniformly accurate, our world-wide budget probably underestimates the sediment loads of small rivers. For every order of magnitude increase in drainage-basin area, the sediment yield decreases about 7-fold (fig. 2). In large part, this reflects the inability of smaller basins to store sediment; what is eroded is more completely removed from the small basin. Similar relationships have been documented in interior continental drainage basins (Schumm and Hadley 1961; Lopatin 1962). Thus the input of sediment to the oceans from small mountainous islands (Oceania) and steep slopes adjacent to the ocean (Pacific coast of North, Central and South America) may have a greater impact upon the world budget than we have calculated.

The bedload transported by rivers has not been considered, primarily because it has not been measured or even estimated for the great majority of large rivers. However, in some rivers the bedload appears to be appreciable. For instance, in the Zaire River, bedload may be greater than the suspended load (Peters 1978). (In this paper we use the term "suspended load" to describe all the sediment carried in suspension, which includes sand, as well as the silt and clay often referred to as "washload.") Coleman (1969) mentioned sand waves and dune fields within the Brahmaputra that during monsoon floods can reach heights of 15 m, lengths of 200 to 900 m, and migrate downstream by as much

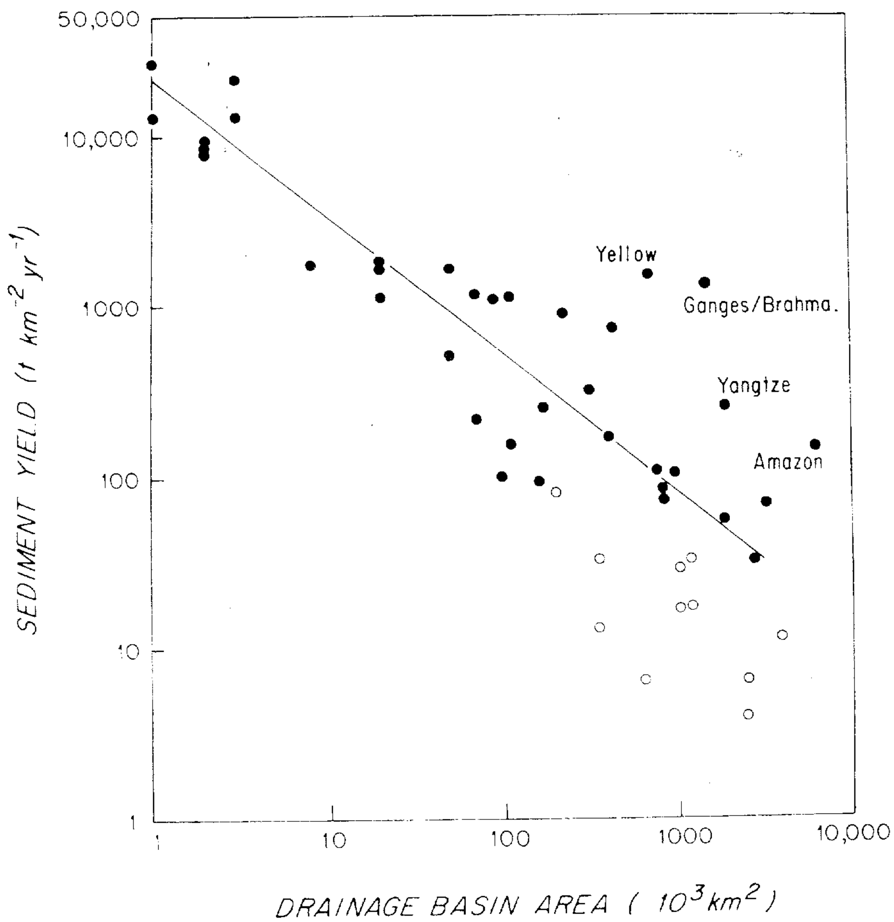

FIG. 2.—Comparison of sediment yields and drainage basin areas for all major sediment-discharging rivers (greater than 10×10^6 t yr^{-1}). Open circles represent low-yield rivers draining Africa and the Eurasian arctic. Smaller basins have larger yields, although the largest rivers (Amazon, Yangtze, Ganges/Brahmaputra and Yellow) all have greater loads than their basin areas would predict.

as 600 m/day. Extrapolating this rate across the river channel gives daily bedloads of 10^6 to 10^7 t; ECI-ACE, 1970, estimated the annual bedload of the Brahmaputra-Ganges (at Bhagyakul, about 80 km upstream from the mouth) to be 734×10^6 t. These examples may be exceptions in that many large rivers presumably have very small bedloads compared to material in suspension. In the Amazon River, for example, our preliminary estimate of bedload at Obidos (Brazil) is only about 10% of the suspended load. A reasonable estimate for the world-wide annual bedload is about 1–2 10^9 t, although how much of this material actually reaches the ocean is debatable.

Finally, these average values do not take into account catastrophic events such as severe floods. This effect probably is particularly important in small rivers. For instance, the Santa Clara River in southern California has a drainage basin of only 4100 km^2 and an average suspended-sediment discharge of 69 $\times 10^3$ t^{-1} yr (Curtis et al. 1973). Yet during a flood in 1969, this river carried 50×10^6 t, 22 $\times 10^6$ t of which were transported in a single day (Drake et al. 1972). Similarly, the Oued Medjerdah (Tunisia) contributed an estimated 25×10^6 t during a 6-day flood in 1973, a sediment yield in excess of 1000 t km^{-2} yr^{-1} (Claude and Loyer 1977). Such catastrophic floods need not occur often to produce a major impact upon the sediment flux to the ocean. Unfortunately, such events are rarely measured.

SEDIMENT LOADS OF MAJOR RIVERS

North America.—The sediment loads of the large rivers in North America have been measured for as many as 50 years, although those of the large rivers in the extreme north have been measured for only a few years. Curtis et al. (1973) have summarized the data collected through 1969 in many of the U.S. rivers.

Rivers draining the eastern part of the continent have small sediment loads. The St. Lawrence River, although its drainage basin is large, transports a very small load because most sediment is trapped in the Great Lakes. Lisitzin (1972) listed the Hudson River as carrying 36×10^6 t yr^{-1}, but in fact this river transports only about 10^6 t yr^{-1}.

Rivers discharging into the Gulf of Mexico transport the greatest amount of sediment in the conterminous United States. The Mississippi River is the largest but, because of reservoir construction, bank stabilization, and improved soil conservation, its sediment load has decreased considerably during recent years. Strakhov/Lisitzin give the annual sediment discharge as 500×10^6 t, Holeman gives 349×10^6 t; our estimate, which is based on the 17-year mean for the period 1963–79, is 210×10^6 t. This estimate includes the Mississippi at Tarbert Landing (130×10^6 t) and Atchafalaya at Simmesport (80×10^6). Similarly, the Brazos River now carries only half the amount estimated by earlier workers (Curtis et al. 1973).

Sediment loads in rivers of the western United States generally are considered to be large, but again dams and reservoirs have decreased them considerably. The best-known example is the Colorado River, which once transported an average of 135×10^6 to yr^{-1} through the Grand Canyon, but now transports less than 0.1×10^6 t into the Gulf of California. Dams apparently have decreased the annual sediment discharge of the Columbia River to about 8×10^6 t. The largest sediment load to the west coast of the conterminous U.S. is by the Eel River of northern California, with an estimated annual sediment discharge of 14×10^6 t; Curtis et al. (1973) reported the annual sediment discharge of the Eel to be 26×10^6 t, but this average includes the December 1964 flood, which was considered to be a 200-year flood (Janda and Nolan 1979). A somewhat larger annual load is carried by the Fraser River, which drains much of interior British Columbia—20×10^6 tons, a considerable amount of which is fine sand (Milliman 1980).

Many of the large rivers in North America, however, are ones that previously have been either inadequately measured or altogether ignored. The Yukon River in Alaska, for instance, contributes an estimated 60×10^6 t yr^{-1}. The estimate for the Yukon River is based on a 5-year average of measurements taken at Eagle and on the assumption that this load remains approximately constant downstream to Rampart (drainage area of 0.52×10^6 km^2). Half the Yukon load, however, is derived from the Tanana River, which joins the Yukon downstream from Rampart (Burrows et al. 1981).

Alaskan rivers that drain glaciers have much greater sediment yields: the Copper River, with a much smaller drainage area and discharge, transports a somewhat greater load than the Yukon. This estimate is based on a 3-year sediment record at Chitina plus the following assumptions: the bed load is small; the sediment yield in the downstream 20% of the basin is twice that of the less mountainous upstream 80% of the basin; and about 15% of the sediment settles out in Miles Lake between Chitina and the river mouth (B. F. Molnia, USGS, 1980 oral comm.). Our estimate of 70×10^6 t yr^{-1} is smaller than the 107×10^6 t yr^{-1} given by Reimnitz (1966), mainly because Reimnitz assumed a larger bed load and no settlement of material in Miles Lake. The Susitna River, even smaller than the Copper, carries almost half that of the Yukon. The Susitna estimate is based on a few miscellaneous sediment measurements (1975–78) at Susitna Station, correlated through a sediment rating curve to water-discharge data.

The Kuskokwim and the Colville Rivers both drain areas that include few modern glaciers, and their sediment loads are both about 5 to 10×10^6 t yr^{-1}. The Kuskokwim River has only a few measurements of sediment at the gaging station at Crooked Creek, which have been plotted to make a limited rating curve, and combined with 10 years of discharge records to estimate the sediment load. Although the station at Crooked Creek is some distance upstream from the river mouth, it is doubtful that the downstream drainage basin increases the sediment load by much. The estimate for the Colville River was determined from suspended-sediment measurements made by Arnborg et al. (1967) during the 1962 runoff season and the U.S. Geological Survey (1978) during the 1977 runoff season.

The MacKenzie River, draining into the Beaufort Sea, has the second largest drainage area in North America, but due to its remote location, has been monitored in detail for suspended sediment for only 2 years. Sediment loads were 57×10^6 t in 1973, and 199×10^6 t in 1974 (Davies 1974, 1975). Neill and Mollard (1980) estimate the average to be 150×10^6 t, but because the 1974 data represent an unusually wet year (flooding in August, after major spring runoff, accounted for a substantial proportion of the total load), 100×10^6 t yr^{-1} per year may be a more realistic estimate.

South America.—The South American continent contains three of the world's largest rivers, the Amazon, Orinoco, and Parana-Plata Rivers, that are rated 1, 3, and 9 in terms of water discharge and 1, 18, and 5 in terms of drainage area. By far the largest in both terms is the Amazon River, but its sediment load is still relatively unknown. Gibbs (1967) estimated its annual sediment load to be 500×10^6 t but did not take into account the large increase in suspended concentration with increasing water depth. On the basis of more detailed measurements and a very preliminary sediment-discharge rating curve, Meade et al. (1979) estimated the annual suspended-sediment discharge of the Amazon to be 900×10^6 t. This estimate, however, still contains a possible margin of error of several hundred million tons.

Very few accurate measurements of sediment in the Orinoco or Parana-Plata Rivers are available. Earlier estimates of the Orinoco ranged from 86 to 100×10^6 t yr^{-1} (van Andel 1967; Eisma et al. 1978) and were based on two samples collected from the river during less-than-normal discharge (Key Sanchez 1950). The new estimate of 210×10^6 t yr^{-1} is based on a sediment-rating curve constructed by David Perez Hernandez (1982 written comm.) from 63 measurements of water discharge and sediment concentration collected during the period 1969–1975 at Musinacio, 650 km upstream from the river mouth. We assume that little additional sediment is transported by the Orinoco before it reaches the ocean; in fact a significant part may be deposited in the inner delta before it reaches the ocean. For the Plata, we use the estimate of 92×10^6 t yr^{-1} given by Urien (1972).

The Magdalena River in Colombia, while appreciably smaller in discharge and drainage area, appears to transport more sediment than either the Orinoco or Parana-Plata Rivers. Jansen et al. (1979) estimate that the annual sediment load of the Magdalena is 220×10^6 t, a value based on an earlier NEDECO (1973) study in 1971–72; it appears to include bedload. The Chira River in Peru is much smaller, but in 1 of the 2 years measured transported 75×10^6 t (Burz 1977). Whether this large sediment load resulted from a rare flood or represents sediment loads that are typical of the steep rivers that drain the western slopes of the Andes Mountains is an important question whose answer requires more data than we have.

Europe.—The rivers that drain Europe are small and carry little sediment. Only the Rhone, Po, and Danube Rivers appear to have annual sediment discharge in excess of 10×10^6 t. The Danube, by far the largest in terms of its drainage area and water discharge, has an estimated sediment discharge of 67×10^6 t yr^{-1} (table 2).

Eurasian Arctic.—The Eurasian Arctic, whose total drainage area is 9.15×10^6 km^2 (nearly 10% of the total land area draining into the oceans) is drained by three large rivers. The Ob, Yenisei, and Lena Rivers all have drainage areas of about 2.5×10^6 km^2 and water discharges of 385 to 560 km^3 yr^{-1}. However, these rivers drain low-lying terrain, areas primarily stripped of sediment by Pleistocene glaciers. Although newer data may change individual estimates, their combined sediment discharge is so small (63×10^6 t annually) that any likely change in discharge values would have little impact on either world-wide or Eurasian values.

China.—Data collected during the last

three decades permit accurate estimates of the sediment loads of major Chinese rivers. An uninterrupted record of the sediment discharge of the Yellow River (Huangho) is available for the years since 1950. This river, the second largest in China in terms of both drainage area and water discharge, drains extensive loess deposits, perhaps the most easily erodible material available to moving water. As a result, sediment loads are tremendous; average yearly concentrations are as great as 48 g L^{-1}, and average monthly concentrations can be in excess of 70 g L^{-1}. These concentrations, as shown in figure 3, are far greater than those for any other large river in the world. Strakhov/Lisitzin and Holeman listed the Yellow as contributing 1890 × 10^6 t annually, but this value apparently reflects loads measured at a station as the river leaves the loess plateaus. Between this station and the ocean, some 850 km, the river deposits considerable sediment: present-day estimates indicate that the river transports approximately 1500 × 10^6 t as it leaves the plateaus (Long and Xiong 1981), whereas the 31-year (1950–80) mean sediment discharge at Lijin, a few km from the coast, is only 1080 × 10^6 t. The 420 × 10^6 t of "missing" sediment is deposited on the intervening alluvial plain. In addition, more than half of the sediment that passes Lijin is deposited on the Yellow River delta before it reaches the open waters of the Gulf of Bohai (fig. 1; Long and Xiong 1981).

Estimated sediment load for the Yangtze River measured at Datong (about 400 km above the river mouth) is 478 × 10^6 t yr^{-1} (average concentration—550 mg/L). Several smaller rivers join the Yangtze downstream of Datong, presumably increasing the discharge into the oceans to about 500 × 10^6 t (Chen Chiyu, East China Normal University, oral comm. 1981).

Compared with the Yangtze and Yellow Rivers, other Chinese rivers appear small, although three rivers in northeast China (Haiho, Daling, and Liaohe Rivers) discharge a combined average of 158 × 10^6 t yr^{-1}. The Huaihe and Zhu Jiang (Pearl River) transport 14 and 69 × 10^6 t yr^{-1}, respectively. In terms of sediment yield, these seven Chinese rivers have an areally-weighted average of 540 t km^{-2} yr^{-1}.

Asia Exclusive of China.—Rivers draining the Himalayas into southeast Asia are large but most are poorly documented. The Hungho (Red River), Mekong, and Irrawady may contribute a combined sediment discharge in excess of 500 × 10^6 t yr^{-1}, but estimates for these rivers are so recycled that the true data bases are poor or unknown. The 1885 report of Gordon, for example, refers to "carefully measured" silt concentrations made during the 1870's, but methods are not discussed. Only the fewer observations for the Mekong (Borland 1973) can be considered reliable. Further west, the rivers also transport large sediment loads. The Ganges-Brahmaputra River apparently carries the largest load of river sediment in the world, but the actual mass is not well defined because of the few available sediment measurements. Our estimate comes from a sediment rating curve based on 53 sediment samples collected by Engineering Consultants, Inc. and Associated Consulting Engineers, Ltd. (1970) in the Padna River at Bhagyakul (downstream from the confluence of the Ganges and Brahmaputra) during 1966–67. This curve was applied to mean combined discharge data from the Ganges (measured at Paksey) and the Brahmaputra (measured at Bahadurabad) for 1969–70, 1973–75 (UNESCO 1974, 1979). Our estimate of 1670 × 10^6 t yr^{-1} is considerably larger than the suspended load estimates quoted by Subramanian (1978—1180 × 10^6 t), Coleman (1969—980 × 10^6 t) and ECI-ACE (1970—834 × 10^6 t), but smaller than the estimate quoted by Strahkov/Lisitzin and Holeman (2180 × 10^6 t). According to our calculations, excessive runoff during 1973 transported more than 2000 × 10^6 t.

The Indus River and its tributaries, which drain much of Pakistan, transport about 400 × 10^6 t of sediment in its upper reaches, 60% of which is sand (Peshawar University 1970). Presumably the estimates at Darband (more than 800 km from the ocean) are the ones that have been quoted by Strahkov/Lisitzin and Holeman. As the river reaches the alluvial plain below Darband, however, large but indeterminate amounts of sediment settle out, almost certainly exceeding the sediment contributed by downstream tributaries (180 × 10^6 t yr^{-1}, Peshawar University 1970). Thus, the actual mass of sediment that reached the ocean after 600 km of transport in the downstream portions of the Indus was probably

TABLE 2

Drainage Area, Water and Suspended Sediment Discharges for Major Rivers of the World

River	Drainage Area ($\times 10^6 km^2$)	Water Discharge ($km^3 yr^{-1}$)	Sediment Discharge ($10^6 t yr^{-1}$): Strakhov (1961) and Lisitzin (1972)	Holeman (1968)	This Paper	Reference
North America						
St. Lawrence (Canada)	1.03	447	4	4	4	Holeman 1968
Hudson (USA)	.02	12	36	...	1	Curtis et al. 1973
Mississippi (USA) (including Atchafalaya)	3.27	580	500	349	210	New estimate
Brazos (USA)	.11	7	32	32	16	Curtis et al. 1973
Colorado (Mexico)	.64	20	135	135	.1	Curtis et al. 1973
Eel (USA)	.008	...	...	16	14	Janda & Nolan 1979
Columbia (USA)	.67	251	36	9	8	New estimate
Fraser (Canada)	.22	112	...	...	20	Milliman 1980
Yukon (USA)	.84	195	88	...	60	New estimate
Copper (USA)	.06	39	...	...	70	New estimate
Susitna (USA)	.05	40	...	...	25	New estimate
MacKenzie (Canada)	1.81	306	15	...	100	New estimate
Total North America	9.57				528	
South America						
Chira (Peru)	.02	5	...	...	4–75	Burz 1977
Magdalena (Colombia)	.24	237	...	...	220	NEDECO 1973
Orinoco (Venezuela)	.99	1100	86	86	210	D. Perez Hernandez written comm.
Amazon (Brazil)	6.15	6300	498	364	900	Meade et al. 1979
Sao Francisco (Brazil)	.64	97	...	...	6	Milliman 1975
La Plata (Argentina)	2.83	470	129	82	92	Urien 1972
Negro (Argentina)	.10	30	...	...	13	Depetris 1980
Total South America	10.85				1420	

Europe						
Rhone (France)	.09	49	31	...	10	Jansen et al. 1979
Po (Italy)	.07	46	18	15	15	Jansen et al. 1979
Danube (Romania)	.81	206	67	19	67	Boisnard et al. 1967
Semani (Albania)	...	...	...	22	?	
Drini (Albania)	.01	...	...	15	?	
Total Europe	.97				92	
Eurasian Arctic						
Yana (USSR)	.22	29	3	...	3	Lisitzin 1972
Ob (USSR)	2.50	385	16	15	16	Lisitzin 1972
Yenisei (USSR)	2.58	560	13	...	13	Lisitzin 1972
Severnay Dvina (USSR)	.35	106	4.5	...	4.5	Lisitzin 1972
Lena (USSR)	2.50	514	15	...	12	Lisitzin 1972
Kolyma (USSR)	.64	71	6	...	6	Lisitzin 1972
Indigirka (USSR)	.36	55	14	...	14	Lisitzin 1972
Total Euras. Arctic	9.15				68	
Asia						
Amur (USSR)	1.85	325	25	...	52	Jansen et al. 1979
Liaohe (China)	.17	6	...	...	41	Qian & Dai 1980
Daling (China)	.02	1	...	...	36	Qian & Dai 1980
Haiho (China)	.05	2	...	...	81	Qian & Dai 1980
Yellow (Huangho) (China)	.77	49	1890	1890	1080	New estimate
Yangtze (China)	1.94	900	500	502	478	Qian & Dai 1980
Huaihe (China)	.26	...	...	...	14	Qian & Dai 1980
Pearl (Zhu Jiang) (China)	.44	302	...	27	69	Qian & Dai 1980
Hungho (Vietnam)	.12	123	130	130	130	Lisitzin 1972
Mekong (Vietnam)	.79	470	170	170	160	Borland 1973
Irrawaddy (Burma)	.43	428	299	300	265	Gordon 1885
Ganges/Brahmaputra (Bangladesh)	1.48	971	2180	2180	1670	New estimate
Mehandi (India)	.13	67	...	62	2	Subramanian 1978
Damodar (India)	.02	10	...	28	?	
Godavari (India)	.31	84	...	...	96	Bikshamaiah & Subramanian 1980
Indus (Pakistan)	.97	238	435	440	100	New estimate
Tigris-Euphrates (Iraq)	1.05	46	105	53	?	
Total Asia	9.74				4334	

TABLE 2 (*Continued*)

River	Drainage Area ($\times 10^6 km^2$)	Water Discharge ($km^3 yr^{-1}$)	Sediment Discharge ($10^6 t yr^{-1}$): Strakhov (1961) and Lisitzin (1972)	Sediment Discharge: Holeman (1968)	Sediment Discharge: This Paper	Reference
Africa						
Nile (Egypt)	2.96	30	110	111	0	New estimate
Niger (Nigeria)	1.21	192	67	4	40	NEDECO 1959
Zaire (Zaire)	3.82	1250	65	64	43	Eisma et al. 1978
Orange (S. Africa)	1.02	11	153	...	17	Rooseboom & Harmse 1979
Zambesi (Mozambique)	1.20	223	100	...	20	Rooseboom, written comm. 1980
Limpopo (Mozambique)	.41	5	...	...	33	Ward 1980, Rooseboom written comm. 1980
Rufiji (Tanzania)	.18	9	...	...	17	Temple & Sundborg 1972
Tana (Kenya)	.032	...	...	...	32	T. Dunne, oral comm. 1982
Total Africa	7.48 (Minus Nile)				175	
Oceania						
Murray (Aust.)	1.06	22	32	32	30	Jansen et al. 1979
Waiapu (N.Z.)	...	...	...	...	28	Griffiths 1982
Haast (N.Z.)	.001	6	...	...	13	Griffiths 1980
Fly (New Guinea)	.061	77			30	Pickup et al. 1981
Purari (New Guinea)	.031	77			80	Pickup et al. 1980
Choshui (Taiwan)	.003	6	...	...	66	WRPC Taiwan
Kaoping (Taiwan)	.003	9	...	...	39	WRPC Taiwan
Tsengwen (Taiwan)	.001	2	...	...	28	WRPC Taiwan
Hualien (Taiwan)	.002	4	...	...	19	WRPC Taiwan
Peinan (Taiwan)	.002	4	...	...	17	WRPC Taiwan
Hsiukuluan (Taiwan)	.002	4	...	...	16	WRPC Taiwan
Total Oceania (excluding Murray)	1.074	39			336	

NOTE.—Sources of data discussed in text.

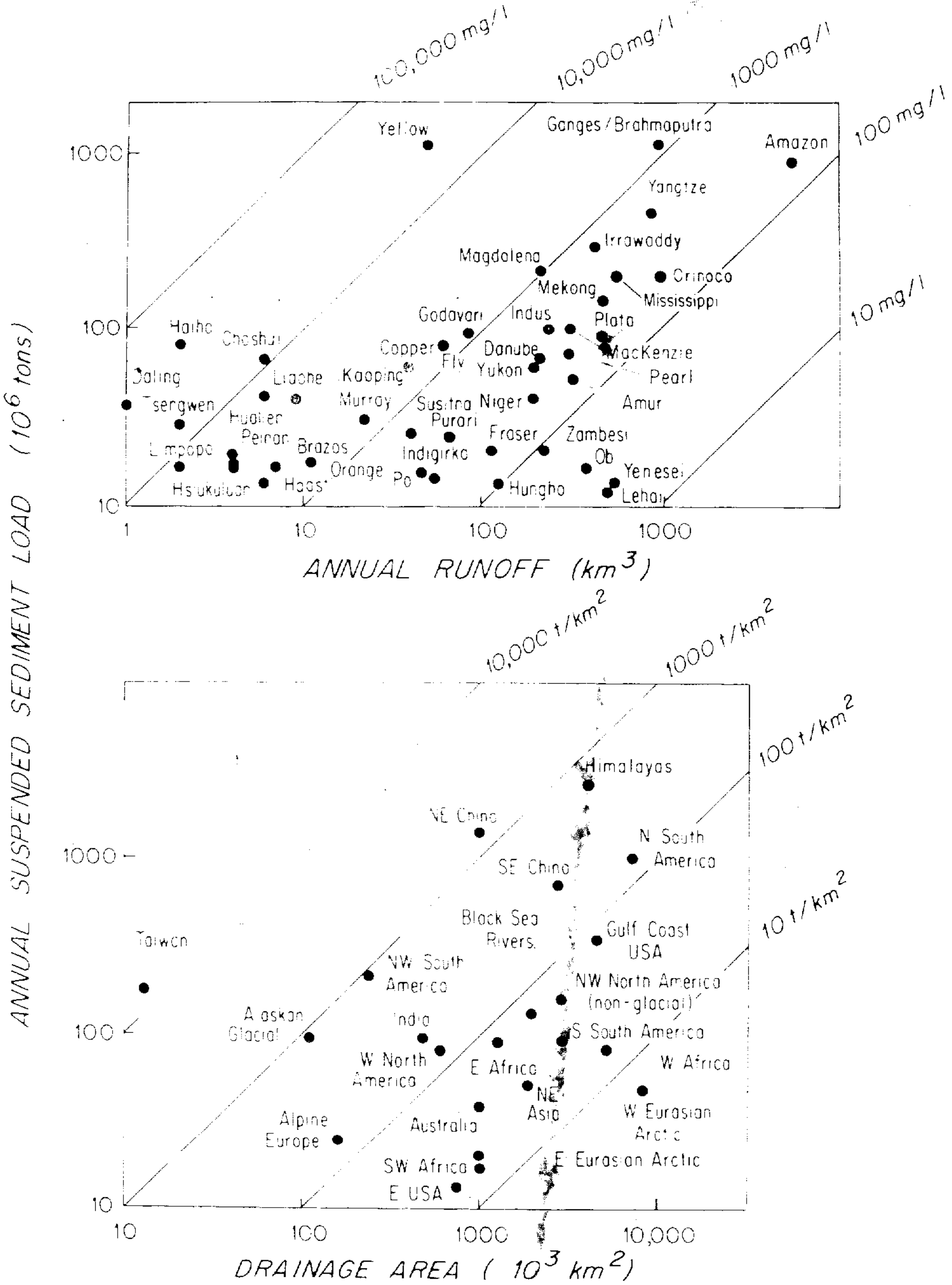

FIG. 3.—Variation of annual suspended sediment load with runoff (upper) and drainage area (lower). Note that the average concentration (upper) is highest in Asian and glacial rivers as well as those rivers draining arid areas (e.g., Orange, Brazos, and Murray). Yields for Asian and glacial rivers also are large, but desert rivers (Australia, SW Africa) have small yields.

much less than previously quoted estimates. An even greater amount of this sediment is now intercepted by the large new dams that have been built at Mangla, Tarbela, and elsewhere. The value of 100×10^6 t yr^{-1} in table 2 is only a rough estimate. Even this amount probably will decrease to near zero within the next decade as the Indus River is controlled by dams like the Nile and Colorado. Smaller loads are transported by rivers draining the southern parts of the Indian subcontinent. Bikshamaiah and Subramanian (1980) estimate a load of 100×10^6 t yr^{-1} for the Godavari, but no discussion of the data base is presented.

Finally, the Tigris-Euphrates is unquestionably the most important river system in Asia Minor. Lisitzin's (1972) and Holeman's (1960) estimates differ by a factor of 2 (105 versus 53×10^6 t yr^{-1}). Most of the fluvial sediment, however, accumulates in the landward part of the delta. The fact that little river sediment reaches the Arabian Gulf is illustrated by the predominance of eolian dust in nearshore sediments (D.H. Al-Bakri, KISR, oral comm. 1981).

Africa.—A number of large rivers drain the African continent, but they now transport very little sediment to the oceans. The Nile, with a drainage area in excess of 2×10^6 km^2, once carried an average of 100×10^6 t yr^{-1} to its delta in the Mediterranean Sea. Since the construction of the high dam at Aswan, the Nile transports virtually sediment to the sea; the result is erosion of the coastline.

The Niger and Zaire Rivers together drain more than 5×10^6 km^2 of west Africa. The Zaire is the second largest river in the world in terms of both drainage basin area and river flow. However, sediment loads from both rivers are small because they drain relatively low-lying terrain and, in the case of the Zaire, empty into lakes prior to reaching the ocean. A NEDECO study (1959) of the Niger estimated an annual sediment discharge at Onitsha (375 km upstream from the river mouth) of 40×10^6 t. This study emphasized navigability of the Niger, and its sampling efforts were concentrated on bed load and suspended sand. Only one sample of wash load (suspended sediment finer than sand) was collected, even though NEDECO's calculations show washload to account for 85% of the total load. Because this one sample was taken during a low stage of the river, we suspect that the NEDECO calculations underestimate the suspended load at Onitsha by a factor of at least 2. On the other hand, some of this sediment probably is deposited on the landward part of the Niger delta before reaching the ocean.

In southwestern Africa, the Orange River has been reported to contribute 153×10^6 t of sediment annually (Lisitzin 1972), which if true would make its sediment load the fifth largest emptying into the Atlantic Ocean. However, later studies have shown that the earlier estimate was much too high, and that the sediment load has decreased more than 50% during the last 50 years. This decrease is due primarily to the change in available material rather than changes in land use (Rooseboom and Harmse 1979). At present the Orange is thought to deliver only about 17×10^6 t yr^{-1} to its mouth.

East Africa has several large rivers on which some measurements have been made. Rooseboom (written comm. 1980) estimates that the Zambesi River transports about 48×10^6 t of sediment annually, but most of it is trapped behind dams. He estimates that less than 20×10^6 t reaches the ocean. Using samples taken only at the surface of the river, Ward (1980) estimated an average sediment discharge of 8.8×10^6 t yr^{-1} for the Zimbabwe-Rhodesian portion of the Limpopo River (200×10^3 km^3). However, Ward's estimate probably is too small: the high concentration of sand within the suspended sediment at the surface (greater than 50%) suggests that sediment concentrations must increase considerably towards the bottom. Rooseboom (written comm. 1980) calculates a sediment yield in this area of 80 t km^{-2} yr^{-1}, or a sediment discharge for the entire Limpopo system of approximately 33×10^6 t yr^{-1}. The high sand concentrations also suggest that the bedloads also may be appreciable in the downstream reaches of the Limpopo. Fleming (1981) calculated the annual load of the Limpopo to be 48.8×10^6 m^3, of which only about 5% was bed load. These calculations were based on terrain, vegetation, and climate of the drainage area as well as the few available river data. Based on a drainage basin area of 37×10^6 km^2, Fleming's sediment yield exceeds 130 t km^{-2} yr^{-1}.

Temple and Sundborg (1972) estimated an

annual sediment discharge of 17 × 10^6 t yr^{-1} for the Rufiji (Tanzania), which gives a slightly higher sediment yield (94 t km^{-2} yr^{-1}) than that of the Limpopo. In contrast, the Tana River, a small river (31,600 km^2 drainage area) in Kenya has a sediment discharge of 30 × 10^6 t yr^{-1}, or a yield of nearly 1000 t km^{-2} yr^{-1}. This extremely high yield results from over-grazing by cattle and marginal agriculture, plus the very high delivery ratios: little sediment appears to be stored on lower hill slopes or in river channels (T. Dunne, oral comm. 1982). Whether the Tana sediment yields are representative of a larger portion of east Africa is not known.

Oceania.—The Murray River in Australia drains a large area (1.06 × 10^6 km^2), but has a small discharge (22 km^3 yr^{-1}) and small annual sediment load (30 × 10^6 t). Far more impressive are the short rivers that drain the mountainous islands of New Zealand, New Guinea, and Taiwan. The 10 rivers (excluding the Murray) listed in table 2 drain slightly more than 100 × 10^3 km^2 but have an annual load in excess of 300 × 10^6 t; for comparison, the Loire (France) has a similar drainage basin area but its discharge is less than 5 × 10^6 t yr^{-1}. Presumably rivers draining tropical mountains on other oceanic islands (e.g., Sumatra and Luzon) also have high yields.

FLUX OF RIVER SEDIMENT FROM THE CONTINENTS

The rivers listed in table 2 drain nearly 50 × 10^6 km^2 of land, or about half the estimated area (102 × 10^6 km^2) draining into the oceans (Livingstone 1963). The combined annual sediment discharge for these rivers is about 7 × 10^9 t. In order to calculate the total riverine load discharged into the oceans, most workers have extrapolated the measured sediment yields of various rivers throughout large areas. Holeman (1968), for example, calculated average sediment yield for the six continents using the river data available for each continent. We have divided the land areas into smaller drainage basins, each one characterized by a different general climate or terrain (table 3).

Because of our familiarity with the published data, estimates for the United States seem most accurate, and we can divide the country into smaller drainage areas. Many of the data we use were compiled by Curtis et al. (1973); other data were updated where necessary. New data from the Fraser and MacKenzie Rivers, and Alaskan rivers, show that these northern rivers, all of which drain mountains and/or glacial terrain, have a combined annual sediment discharge (579 × 10^6 t yr^{-1}), substantially greater than the rest of North America. The large sediment yield applied to glacial areas of southern Alaska (1,000 t km^{-2} yr^{-1}) is justified not only by the measured sediment load of the Copper River, but also by the rapid filling of coastal bays and the large thickness of Holocene sediment deposited in the Gulf of Alaska (Molnia 1979, 1980; Molnia and Carlson 1980). Because few measurements are available for the vast area of northern and northeastern Canada, we have assumed a sediment yield similar to that in the Eurasian Arctic, 8 t km^{-2} yr^{-1}, resulting in a calculated sediment discharge of 30 × 10^6 t yr^{-1} annually. The combined annual load for North America comes to slightly more than 10^9 t.

Because reliable data are difficult to obtain, our estimate of the sediment load from Central American rivers is subject to considerable error. For Mexico we have taken the average yield of the Rio Grande (measured in New Mexico) and the Rio San Juan (Holeman 1968), which gives us a sediment yield of 140 t km^{-2} yr^{-1}. Extrapolating this figure for the 1.5 × 10^6 km^2 of Mexico assumed to drain into the oceans, we calculate 210 × 10^6 t discharged to the oceans annually. Southern Central America is even more difficult to estimate; the only available data are from the Escondido River in Nicaragua, which has a drainage area of 12.3 × 10^3 km^2 and an average sediment load of 5 × 10^6 t (UNESCO 1969; Murray and others 1982). Assuming a total drainage area for Central America of 0.58 × 10^6 km^2, this results in 232 × 10^6 t of sediment per year. The combined load for Central America therefore approximates that for the conterminous United States, although the lack of data clearly makes this estimate subject to considerable revision.

South America has been divided into six parts in table 3 on the basis of sediment yield. Northwestern South America includes western Colombia, Ecuador, and northern Peru; the sediment yield, 500 t km^{-2} yr^{-1}, is based on short-term data from three Peruvian rivers

TABLE 3

CALCULATED TOTAL SUSPENDED SEDIMENT DISCHARGE FROM THE CONTINENTS

	Sediment Yield ($t\ km^{-2}\ yr^{-1}$)	Drainage Area ($10^6\ km^2$)	Sediment Discharge ($10^6 t\ yr^{-1}$)
North America			
St. Lawrence	4	1.03	4
U.S. Atlantic Coast	17	.74	13
Gulf Coast	59	4.50	256
Colorado	.2	.63	.1
Columbia	12	.69	8
Rest of W. U.S.	193	.32	62
Canada West Coast	91	.67	61
S. Alaska (glacial)	1000	.34	340
S. Alaska (non glacial)	76	1.37	104
N. Alaska	120	.35	42
MacKenzie	55	1.81	100
N. NE Canada	8	3.73	30
Subtotals		15.42	1020
Central America			
Mexico	140	1.50	210
Remainder	400	0.58	323
Subtotals		2.08	442
South America			
Northwest	500	.3	150
Magdalena	900	.24	220
Northern	150	7.79	1218
Eastern	9.4	3.00	28
Southern	32	4.38	154
Western & South	10	1.77	18
Subtotals		17.90	1788
Europe			
Western	12	2.60	31
Alpine	120	.55	66
Black Sea	72	1.86	133
Subtotals		4.61	230
Eurasian Arctic			
West of 140°E	6	9.90	59
East of 140°E	20	1.27	25
Subtotals		11.17	84
Asia			
Northeast	28	3.2	100
NE China/Korea	658	1.00	658
Yellow (Huangho)	1400	.77	1080
Rest of China	250	3.72	930
SE Asia and Himalayas (exclusive of Indus)	796	3.93	3128
India	154	1.86	286
Indus			100 (see text)
Asia Minor	50(?)	1.35	67(?)
Subtotals		16.88	6349
Africa			
Northwest	100	1.10	110
West	16.5	6.86	113
Southwest	17	1.02	17
East	80	3.00	240
Zambesi	17	1.20	20
(Tana)	(1000)		(30)
Nile	0	2.16	0
Subtotals		15.34	530
Australia			
East, North	28	2.20	62
Oceanic Islands	1000	3.00	3000
Totals	116	86.40	13,505

(Burz 1977). Northern South America includes the drainage basins of the Amazon and Orinoco Rivers. The Magdalena River basin is listed separately because of its greater sediment yield. Eastern South America refers to the arid eastern area of Brazil; we have assumed that the Rio Sao Francisco represents this area. Southern South America includes southern Brazil, Uruguay, and most of Argentina, and is represented by the Parana-Plata River, whose basin occupies more than 60% of the calculated drainage area. Western South America encompasses the remaining 1.77×10^6 km^2 of land in South America and includes low-lying marshlands in Argentina as well as the western slope of the Andes Mountains. Although we have no sediment data from rivers draining Chile and southern Peru, the extremely arid climate suggests that the sediment yield may be relatively small; consequently, we have arbitrarily assigned this region a sediment yield of 10 t km^{-2} yr^{-1}. The combined annual sediment load for South America is calculated to be 1.79×10^9 t.

Europe is divided into four drainage basins, one of which (the Eurasian Arctic) is discussed in a following paragraph. Of the remaining three, the largest contains many of the rivers draining western and northern Europe. In terms of both water discharge and sediment load, however, these rivers are too small to be listed in table 1. For the purposes of this calculation we have taken data for the Seine, Oder, Vistula, Rhine, and Garonne Rivers (Holeman 1968; Strakhov 1961), resulting in an average sediment yield of 12 t km^{-2} yr^{-1}. The sediment yield for rivers draining southern Europe is an order of magnitude larger (120 t km^{-2} yr^{-1}, based on the weighted average of the Po, Rhone, Tiber, and Ebro Rivers; data from Lisitzin 1972; Jansen et al. 1979; Maldonado 1977), due to the mountainous terrain in which glaciers are locally active. Thus while the drainage area is smaller than western Europe, the calculated sediment discharge is significantly larger (66 versus 31 $\times 10^6$ t yr^{-1}). In terms of total suspended sediment load, however, the most important basin is the Black Sea, including the Danube and Dneper Rivers. Rivers draining this basin contribute 133×10^6 t of sediment annually (Shimkus and Trimonis 1974). The total for Europe (minus the Arctic), then, is 277 s 10^6 t. Considering that more than half of it is trapped in the Black Sea and most of the remainder is deposited in the Mediterranean, only a very small amount of the sediment leaving Europe reaches the Atlantic Ocean (fig. 4).

In terms of contiguous area of similar climate and terrain, the Eurasian Arctic is the biggest drainage basin in the world, containing a number of extremely large rivers. The Yenisei, Ob, and Lena Rivers all have drainage-basin areas in excess of 2.5×10^6 km^2. The total area for the Arctic drainage is more than 11×10^6 km^2. West of about 140°E, the rivers drain low-lying terrain and have the smallest sediment yield of any large basin reported in this paper—6 t km^{-2} yr^{-1}. Rivers to the east drain somewhat more mountainous terrain and have a larger yield—20 t km^{-2} yr^{-1}. These huge areas together, therefore, only contribute a calculated 84×10^6 t of sediment yearly to the Arctic Ocean.

Although most of the world's largest sediment loads are carried by rivers that drain parts of Asia, there are large areas of this continent in which sediment yields are surprisingly small. The Asian Arctic is one example. Another is northeastern Asia, where the Amur River basin yields only 28 t km^{-2} yr^{-1}. Similarly, most of Asia Minor appears to have small sediment yields. In contrast, the Chinese rivers and those draining the Himalayas and southeastern Asia have an average yield of about 600 t km^{-2} yr^{-1}. Qian and Dai (1980) state that 1.94×10^9 t yr^{-1} are transported to the ocean from Chinese rivers. The loads from southeast Asia and the Himalayas may contain a greater potential error because of the limited data base. Still, the tremendous annual sediment load derived from this area (3068×10^6 t) appears to be the largest in the world. Taken in total, the high yield rivers between Korea and Pakistan contribute more than 6400×10^6 t yr^{-1}, or nearly half of the total world input. In contrast, the other Asian rivers, although draining a far larger area, contribute less than 300×10^6 t yr^{-1}.

Africa contributes far less sediment than one might expect. Man's influence, arid climate, and the generally low relief of the continent account for this small input, but it is entirely possible that better measurements of more rivers (particularly in east Africa) may

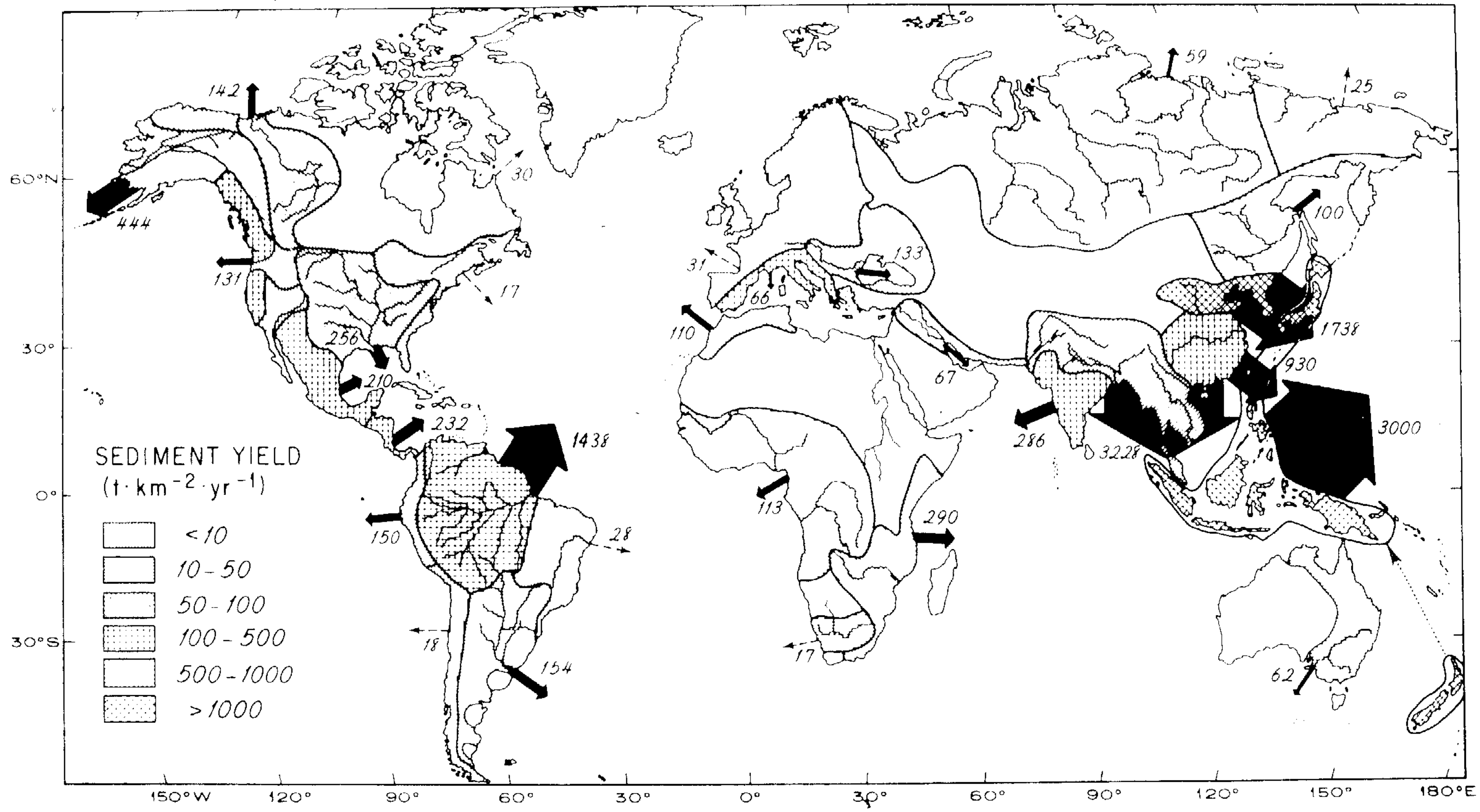

FIG. 4.—Annual discharge of suspended sediment from various drainage basins of the world; width of arrows corresponds to relative discharge. Numbers refer to average annual input in millions of tons. Direction of arrows does not indicate direction of sediment movement. The sediment yields and major rivers of the various basins also are shown; open patterns indicate essentially no discharge to the ocean.

increase these estimates. The damming of the Nile River eliminated sediment discharge from most of northeastern Africa (2.16×10^6 km^2), and both the Orange and Zambesi Rivers have present-day loads that are lower than in previous years. The small loads of the Niger and Zaire mean that sediment discharge into the ocean from equatorial West Africa (113×10^6 t yr^{-1}) is small considering the large drainage area (6.86×10^6 km^2). The Orange River basin contributes 17×10^6 t yr^{-1}, while the Namib Desert to the north is assumed to contribute little riverine input. We assume the Limpopo and Rufiji are representative of east Africa, with a sediment yield of 80 t km^{-2} yr^{-1}; the large yield from the Tana River basin presumably represents a local anomaly (over-grazing of pasture land with no intermediate storage areas). Assuming a drainage area of 3×10^6 km^2 (excluding the Zambesi basin), this amounts to 240×10^6 t yr^{-1}. To this discharge is added the 20×10^6 t derived from the Zambesi River and 30×10^6 t from the Tana River, giving a total contribution from east Africa of about 290×10^6 t yr^{-1}. Fleming (1981) calculates 135×10^6 t for the rivers draining South Africa and Zimbabwe-Rhodesia, an average yield of nearly 140 t km^{-2} yr^{-1}, a value that may not be unrealistic according to the sediment yields reported by Rooseboom (1978). If this number is more representative of East Africa, then the annual sediment discharge would be 470×10^6 t yr^{-1}. Most rivers draining arid northwest Africa (primarily Morocco, northern Algeria and Tunisia) flow sporadically and are inadequately documented. They are, however, subject to episodic major floods: Claude and Loyer (1977), for example, show yields from Tunisian river basins to range from 700 to 6000 t km^{-2} during floods. Because flooding is infrequent and generally limited to small areas, we assume for northwestern Africa a more conservative yield of 100 t km^{-2} yr^{-1} and an annual input of 110×10^6 t.

Most of Australia is arid, and cannot be considered to contribute much riverine sediment to the oceans. Only the east and northeast coasts are drained by rivers capable of transporting significant quantities of sediment. We estimate the total drainage area to be 2.2×10^6 km^2. Assuming that the sediment yield of this area is equal to that of the Murray River, this computes to 62×10^6 t of sediment annually.

The large islands of the western Pacific Ocean are among the most prodigious producers of river sediment. We refer to Japan, Taiwan, Philippines, Indonesia (including Borneo), New Guinea, and New Zealand, whose combined land area is about 3×10^6 km^2. Because of their active tectonism and volcanism, steep slopes, heavy rainfall, and intense human activity, these islands contribute large quantities of river sediment to the ocean. The most spectacular of these contributors is Taiwan (WRPC, Taiwan 1978; Li 1976), whose average sediment yield to the ocean is about 10,000 t km^{-2} yr^{-1}, and whose calculated annual sediment load is about 300×10^6 t—only slightly smaller than that of the conterminous United States! In another area of the western Pacific, Adams (1980) compiled the existing data for South Island, New Zealand, and estimated that most of the calculated 265×10^6 t of eroded sediment is discharged annually to the sea. This figure represents an average sediment yield of about 1,300 t km^{-2} yr^{-1} from South Island. Griffiths (1979, 1981, 1982) has used the same data in what appears to be a more reasonable set of calculations; his results indicate that the average sediment yield for South Island is about 1000 t km^{-2} yr^{-1}. Two small rivers in Japan listed by Jansen et al. (1979) have a yearly sediment yield of nearly 2000 t km^{-2}, while the Fly and Purari Rivers in New Guinea have a yield of 1200 t km^{-2}. If we apply a conservative estimate of sediment yield of 1,000 t km^{-2} yr^{-1} to the 3×10^6 km^2 of large western Pacific islands, we obtain 3×10^9 t yr^{-1} for the total discharge of river sediment from these islands.

The total area discussed is slightly less than 90×10^6 km^2. Added to this area should be the arid zones in Australia, Saudi Arabia, and northern Africa, whose basins theoretically empty into the oceans but which contain virtually no rivers. While sporadic floods may contribute material to the oceans, we assume that the average contribution is small. Finally, we have excluded rather large drainage basins for the Caspian and Aral Seas (including the Volga, Syr Darya, and Amu Darya rivers) and all other interior drainage basins, since none of their material reaches the ocean.

TABLE 4

COMPARISON OF PROPOSED WORLD BUDGET WITH THAT OF HOLEMAN (1968)

Area	Drainage area (10^6 km^2)		Sediment Yield (t km^{-2} yr^{-1})		Sediment Discharge (10^6t yr^{-1})	
	Holeman	This paper	Holeman	This paper	Holeman	This paper
N. & C. America	20.48	17.50	87	84	1780	1462
S. America	19.20	17.90	57	97	1090	1788
Europe	9.2	4.61	32	50	290	230
Eurasian Arctic	...	11.17	...	8	...	84
Asia	26.6	16.88	543	380	14,480	6349
Africa	19.7	15.34	25	35	490	530
Australia	5.1	2.20	41	28	210	62
Large Pacific Islands	...	3.00	...	1000	...	3000
Totals	100	88.60	183	150	18,300	13,505

NOTE.—Northern Africa, Saudi Arabian peninsula and western Australia are primarily desert, and assumed to have little annual discharge of river sediment. Total land area is 11.40 km^2.

COMPARISON WITH HOLEMAN'S BUDGET

Compared to the estimates made by other workers, our estimate of 13.5×10^9 t of riverine sediment entering the ocean annually seems small. Holeman's often quoted review (1968), for example, shows a world figure of more than 18×10^9 t (table 4). The disagreement comes from two main sources:

1) The sediment discharges that we list in table 2 generally are smaller than those of earlier compilers, because more recent measurements and estimates usually give lower values (particularly for Asian rivers) or because dams and land-conservation practices have decreased river-sediment loads—the Colorado, Mississippi, Nile, and Indus Rivers being obvious examples. These decreased estimates are offset somewhat by the new estimates of the sediment loads of the Amazon, Orinoco and Magdalena Rivers that give us a larger sediment discharge from South America.

2) A more important source of discrepancy is in the calculations of the sediment load from Asia. Holeman used an average sediment yield for Asian river basins of 543 t km^{-2} yr^{-1}, which is slightly less than our value for the Himalayan and Chinese rivers. However, by applying this value to all of Asia, Holeman overlooked the fact that for much of the continent the sediment yield is small. In the Eurasian Arctic and northeast Asia, the sediment yield ranges from 6 to 28 t km^{-2} yr^{-1}. The larger sediment yields only apply to an area of approximately 9.7×10^6 km^2, and not to the entire 26.6×10^6 km^2 used by Holeman. This major discrepancy for Asia is somewhat offset by the high sediment loads from the large western Pacific islands, which Holeman's estimate did not take into account (table 4).

It should be restated that our estimate includes neither bed load nor the sediment transported during catastrophic floods. Nor does it adequately take into account smaller river basins, particularly those draining mountains and high-standing islands. Bed load and floods may increase the average annual input by $1\text{–}2 \times 10^9$ t, but we cannot presently estimate the loads from smaller rivers. An average annual total sediment (suspended-bed) input of 16×10^9 t, therefore, is not an unreasonable estimate.

SOURCES OF ERROR IN INTERPRETATION

The sediment yields reported here should not be confused with rates of soil erosion. In many areas of the world, sediment has been eroded from upland soils at rates much greater than it has been transported away by rivers, the decreased sediment yield in larger basins being one example (Schumm and Hadley 1961). Holeman (1980) reports that soil erosion in the conterminous United States is more than 5×10^9 t yr^{-1}, whereas the annual sediment discharge from the same area to the ocean (table 3) is less than 0.4×10^9 t. Such observations indicate that sediment eroded from upland soils has been or is being stored progressively downstream in river valleys. These data also show that it is often meaningless and misleading to express modern sediment inputs to the ocean in terms of millimeters of soil erosion per unit time.

Although most summaries of world-wide sediment discharge, including this one, claim to be reporting the discharge to the oceans, relatively little river sediment appears to escape the present-day continental shelf. As mentioned previously, much of the sediment probably accumulates on the subaerial parts of subsiding deltas, never really reaching salt water. Along coastlines that include a number of large estuaries, most of the inflowing river sediment is trapped in embayments. This is true of the eastern USA, where many small rivers flow into large estuaries (Meade 1974). It is also true of at least one large river system, the Parana-Plata (Urien 1972). Even where rivers debouch onto continental shelves, much of their sediment accumulates on large deltas (Yellow, Mississippi, Niger) or along the adjacent coastline (Yangtze and Amazon). Only a small proportion of the modern river sediment brought to the coastlines of the world accumulates on the floor of the deep sea.

Finally, today's river-sediment discharges should not be extrapolated backward in time. Present-day climates and erosional regimes do not resemble even those of a few thousand years ago, and glacial rivers in particular must have been more numerous during glacial epochs. Moreover, with a few notable exceptions (Amazon, Zaire, and Yukon Rivers, for example), today's river-sediment loads are strongly affected by man. One of the most pervasive of man's effects on sediment loads has resulted from the changes of vegetation and soil structure that have accompanied deforestation and crop farming. The tremendous sediment loads transported by the Yellow and Ganges/Brahmaputra Rivers are at least partly due to poor soil-management practices in their drainage basins, while the high yield of the Tana is related to over-grazing. More recently, sediment loads have been decreased drastically by the construction of reservoirs; those in the Nile and Colorado Rivers are only the most spectacular examples. In some river basins, man-made changes have been made recently enough that the data can be adjusted to obtain some indication of natural conditions. In other river basins (those in India and China, for example), any indicators of natural conditions have been obscured for millennia.

Acknowledgements.—Compiling such a long list of rivers clearly involves the cooperation and advice of many individuals. We thank Chen Chi-yu (East China Normal University, Shanghai), Long Yuqian and Huang Younqian (Yellow River Conservancy Commission, Zhengzhou), G. A. Griffiths (Ministry of Works and Development, Christchurch, N.Z.), G. Pickup (CSIRO, Alice Springs, Australia), T. Dunne (University of Washington, Seattle), D. Perez Hernandez (Ministerio del Ambiente y Recursos Naturales Renovables, Caracas, Venezuela), D. H. Al-Bakri (Kuwait Institute for Scientific Research), A Rooseboom (Universiteit van Pretoria, South Africa), B. Molnia (U.S. Geological Survey, Menlo Park), K. F. Davies (Water Survey of Canada, Calgary) and S. P. Murray (Louisiana State University, Baton Rouge) for their assistance in providing data, reprints, and unpublished insights to various rivers. C. F. Nordin, Jr., I. N. McCave, J. N. Holeman, K. O. Emery, and D. Eisma all gave valuable comments on earlier versions of the manuscript. Part of the support for this paper came from a contract to the Woods Hole Oceanographic Institution from the Office of Naval Research, Contract No. N00014-81-C-0009.

REFERENCES CITED

Adams, J., 1980, Contemporary uplift and erosion of the Southern Alps, New Zealand: Geol. Soc. America Bull., v. 91, p. 1–114.

Arnborg, L.; Walker, H. J.; and Peippo, J., 1967, Suspended load in the Colville River, Alaska, 1962: Geografiska Annaler, v. 49(A), p. 131–144.

Bikshamaiah, G., and Subramanian, V., 1980, Chemical and sediment mass transfer in the Godavari River basin in India: Jour. Hydrol., v. 46, p. 331–342.

Boisnard, J.; Mociornita, C.; and Stanescu, V., 1967, Caracterizarea hidrologica, *in* Banu, A. C.

et al., eds., Limnologia Sectorului Romanesc al Dunarii: Editura Acad. Rep. Social. Romania, p. 115–156.

Borland, W. M., 1973, Pa Mong phase II, Supplement to Main Report (Hydraulics and Sediment Studies): U.S. Bur. Recl., v. 1, 282 p., v. 2, 304 p.

Burrows, R. L.; Emmett, W. W.; and Parks, B., 1981, Sediment transport in the Tanana River near Fairbanks, Alaska, 1977–79: U.S. Geol. Survey Water Res. Invest. 81-20, 56 p.

Burz, J., 1977, Suspended-load discharge in the semiarid region of northern Peru: Int. Assoc. Hydrol. Sci. Publ. 122, p. 269–277.

Claude, J., and Loyer, J. Y., 1977, Les alluvions deposees par l'Oued Medjerdah lors de la crue exceptionnelle de Mars 1973 en Tunisie: aspects quantitatif et qualitatif du transport et du depot: Int. Assoc. Hydrol. Sci. Publ. 122, p. 211–218.

Coleman, J. M., 1969, Brahmaputra River: channel processes and sedimentation: Sed. Geol., v. 3, p. 131–239.

Curtis, W. F.; Culbertson, J. K., and Chase, E. B., 1973, Fluvial-sediment discharge to the oceans from the conterminous United States: U.S. Geol. Surv. Circular 670, 17 p.

Davies, K. F., 1974, Hydrometric data summary, MacKenzie River Basin: Infor. Canada Cat. R57-6/1973, QS-1559-000-EE-A1, 84 p.

——— 1975, MacKenzie River input to the Beaufort Sea: Water Surv. Canada Beaufort Sea Project Tech. Rept. 15, 72 p.

Depetris, P. J., 1980, Hydrochemical aspects of the Negro River, Patagonia, Argentina: Earth Surf. Proc., v. 5, p. 181–186.

Drake, D. E.; Kolpack, R. L.; and Fischer, P. J., 1972, Sediment transport on the Santa Barbara-Oxnard shelf, Santa Barbara Channel, California, *in* Swift, D. J. P.; Duane, D. B.; and Pilkey, O. H., eds., Shelf Sediment Transport: Process and Pattern: Stroudsburg, Pa., Dowden, Hutchinson and Ross, p. 307–331.

Eisma, D.; van der Gaast, S. J.; Martin, J. M.; and Thomas, A. J., 1978, Suspended matter and bottom deposits of the Orinoco delta: turbidity, mineralogy, and elementary composition: Netherlands Jour. Sea Res., v. 12, p. 224–251.

———; Kalf, J.; van der Gaast, S. J., 1978, Suspended matter in the Zaire estuary and the adjacent Atlantic Ocean: Netherlands Jour. Sea Res., v. 12, p. 382–406.

Engineering Consultants, Inc., and Associated Consulting Engineers, Ltd., 1970, Feasibility Report, v. 4, Hydrology and River Hydraulics: East Pakistan Water and Power Development Authority, Dacca Southwest Project.

Fleming, B. W., 1981, Factors controlling shelf sediment dispersal along the southeast African continental margin: Marine Geol., v. 42, p. 259–277.

Fournier, F., 1960, Climat et erosion: Paris, Presses Universitaires de France.

Gibbs, R. J., 1967, The geochemistry of the Amazon River system: part I. The factors that control the salinity and the composition and concentration of the suspended solids: Geol. Soc. America Bull., v. 78, p. 1203–1232.

Gilluly, J., 1955, Geologic contrasts between continents and ocean basins: Geol. Soc. America Spec. Paper 62, p. 7–18.

Gordon, R., 1885, The Irawadi River: Royal Geographical Society (London) Proc. (new series), v. 7, p. 292–331.

Griffiths, G. A., 1979, High sediment yields from major rivers of the western Southern Alps, New Zealand: Nature, v. 282, p. 61–63, (see also Discussion in Nature, 1980, v. 287, p. 88–89).

——— 1981, Some suspended sediment yields from South Island catchments, New Zealand: Water Res. Bull., v. 17, p. 662–671.

——— 1983, Spatial and temporal variability in suspended sediment yields of North Island basins, New Zealand: New Zealand Acad. Sci., v. 18, p. 575–584.

Holeman, J. N., 1968, Sediment yield of major rivers of the world: Water Resources Res., v. 4, p. 737–747.

——— 1980, Erosion rates in the U.S. estimated by the Soil Conservation Service's inventory (abs.): EOS (American Geophys. Union Trans.), v. 61, p. 954.

Janda, R. J., and Nolan, K. M., 1979, Stream sediment discharge in northwestern California, *in* Guidebook for a Field Trip to Observe Natural and Management-Related Erosion in Franciscan Terrane of Northern California: Geol. Soc. America, Cordilleran Section, p. IV-1-27.

Jansen, P. P.; van Bendegom, L.; van den Berg, J.; de Vries, M.; and Zanen, A., 1979, Principles of River Engineering: London, Pitman, 509 p.

Key Sanchez, F., 1950, Algunas consideraciones con respecto a la determinacion del acarreo solido y su magnitud en algunos rios de Venezuela: Revista Colegio de Ingenieria de Venezuela, v. 177, p. 28–29.

Kuenen, P. H., 1950, Marine Geology: New York, John Wiley, 568 p.

Li, Y. H., 1976, Denudation of Taiwan Island since the Pliocene epoch: Geology, v. 4, p. 105–107.

Lisitzin, A. P., 1972, Sedimentation in the world ocean: Soc. Econ. Paleont. Mineral. Spec. Pub. 17, 218 p.

Livingstone, D. A., 1963, Chemical composition of rivers and lakes: U.S. Geol. Surv. Prof. Paper 440-G, 64 p.

Long, Y.-Q., and Xiong, G.-S., 1981, Sediment measurement in the Yellow River, in Erosion and sediment transport measurement: Int. Assoc. Hydrol. Sci. Pub. 133, p. 275–285.

Lopatin, G. V., 1950, Erozia y stok nanosov: Priroda, no. 7.

Lopatin, G. W., 1962, Intensitat der Wassererosion auf dem Gebiet der Ud. S.S.R: International Assoc. Sci. Hydrol. Pub., v. 59, p. 43–51.

Maldonado, A., 1977, Introduccion geologica al delta del Ebro: Treb. Inst. Cat. Hist. Nat. (Barcelona), v. 8, p. 7–45.

Meade, R. H., 1974, Net transport of sediment through the mouths of estuaries: seaward or landward?: Inst. Geologie Bassin d'Aquitaine Bordeaux University, Mem. 7, p. 207–213.

———; Nordin, C. F., Jr.; Curtis, W. F., Costa Rodrigues, F. M.; do Vale, C. M.; and Edmond,

J. M., 1979, Sediment loads in the Amazon River: Nature, v. 278, p. 161–163.

MILLIMAN, J. D., 1975, Upper continental margin sedimentation off Brazil. A synthesis: Contrib. Sedimentol. 4, p. 151–175.

——— 1980, Sedimentation in the Fraser River and its estuary, southwestern British Columbia (Canada): Estuar. Coast. Mar. Sci., v. 10, p. 609–633.

MOLNIA, B. F., 1979, Sedimentation in coastal embayments, northeastern Gulf of Alaska: Proc. 11th Offs. Tech. Conf., Houston, p. 665–670.

——— 1980, Twentieth-century history of the Gulf of Alaska coastline, Cape Suckling to Cape Spencer, *in* FIELD, M., et al., eds., Quaternary depositional environments of the Pacific coast: SEPM Pacific Coast Paleogeog. Sym. 4, p. 121–141.

———, and CARLSON, P. R., 1980, Quaternary sedimentary facies on the continental shelf of the northeast Gulf of Alaska, *in* FIELD, M., et al., eds., Quaternary depositional environments of the Pacific coast: SEPM Pacific Coast Paleogeog. Sym. 4, p. 157–168.

MURRAY, S. P.; HSU, S. A.; ROBERTS, H. H.; OWENS, E. H.; and CROUT, R. L., 1983, Physical processes and sedimentation on a broad shallow bank: Estuarine, Coast. Shelf Sci., v. 14 (in press).

NEDECO, 1959, River Studies and Recommendations on Improvement of Niger and Benue: Amsterdam, North Holland Publ. Co., 1000 p.

——— 1973, Rio Magdalena and Canal del Dique Survey Project. The Hague, Netherlands Engineering Consultants, 397 p.

NEILL, C. R., and MOLLARD, J. D. 1980, Examples of erosion and sedimentation along some northern Canadian rivers: Chinese Soc. Hydraulic Eng. Proc. Int. Sym. River Sedimentation, v. 1, p. 565–600.

PESHAWAR UNIVERSITY, 1970, The sediment load and measurements for their control in rivers of West Pakistan: Peshawar University Civil Eng. Dept. Water Res. Div., v. 1, 214 p., v. 2, 320 p.

PETERS, J. J., 1978, Discharge and sand transport in the braided zone of the Zaire estuary: Netherlands Jour. Sea Res., v. 12, p. 273–292.

PICKUP, G., 1980, Hydrologic and sediment modelling studies in the environmental impact assessment of a major tropical dam project: Earth Surf. Proc., v. 5, p. 61–75.

———; HIGGINS, R. J.; and WARNER, R. F., 1981, Erosion and sediment yield in Fly River drainage basins, Papua New Guinea: Int. Assoc. Hydrol. Sci. Publ. 132, p. 438–456.

QIAN, N., and DAI, D. Z., 1980, The problems of river sedimentation and the present status of its research in China. Chinese Soc. Hydraulic Eng. Proc. Int. Sym. River Sedimentation, v. 1, p. 1–39.

REIMNITZ, E., 1966, Late Quaternary history and sedimentation of the Copper River delta and vicinity, Alaska: Unpubl. Ph.D. dissertation, University of California, San Diego, 160 p.

ROOSEBOOM, A., 1978, Sedimentafvoer in Suider-Afrikaanse Riviere: Water S. A., v. 4(1), 14–17.

———, and HARMSE, H. J. VON M., 1979, Changes in the sediment load of the Orange River during the period 1929–1969: Int. Assoc. Hydrol. Sci. Publ. 128, p. 459–470.

SCHUMM, S. A., 1963, The disparity between present rates of denudation and orogeny: U.S. Geol. Survey Prof. Paper 454-H, 13 p.

———, and HADLEY, R. F., 1961, Progress in the application of landform analysis in studies of semiarid erosion: U.S. Geol. Survey Circular 437, 14 p.

SHIMKUS, K. M., and TRIMONIS, E. S., 1974, Modern sedimentation in Black Sea, *in* DEGENS, E. T., and ROSS, D. A., eds., The Black Sea—geology, chemistry, and biology: Am. Assoc. Petrol. Geol. Mem. 20, p. 249–278.

STRAKHOV, N. M., 196., Onekotroykh zakonomernostiakh denudatsii i perenosa osadochnogo materiala na ploshchadyakh gymidnykh klimatov, *in* STRAKHOV, N. M.; BEZRYKOV, P. L.; and YABLOKOV, V. S., eds., Sovremennye osadki moei i oceanov: Moscow, Izdatelstovo Akademia Nauk SSSR, p. 5–27.

SUBRAMANIAN, V., 1978, Input by Indian rivers into the world oceans: Proc. Indian Acad. Sci., v. 87A, pp. 77–88.

TEMPLE, P. H., and SUNDBORG, A., 1972, The Rufiji River, Tanzania, hydrology and sediment transport: Geograf. Annaler, v. 54A, p. 345–368.

UNESCO, 1972, Discharge of selected rivers of the world, general and regime characteristics of stations selected: Stud. Repts. Hydrol. 5, v. 1, 70 p.

——— 1974, Discharge of selected rivers of the world, mean monthly and extreme discharges (1969–1972): Stud. Repts. Hydrol., 5, v. 3, pt. 2, 124 p.

——— 1978, World register of rivers discharging into the oceans: Unpubl. manuscript.

——— 1979, Discharge of selected rivers of the world, mean monthly and extreme discharges (1972–1975): Stud. Repts. Hydrol., 5, v. 3, pt. 3, 104 p.

URIEN, C. M., 1972, Rio de la Plata estuary environments: Geol. Soc. America Mem. 133, p. 213–234.

U.S. GEOLOGICAL SURVEY, 1978, Water resources data for Alaska, Water Year 1977: U.S. Geol. Survey Water Data Report AK-77-1, 439 p.

VAN ANDEL, T. H., 1967, The Orinoco delta: Jour. Sed. Petrol., v. 37, p. 297–310.

WARD, P. R. B., 1980, Sediment transport and a reservoir siltation formula for Zimbabwe-Rhodesia: Die Siviele Ingenieur, Suid-Afrika, Jan., 1980, p. 9–15.

WATER RESOURCES PLANNING COMMISSION (TAIWAN), 1978, Hydrological year book of Taiwan, Republic of China, 1977: Ministry of Economic Affairs, (Taiwan), 315 p.