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Joint Group of Experts on the Scientific Aspects
of Marine Environmental Protection (GESAMP)

Anthropogenic Influences on Sediment Discharge to the Coastal Zone and Environmental Consequences

GESAMP REPORTS AND STUDIES No. 52

ANTHROPOGENIC INFLUENCES ON SEDIMENT DISCHARGE TO THE COASTAL ZONE AND ENVIRONMENTAL CONSEQUENCES

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1. INTRODUCTION

Changes in the delivery of sediment to coastal areas from land may have deleterious effects on the marine environment. Such effects include harm to living resources, hindrance to marine activities and reduction of amenities. These effects are brought about by increased sediment delivery, which causes such problems as increased sedimentation and turbidity, or decreased sediment delivery, which may lead to accelerated coastal erosion as well as uncompensated subsidence.

Although natural changes take place, man's activities on land presently represent the main cause for historically recent changes in sediment delivery to coastal environments. Acknowledging this problem, GESAMP, during its eighteenth session in 1988 formed a Working Group on the Impacts of Anthropogenically Mobilized Sediments in the Coastal Environment (WG 30). During the following years this subject was reviewed, culminating in a Workshop on the subject that was convened in Penang, Malaysia in November 1991. The results of this Workshop, as reported to the twenty-second session of GESAMP, indicated the widespread concern related to this problem.

During the review of the progress of Working Group 30 at GESAMP XXII, it was recommended that the work of this group should continue but with modified terms of reference. It was recommended that the new terms of reference should "reflect the need for a more holistic river basin scale evaluation of the problem with the aim of providing a more appropriate scientific framework for managing the impacts of changing sediment inputs to coastal zones". These new terms of reference were adopted by GESAMP as follows:

- Review and quantify, where possible, the effect of human land-based activities on sediment transport rates and volumes in relation to watershed characteristics;
- Review on a regional basis the known and potential impacts of changes in sediment flux to coastal and nearshore waters on coastal environments, resources, amenities and human use; and
- Develop conceptual models that would provide a better understanding of the time scales that connect watershed activities and coastal impacts in different watershed types and regions.

These terms of reference were used as the basis of a Working Group meeting held in Savannah, Georgia USA on 11-15 January 1993. Following the recommendations of GESAMP XXII, the participants of the meeting (listed in Section 7) attempted to address the terms of reference in a holistic way. Thus this report addresses the links between activities in watersheds and effects in the coastal zone. The report also attempts to identify characteristics of watersheds and coastal areas that place them at greatest risk *vis a vis* man's activities that affect sediment mobilization and transport.

2. GLOBAL SEDIMENT INPUTS TO THE MARINE ENVIRONMENT

2.1. Natural Characteristics of Watersheds that Control Water and Sediment Yields

Predicting changes in fluvial processes and impacts assumes knowledge of river flow, transport and discharge to the sea as well as an understanding of the fate of the discharged products. Because both water and sediment are important, at least indirectly, in this context, we treat both briefly in this section.

2.1.1. Water Discharge In terms of water, river discharge is essentially a function of the net difference between precipitation and evapotranspiration (P-E) integrated over the river basin. On a global scale, the amount of water discharged by rivers to the ocean is estimated to be between 32 and 39 x 10^3 km^3/yr (Livingstone, 1963; Unesco, 1978; Meybeck, 1979; Milliman, 1991). For the purposes of this discussion, a value of 35 x 10^3 km^3 seems a realistic estimate, which is about 10 percent lower than P-E as calculated by Baumgartner and Reichel (1975); presumably at least some of this difference represents groundwater flow.

In terms of world-wide water discharge, the world's ten largest rivers account for about 38 percent of the total fluvial water entering the ocean, slightly greater than their combined percentage of drainage basin area (Table 1). The Amazon River alone contributes about 18 percent of the world total (about 6300 km^3/yr), more than the combined total of the next 7 largest rivers! Not surprisingly, tropical areas with heavy rainfall - specifically southern Asia, Oceania and northeastern South America - are the prime contributors, about 65 percent of the global total. In contrast, with the exception of the Zaire and Niger Rivers, Africa contributes virtually no fluvial water to the oceans (the Nile River being effectively dammed).

2.1.2. Sediment Flux The erosion, transport and discharge of drainage basin sediment are functions of many more variables than is water discharge. To predict the sediment load of a small river we need to understand the interaction of a number of factors, including climate, precipitation (both average and peak), discharge (volume and velocity), basin geology (i.e. the erodability of the substrate), human impact, and the size of the drainage basin.

Because the erosional and transport capacity of water is a direct function of velocity, many researchers have tried relating sediment load (or yield - load normalized for basin area) to river velocity (e.g. rating curves) as well as net/gross precipitation. However, the wide differences in results suggest that, "...current evidence concerning the relationship between climate and sediment yield emphasizes that no simple relationship exists.' (Walling and Webb (1983, p. 84). Although it is difficult to measure, there does seem to be a complex relation between erosion of a river and the ratio of peak to average flow. For instance, in arid areas (where vegetation cover is sparse) peak rainfall may be orders of magnitude greater than mean rainfall, and in such areas the erosive capacity of rivers can be as great or greater than rivers that drain terrain with consistently high amounts of rainfall (Milliman and Syvitiski, 1992).

While many of the data need to be re-evaluated and updated, the topography and basin

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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

*Copied from Milliman and Syvitski (1992). Some inconsistencies have been discovered in this table since publication. For example, the Murray (Austr) is in Australia, not Austria. Data should be checked against original source since more recent estimates for sediment load, reflecting the influence of dams, etc. may be available.

Table 1. Continued

River	Area (× 10^6km^2)	Load (× 10^6t/yr)	Yield (t/km^2/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

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Table 1. Continued

River	Area ($\times 10^6 km^2$)	Load ($\times 10^6 t/yr$)	Yield ($t/km^2/yr$)	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
Erhjan (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 (×10⁶km²)	Load (×10⁶t/yr)	Yield (t/km²/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 Älv (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.

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Table 1. Continued

River	Area (× 10^{6}km^2)	Load (× 10^{6}t/yr)	Yield (t/km^2/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. 1990*a*
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. 1990*b*

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 >2 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

area appear to have a first-order control over sediment discharge of most rivers (Milliman and Syvitski, 1992). Elevation or relief is, in some ways at least, only a surrogate variable for tectonism. Milliman and Syvitski (1992) as well as earlier workers (e.g. Hay *et al.*, 1989) emphasized the correlation between topography relief or elevation and sediment yield. 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. Mountainous areas also experience 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 a few years after the eruption, the Columbia River discharged an estimated 35 mt/yr (Meade and Parker, 1985).

Geomorphologists and hydrologists often use the term "sediment yield" ($t/m^2/yr$). In this way, the relative sediment load of various size basins can be compared. Sediment yield increases with decreasing river basin area (Fig. 1), a direct function of the inability of smaller river basins to store sediment. In large river basins, for example, only a small portion of the sediment eroded in the upper reaches of the river may be transported to the ocean, the rest being stored, either temporarily or permanently, in the rivers' flood plains. Smaller rivers, in contrast, have a smaller amount of flood plains in which to store eroded sediment, so that a larger percentage of the sediment actually reaches the ocean. Thus, while the sediment load of rivers is usually directly related to the size of the river basin, the sediment yield is indirectly related to basin size (Fig. 1). The importance of smaller rivers with high yields becomes important when it is realized that while small rivers drain only about 20 percent of the global land area, they number in the many thousands and therefore collectively contribute much more sediment than envisioned by most scientists.

Small basins also are more affected by major episodic events (such as floods), as the impact of these events cannot be modulated throughout the basin. One of the most dramatic examples is the Santa Clara River (southern California), in which three floods (representing a total of 6 days) in the span of 18 years accounted for nearly 60 percent of the total sediment transport measured during that period (Meade *et al.*, 1990b).

Mountainous rivers have greater loads and yields than do upland rivers, which in turn have greater loads and yields than lowland rivers (Fig. 1), 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). 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, which probably reflects the dominance of single types of geology or microclimate in small basins; larger river basins are

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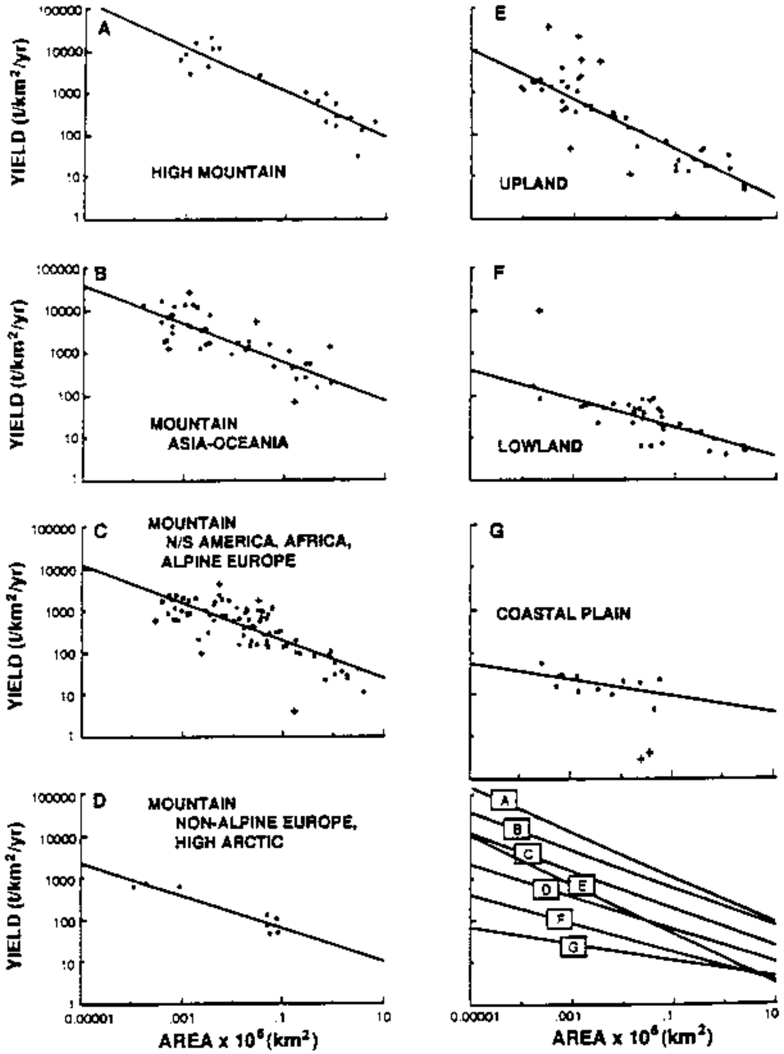

Figure 1. Variation of sediment yield with basin area for the seven topographic categories of river basins listed in Table 1. For all river types, except lowland and coastal plain rivers, the correlation is strong (r^2 ranging from 0.70 to 0.89). From Milliman andd Syvitski, 1992.

modulated by a greater range of conditions.

The role of sediment erodability (mainly a function of geology, vegetation cover and human activity; see next section) is also clearly an important factor, and helps explain many of the deviations from the trends shown in Fig. 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. High erosion rates throughout much of southern Asia, however, partly reflect poor soil conservation, the result of deforestation and over-farming (see below).

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 an effect of latitude, but an effect of the active glaciers that deliver large loads of sediment to the headwaters of the Copper, Yukon and MacKenzie Rivers; headwaters of the Colville and Babbage Rivers are not influenced by large glaciers.

2.2. Man's Impact on Sediment Yields of Watersheds

2.2.1. Human Activities that Increase River-Sediment Discharges to the Coastal Zone. Increases in the sediment discharge due to human activities are evident in many rivers of the world. For example, the very high sediment loads in modern Asian rivers reflect a considerable influence from human activities, particularly poor agricultural practices in conserving soil. Deforested land, which in tropical areas alone is increasing by 100,000 km^2/yr (Myers, 1988), is less likely to retain either water or sediment. Agriculture, such as rice growing, is also conducive to sediment erosion, and heavy monsoon-related rains have great erosive power (e.g. Walling, 1983).

Assuming that present-day Asian and Oceania river loads are 5 times greater than before man began deforestation and farming, the world-wide quantity of fluvial sediment reaching the ocean 2500 years ago might have been less than 7 x 10^9 t/yr, and the percentages from Asia and Oceania would have accounted for correspondingly smaller fractions of the world's total than they do at present.

This stripping of soil and nutrients from the soils results in increased fluxes to the sea if the rivers remain undammed. It is not unlikely, for example, that some coastal areas might become overly productive and subsequently anoxic because of the increased discharge of nutrients, and subsequently anoxic. Another result of this increased river discharge in Asia has been accelerated land progradation and delta growth over the past few millennia. The city of Shanghai, for example, which presently has a metropolitan population of nearly 20 million, was tidal flat as recently as 2-3 thousand years ago.

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However, more rivers are being diverted or dammed for irrigation, flood control and hydroelectric power. Several examples of damming are well known - for example the virtually complete cessation of sediment flux from the Colorado and Nile rivers. The Rhone carries only about 5 percent of the load it did in the 19th century (Corre *et al.*, 1990), and the Indus River discharges less than 20 percent of the load it did before construction of barrages in the late 1940's (Milliman *et al.*, 1984). Values for many other Asian and South American rivers may be similarly misleading, either because of sparse or erroneous data or because new river diversions have changed the loads dramatically since the cited data were obtained.

2.2.1.1. Crop Farming. On a global scale, the most massive anthropogenic increases in river sediment loads have come about as a result of crop farming, especially in areas where forests have been cut down to make way for croplands. The settlement of the eastern parts of Canada and the United States during the 17th, 18th, and 19th centuries was marked by the replacement of native forests by croplands. During the 19th century, especially after the general adoption of the moldboard plow, prairie grasslands were converted to deeply plowed fields. These conversions caused order-of-magnitude increases in soil erosion and corresponding increases in the sediment yields of rivers (Meade, 1969, 1982). Similarly, the extensive agricultural development of the loess plateau of northern China that began about 200 BC also is believed to have caused an order-of-magnitude increase in the suspended-sediment discharge of the Yellow River (Milliman *et al.*, 1987). Because of the storage of sediment in river systems and the time lags between upland erosion and the delivery of river sediment to the coastal zone, the agriculturally-induced increases in the growth rates of large river deltas are most appropriately considered in temporal frameworks of millennial scale.

2.2.1.2. Deforestation for Timber or Grazing. The effects of deforestation for purposes other than clearing land for crop farming depend on the degree of soil disturbance. This is especially true if the deforested areas are in regions of active tectonism where other factors such as sheared bedrock and steep hillslopes come into play. Most of the information on timber harvesting under such conditions comes, not surprisingly, from the Pacific Rim, especially from places like New Zealand and the northwestern United States. Timber cutting on steep slopes of the Pacific Northwest of the United States has resulted in sediment yields 2-4 times the natural yields in streams draining the logged areas (Swanston and Swanson, 1976). The effects are clearly related to the amount of soil disturbance during logging. Often, the greatest sediment yields (8-10 times natural yields) are derived from the construction of the roads that are needed to transport the logs away from the cutting sites.

Whether or not livestock grazing strongly influences river-sediment yields is still a controversial issue. An onset of intense degradation and gullying during the late 1800s in the southwestern United States was thought by many to have been caused by overgrazing by livestock (Cooke and Reeves, 1976). When a marked decrease of suspended-sediment discharge was recorded in the middle 1940s in the Colorado River (which drains much of the southwestern U.S.), at least one author speculated that the decrease might have been due to a change in livestock grazing practices (Hadley, 1974). However, more recent field studies have delineated a regional pattern of increased aggradation and accumulation of sediment since the 1940s in the tributary basins of the Colorado River (Hereford, 1984). A consensus among field investigators favors the conclusion that the present episode of aggradation followed a subtle shift in climate, which perhaps was the obverse of the conditions that triggered the episode of intense degradation and gullying that characterized the region during the late 1800s (Cooke and Reeves, 1976). In any event, the causes of this century-scale cycle of degradation and aggradation are presently considered to have been natural rather than induced by humans or livestock.

Recent conversions of virgin forest lands to cattle-grazing lands in the Amazon region so far have not caused any discernible changes in the hydrology and sediment loads of the major trunk rivers. An expected effect of deforestation would be an increase in erosion rates and sediment yields. However, small incremental increases in sediment contributed by deforested areas to large trunk rivers that already transport large natural sediment loads from the Andes would not be easily detectible in the rivers themselves. Tributary rivers not already burdened with heavy natural sediment loads would seem to be more promising places to look. But even in the Jamari and Jiparana Rivers, two large but sediment-poor tributaries of the Madeira River that drain some of the most heavily deforested regions of Amazonia, Mortatti *et al.* (1992) were unable to demonstrate the effects of deforestation on hydrological and geochemical characteristics of the rivers.

2.2.1.3. <u>Surface Mining</u>. Another human activity whose influence on sediment loads has been large on a river-basin scale is surface mining. Mining wastes have clogged the channels and inundated the flood plains of rivers of at least moderate size. Perhaps the best known example is that of the hydraulic gold-mining wastes in the Sacramento River valley of California. Beginning around 1850, during the gold-rush days in California, gold-bearing alluvial terrace deposits in the Sierra Nevada foothills were mined intensively with water cannons. The alluvium was hosed out of the terraces into sluices and, after the gold was extracted, into the tributary streams that flowed off the Sierra Nevada to join the Sacramento River. By about 1880, the beds of the stream channels had risen several meters, and mining debris had been carried onto the flood plains in sufficient quantities to cover houses and destroy farms. The farmers went to court and got the mining stopped in 1884, but by then the damage was done. In a study of the subject, Gilbert (1917) estimated that the quantity of earth mobilized by the hydraulic mining was 1.2×10^9 cubic meters, which, as he pointed out, "was nearly eight times as great as the volume moved in making the Panama Canal". Natural sediment sources during the same period contributed only 0.1×10^9 cubic meters. Most of the mining debris that passed down the channel ended up in San Francisco Bay; the mining debris that was deposited on the floodplains, which amounted to about 90 percent of the total mobilized sediment, still remains stored in the floodplains.

A more recent example is that of the copper-mining wastes in the Kawerong and Jaba Rivers of Papua New Guinea, described by Pickup *et al.* (1979, 1983). Mining activities during an 8-year period (1968-1976) contributed 0.2×10^9 tons of sediment to a small river system whose natural sediment load was negligible by comparison. One third of this vast quantity of sediment was deposited on flood plains and in the delta of the Jaba River. Because the Jaba River is short and steep, descending 2250 meters over a length of only 50 kilometers, it discharges a sandy bedload directly to the coastline where its large delta has prograded into

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2.2.1.4. Urbanization. Urbanization is one of the more recent human influences that contributes large sediment loads to streams, and its effects have been studied most intensively and extensively in the areas surrounding the cities of Washington and Baltimore (Roberts and Pierce, 1974; Vice *et al.*, 1969; Yorke and Herb, 1978). Wolman and Schick (1967, p. 454) reported annual sediment yields from construction sites in the Washington-Baltimore area that ranged from 2,000 to 50,000 ton/km^2. Guy (1965, p. 37) estimated that the extra sediment produced by urbanization near Washington was sufficient to double the discharge of suspended sediment by the Potomac River to its estuary.

Wolman's (1967) schematic summary of changes in sediment yield with changing land use in a typical area between Washington and Baltimore is shown in Figure 2. Until the end of the 18th century, the area remained in its original forested condition, and sediment yields were low. The area was converted to crop farms in the 19th century, and the sediment yields increased accordingly. During the first half of the 20th century, soil-conservation measures were introduced and some lands reverted to woods and pasture while awaiting their conversion to suburb and cities; both these effects caused the sediment yields to decrease. During the period when the lands are converted to urban use, the sediment yields are extraordinarily large, but this period is relatively short. After the area becomes a city or suburb with paved streets and planted lawns, the sediment yields become small again.

2.2.2. Human Activities that Decrease River-Sediment Discharges to the Coastal Zones

2.2.2.1. Dams and Reservoirs. One of the most pervasive influences on sediment loads delivered to the coastal zones of the world is exerted by the dams and reservoirs that have been built in large numbers across large rivers. Dams are built to impound water for various purposes, and the reservoirs they form interrupt the downriver flow of sediment. Although the river water that enters a reservoir is released eventually (through a power plant, into a diversion canal, or over a spillway), much of the sediment is trapped permanently in the reservoir. Prior to 1900 the rate of dam construction (i.e., dams greater than 15 km in height) was small. Between 1900 and 1945 dam construction increased between wars and economic depression (Petts, 1984, Fig. 3). Since 1945 the rate of dam construction has continued to rise, with the global rate averaging over 900 per year (indicating major and minor dams) between 1951 and 1982 (Van der Leeden *et al.*, 1990). Over half of these dams were constructed in China during this time period.

Nearly all reservoirs on major rivers trap at least one-half of the river sediment that flows into them, and some like Lake Mead on the Colorado River and Lake Nasser on the Nile River, trap virtually all the sediment. Examples are described below from rivers of North America where sufficient historical data are available. The effects shown in the North American examples can be presumed to follow the construction of dams and reservoirs on other major rivers of the world.

The classic example in North America of the interruption of a large discharge of river

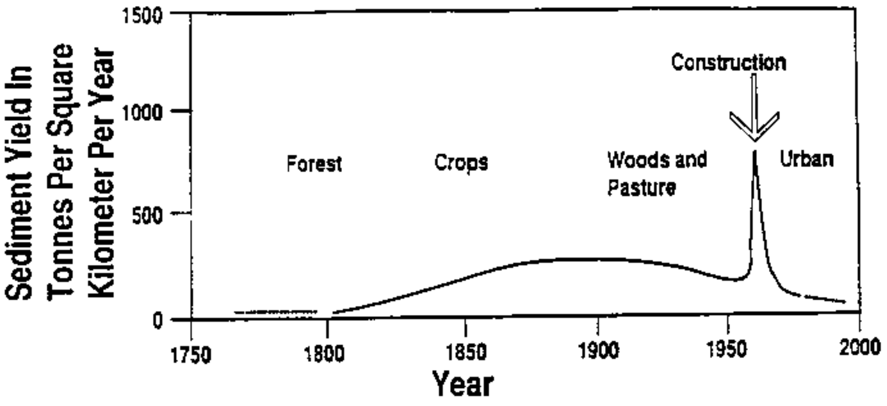
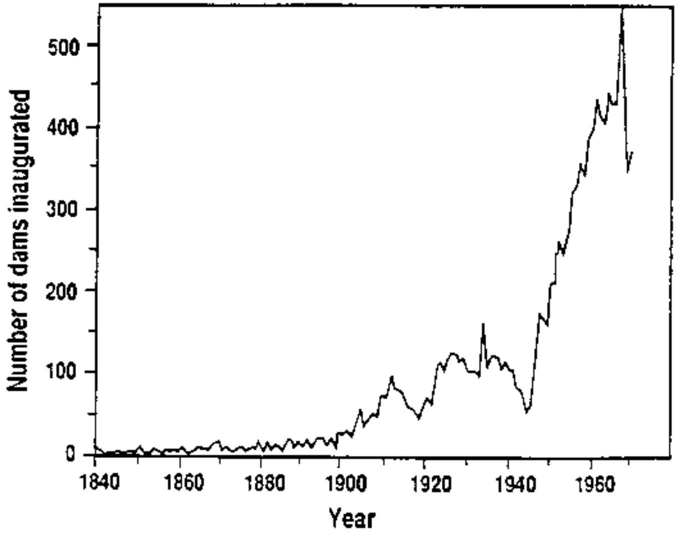


Figure 2. Schematic representation of changes in sediment yield related to changes in land use between the years 1800 - 2000 in a fixed area of the Maryland Piedmont (modified after Wolman, 1967, p. 386).



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sediment to the coastline is that of the Colorado River. Before about 1930, the Colorado River delivered an average of 125 to 150 x 10^6 tons of suspended sediment per year to its delta at the head of the Gulf of California. Since the closure of Hoover Dam, which began in 1935, this rate of sediment delivery has declined, first precipitously and then more gradually, to an average annual amount today of about 10^5 tons. Aside from a period between 1934 and 1938, when 30 x 10^9 m^3 of the river water was appropriated for the initial filling of Lake Mead behind Hoover Dam, the quantity of water carried by the Colorado River past Yuma, Arizona, has declined more or less progressively (Figure 4A). This decline has been in response to the increasing diversion of water from the Colorado River for irrigation of croplands and for municipal water supplies. The more abrupt decline in sediment discharge at Yuma (Figure 4B) clearly was related to a single event, the closing of Hoover Dam. This sequence of events is strongly analogous to that in the lower Nile River, wherein the annual suspended-sediment discharges were decreased from about 125 x 10^6 tons to less than 3 x 10^6 tons following the closure of the high dam at Aswan (Shahin, 1985, p.460).

Another large river system whose sediment loads are strongly influenced by reservoirs is the Mississippi. Previous to extensive European settlement of the Mississippi Valley, and up to about 1950, the major sources of sediment in the river were the western tributaries, the Missouri River and, to a lesser extent, the Arkansas River. Following World War II, a series of five large dams was completed on the Missouri River for irrigation, hydroelectric power, and navigation control (Meade and Parker, 1985). During the same time, a series of locks and dams was constructed for navigation on the Arkansas River (Madden, 1965). Beginning in the early 1950s, downstream sediment loads were diminished, and the effect could be observed all the way to the mouth of the Mississippi River. Partly because of the construction of reservoirs, and partly as a result of other channel-stabilization works (Keown *et al.*, 1986), sediment discharges to the Gulf of Mexico by the Mississippi River are now less than one-half of what they were before 1950. The diagrams in Figure 5 compare the estimated sediment discharges as of circa 1700 with those measured circa 1980. Partly offsetting the decrease in sediment loads from the western tributaries is an increase in the sediment inputs from the more humid Ohio River Valley. This inferred increase is related mainly to the conversion of the original forests to croplands.

In addition to the well publicized impact of the Aswan dam, the impacts of other water diversion projects in Africa have been documented. For example, Jacobsen *et al.* (1989) concluded that several major engineering works in the west African region have resulted in redistribution of sediment load and resulting coastal degradation. For example, the Akosombo dam on the Volta River in Cihane which resulted in starved the beaches because of the deposition of sand behind the dam and in the estuary. Beach erosion along the down drift side has also become a major problem. The Shiroro and Kainji dams on the Niger River have also led to a reduction of sediment load, previously estimated at 40 x 10^6 tons (Milliman and Syvitski, 1992), reaching the Niger delta coastline. The once progradating Niger delta has hence become erosional (Ibe *et al.*, 1986), and the building of Diama and Manantali dams on the Senegal River has reduced substantially the amount of sand reaching the Senegal delta, thereby aggravating erosion (Michel and Sall, 1984).

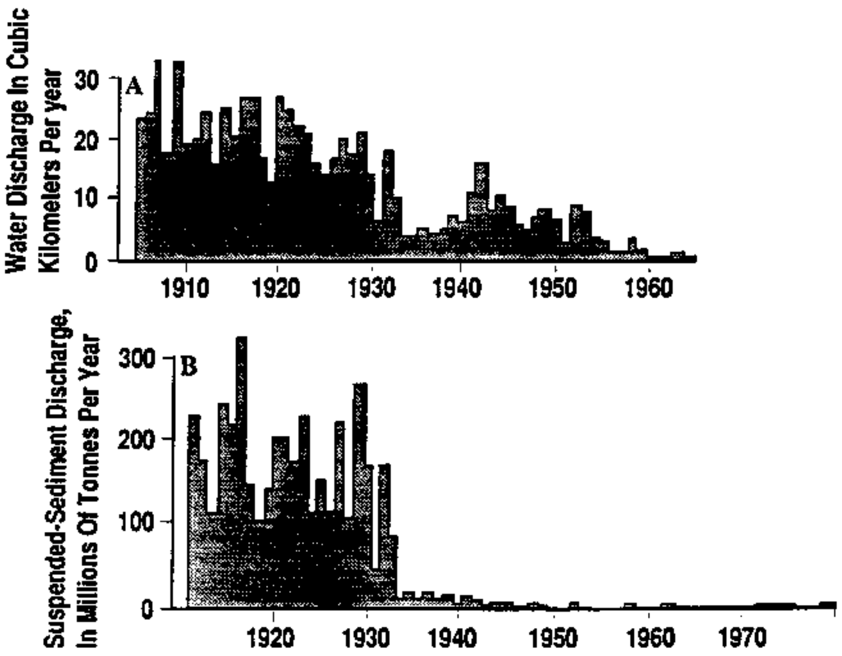

Figure 4. Annual discharges of water (1905-1964) and suspended sediment (1911-1979) in the Colorado River at Yuma, Arizona (Curtis and others, 1973, p. 9; Meade and Parker, 1985, p. 55).

A: Water discharges. Compiled from data of U.S. Geological Survey. $1\ km^3 = 10^9 m^3$.

B: Suspended-sediment discharges. Compiled from data of U.S. Bureau of Reclamation. The abrupt decrease in suspended-sediment discharge in the middle 1930s coincided with the closure of the Hoover Dam, 500 km upriver of Yuma.

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and (4) a complex pattern of scour in the 100-km reach immediately below the reservoir and deposition farther downriver (resulting in a net deposition of 100 million tons per year) during the latest operation mode that specifically impounds clear water and sluices sediment-laden waters. Based on the experience at Sanmenxia, similar sluicing works were incorporated in the Gezhouba Dam on the Yangtze River, and similar structures are being included in the design for the proposed Three Gorges Project on the same river. Consequently, the effects of these large dams on the sediment discharge to the Yangtze delta are expected to be slight (Qian *et al.*, 1987; Tang and Lin, 1987).

What of the future of large reservoirs? In the absence of widespread adoption of bypassing measures such as those at Sanmenxia and Gezhouba, many of the world's major reservoirs may well be completely filled with deposited sediment by the end of the 21st Century. In the United States, for example, some of the major reservoirs built during the middle years of the 20th Century were designed to accommodate only 100 years worth of sediment accumulation. More recent changes -- construction of additional reservoirs upstream and perhaps alterations of land-use patterns and increased soil conservation -- have extended the projected life of many of these major reservoirs. However, at some point in the second half of the 21st Century, the capacities of many major reservoirs for trapping sediment will be approaching zero.

What scenarios can we project for the years 2050-2150? The answers to this question depends on the answers to two important related questions: (1) Are the sediment loads of major river systems, which were increased by man-induced acceleration of soil erosion during the last few millennia, and which have been decreased by dams and reservoirs during the last few decades, likely to be increased again when the reservoirs become too full to trap any more sediment? and (2) Are the time frames of anticipated sea-level rise or deltaic subsidence such that they may be significantly offset by resumed inputs of large loads of river sediment?

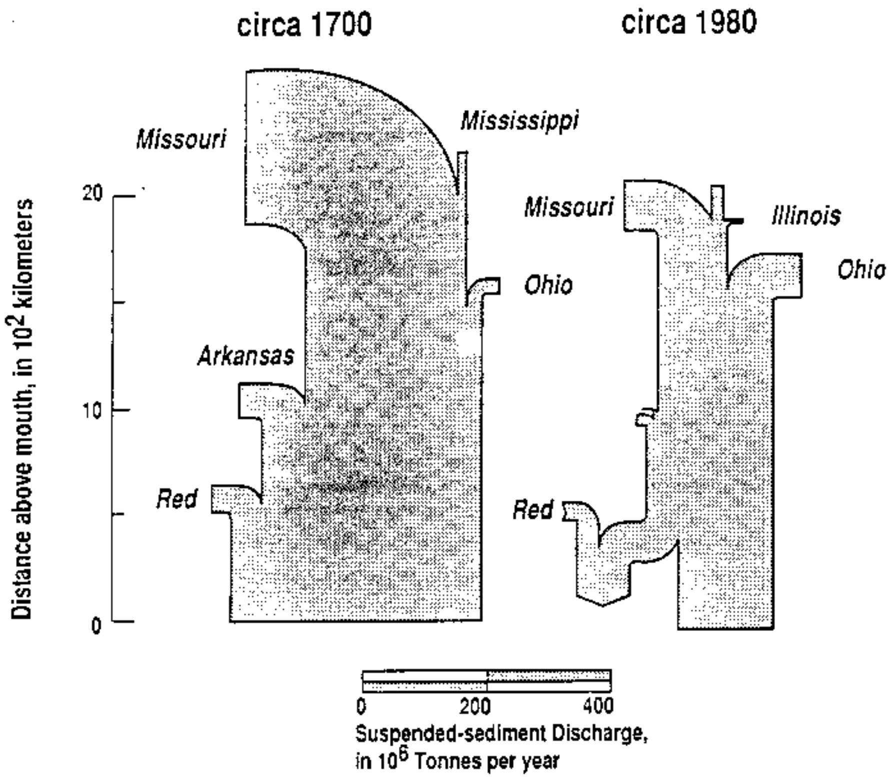

Figure 5. Long-term average discharges of suspended sediment in the lower Mississippi River circa 1700 and circa 1980. Estimate of discharge circa 1700 from Meade *et al.* (1990). Discharge circa 1980 from compilation by Keown *et al.* (1986).

2.2.2.2. Channel Stabilization Works. In addition to the cross-channel structures such as dams, in-channel structures like wing dams, and along-channel alterations such as revetments, tend to decrease the amount of sediment that a river transports to the coastal zone. Wing dams are designed specifically to narrow and deepen a channel, usually for navigation purposes, and the areas between wing dams are likely sites for the long-term storage of sediment that might otherwise continue moving downriver. Revetments and other bank-protection works are specifically designed to retard the erosion of river banks, thus preventing the mobilization of new sediment or the remobilization of sediment previously stored on its banks by the river.

3. IMPACTS ON THE COASTAL MARINE ENVIRONMENT

3.1. Problems in Relating River-Sediment Loads to Coastal Processes

3.1.1. Upriver Locations of Gauging Stations. The first difficulty in relating river-sediment loads to coastal processes is in the spatial separation of the available data. The farthest downstream point at which sediment discharge is conventionally measured in a river is usually some distance upriver of the coastline. Routine measurements of water and sediment discharge are best made where the fluctuations of river flow and river level are not influenced by oceanic tides. For example, the points farthest downstream where sediment loads are measured in the Mississippi and Amazon Rivers are, respectively, 500 and 800 km inland of the river mouths.

The three rivers that transport the largest sediment loads, the Amazon, Ganges, and Yellow Rivers, all deliver about a billion tons per year to the upriver ends of their deltas. However, different proportions of these river-sediment loads actually reach the coastline or the deep sea (Figure 6). Of the 10 x 10^8 tons that the Amazon River delivers annually to its delta (already less, because of deposition on the intervening floodplain, than the annual load of 12 x 10^8 tons of sediment measured 500 km upriver at Obidos), only about 8 x 10^8 tons reach the mouth of the river. The other 2 x 10^8 tons are deposited in the delta, through which the river flows for 300 km of its length. Of the 8 x 10^8 tons discharged through the mouth, about 6 x 10^8 are deposited on the continental shelf (Kuehl *et al.*, 1986), and the remaining 2 x 10^8 tons are transported northwestward along the coasts of the Guyanas, perhaps to be deposited in the delta of the Orinoco River (Eisma *et al.*, 1991). Virtually no sediment escapes offshore.

The combined Ganges and Brahmaputra Rivers deliver about 11 x 10^8 tons of sediment per year to the head of the delta in Bangladesh (Figure 6B). A little more than half this amount, about 6 x 10^8 tons per year, is deposited in the delta. Of the 5 x 10^8 tons that reach the coastline, a small proportion (about 1 x 10^8 tons?) is moved alongshore (mostly westward) while the rest is dispersed onto the continental shelf (Kuehl *et al.*, 1989). As much as 1 x 10^8 tons of material in the latter category may cross the shelf and be deposited in the deep sea.

Of the 11 x 10^8 tons of sediment transported to the delta of the Yellow River during an average year, more than 9 x 10^8 tons are deposited within the delta (Figure 6C). Evidence of this large proportion of deposition is the extensive growth of the Yellow River delta, whose shoreline

Steep islands, such as those of the South Pacific are of particular risk. Because of their generally growing agriculture, the tectonic instability of watersheds, and the pattern of precipitation, which is dominated by short duration, high intensity rainfalls, soils are easily eroded and transported to the coast. A recent symposium (Research Needs and Applications to Reduce Erosion and Sedimentation in Tropical Steeplands, edited by R.R. Ziemer, C.L. O'Loughlin and L.S. Hamilton) addresses these problems not only for island but for tropical steeplands in general.

South Asian countries (including China) have had long agrarian histories in which sediment erosion has increased up to 10-fold (in the case of the Yellow River). As a result of these long-term (in some cases more than 2000 years) elevated influx of sediment to the coastal region along southern and eastern Asia, shoreline progradation has been (at least locally) appreciable. Damming these Asian Rivers, if the sediment becomes entrapped behind the dams, therefore, can reduce sediment fluxes to the coastline to or below the pre-human levels. In these cases, erosion or subsidence can result in the rapid retreat of the coastline.

5.4. Amelioration of Human Influences on River-Sediment Loads

Considering how river-sediment loads have been changed by human activities, it seems reasonable to suggest that these changes might be reversed by other, compensatory, activities. For example, if sediment loads have been increased by the conversion of forests to croplands, might not such loads be decreased by introducing soil-conservation measures or even by converting croplands back to woodlands? Where such measures have been introduced, however, their effects have not been discernible in rivers of moderate size (Meade and Trimble, 1974; Trimble, 1977, 1985; Meade, 1982), and their effects are likely to be even less detectible in large rivers. The importance of the storage effects discussed above probably increases with increasing river size. The remobilization of stored materials from the bed and banks of a large river can overwhelm the effects of any change in the sediment supply from eroded uplands for time periods measurable in centuries or even millennia.

More immediate effects are possible in the design and operation of dams and reservoirs. Sediment that was formerly trapped in a reservoir can be flushed downriver by changing the design of the dam or by altering the operating schedule of the reservoir. For example, the Sanmenxia Dam on the Yellow River was originally completed in 1960 with no provision for bypassing large sediment loads. After only four years of operation, the deposition of sediment had decreased the water-storage capacity of the reservoir by more than 60 percent. A major reconstruction project (1965-1973) installed new sluicing outlets through which the sediment is now flushed downriver toward the Yellow River delta. The different operational routines of the reservoir have caused different longitudinal patterns of scour and deposition in the 700-km reach of the Yellow River between Sanmenxia and the Gulf of Bohai (Zhao *et al.*, 1989): (1) net deposition of 360 million tons of sediment per year in the decade before completion of the reservoir; (2) net scour of 580 million tons per year during the 4-year period when the reservoir impounded floods; (3) net deposition of 440 million tons per year during the 9-year period when the reservoir was operated to retard floods and sluice sediment (including sediment formerly trapped and stored in the reservoir);

TABLE 6.

Risk Factors for Major Regions of the World*

Region	Tectonic Factor	Anthropogenic Impact Increased Input (Erosion)	 Decreased Input (Dams)
Africa			
East	mod-high	mod (?)	low (?)
West	low	low	incr.
North	high	mod-high	mod-high
S. America			
East	low	low	mod.
West	high	mod.	low
C. America	high	mod (?)	low
S. Asia**	high	high	mod-low
S.E. Asia**	high	high	mod-low
China	high	high	high
Oceania	high	high	high

*North America, Europe and North Asia are excluded because of lower general risk of drastic alteration of sediment discharge to coastal regions, although thre are clearly regional exceptions (e.g., N.W. North America).

**S. Asia refers to India, Pakistan, Sri Lanka and Bangladesh

**S.E. Asia refers to Thilannnd, Malaysia, Burma, Indonesia, Philippines, etc.

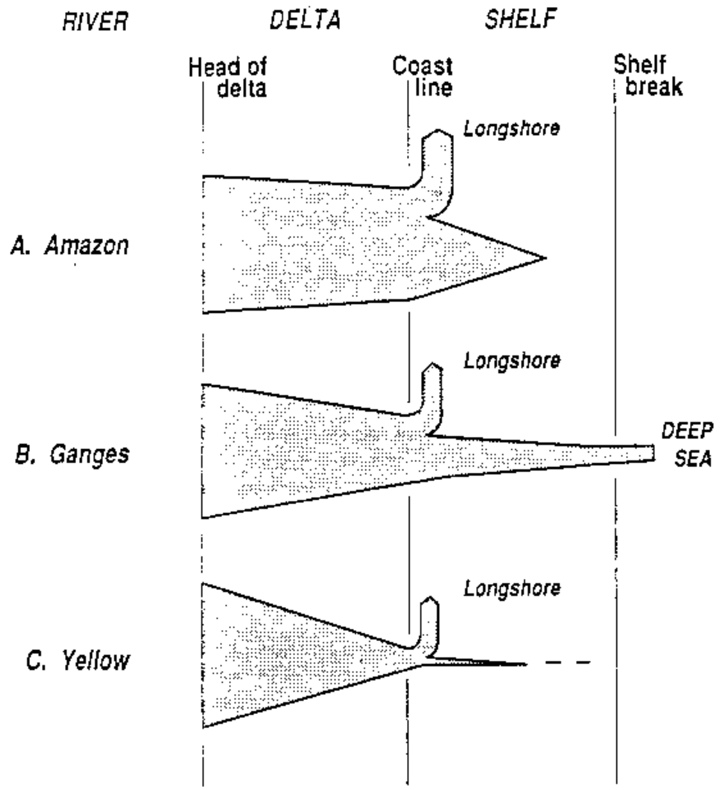

Figure 6. Different proportions of average sediment discharges that are delivered to deltas, coastlines, continental shelves, and the deep sea by three major rivers. Sediment discharge at the head of each delta is portrayed the same quantity (100%) regardless of its absolute value (values range from 1000 to 1200 x 10^6 t/yr) and regardless of changes in sediment discharges upriver of the delta.
A: Amazon River of Brazil (Eisma *et al.*, 1991; Kuehl *et al.*, 1986; Meade *et al.*, 1985).
B: Ganges (including Brahmaputra) River of Bangladesh (Kuehl *et al.*, 1989; Milliman, in preparation)
C: Yellow River of China (Bornhold *et al.*, 1986; Milliman *et al.*, 1987; Ding, 1989)

has prograded about 100 km since 1855. Southeastward transport alongshore takes about 1×10^8 of the sediment that passes the mouth. The remainder is deposited on the continental shelf, virtually all within the Gulf of Bohai. (Bornhold *et al.*, 1986).

3.1.2. Coarse and Fine Sediments. The second dilemma of trying to relate inputs of river-borne sediments (regardless of whether those sediments are natural or anthropogenic) to the coastal zone is the reversal of the relative importance of fine and coarse sediments. In most rivers, and certainly in all but a few of the world's largest rivers, the quantities of finer sediment transported seaward in suspension (clay, silt, and very fine sand) are greater by factors of ten than the quantities of coarser sediment transported by rolling and skipping along the river bed (gravel, coarse and medium sand). The coarser sediment, however, plays the greater role in determining the stability of the barrier islands and beaches that define most of the exposed coastlines of the world.

Bedload transport of rivers is difficult to measure because it happens mostly in a narrow zone near the bottom where velocity and turbulence are highly variable. In general, the practical difficulty of measuring bedload increases directly with the size of the river, and bedload transports of large rivers are usually computed from standard formulas rather than measured directly (Vanoni, 1975). Consequently, the sediment grains that are potentially most important to the coastal zone are those whose transport in rivers is subject to the greatest errors of measurement or estimation.

Fluvial transport of fine sediment, on the other hand, has to be measured. Given the present state of understanding, the discharge of fine sediment cannot be computed from knowledge of river hydraulics nor can it be predicted accurately from a knowledge of such factors as rainfall, geology, soil types, and land use. Methods that have been devised for computing soil erosion (e.g., the universal soil-loss equation of Wischmeier and Smith, 1965) are unable to predict the actual sediment loads transported by rivers because of the lack of direct one-to-one linkage between upland erosion and sediment yields (Walling, 1983). Although they may be less obvious in the more exposed coastal areas, the fine sediments continue to influence the configuration and character of less exposed coastal areas by providing the basic material of which most coastal marshlands are constructed and by being the chief conveyor of hydrophobic toxic pollutants such as PCBs, insecticides, and heavy metals.

3.2. Morphologic Effects

3.2.1. The Importance of Sediments. On a global scale, shorelines and shallow marine environments receive approximately 80% of their sediments from rivers and the remaining 20% from biogenic production and transport by a combination of by ice, wind, and volcanoes (The Open University, 1989). Changes in sediment delivery, whether natural or anthropogenic, produce effects that range from moderate to profound on the geomorphology of coastal environments. The impacts on humans, even from moderate geomorphological effects, are usually significant because an astonishing 70% of the world's population lives within 60 km of the coast (U.N., 1985).

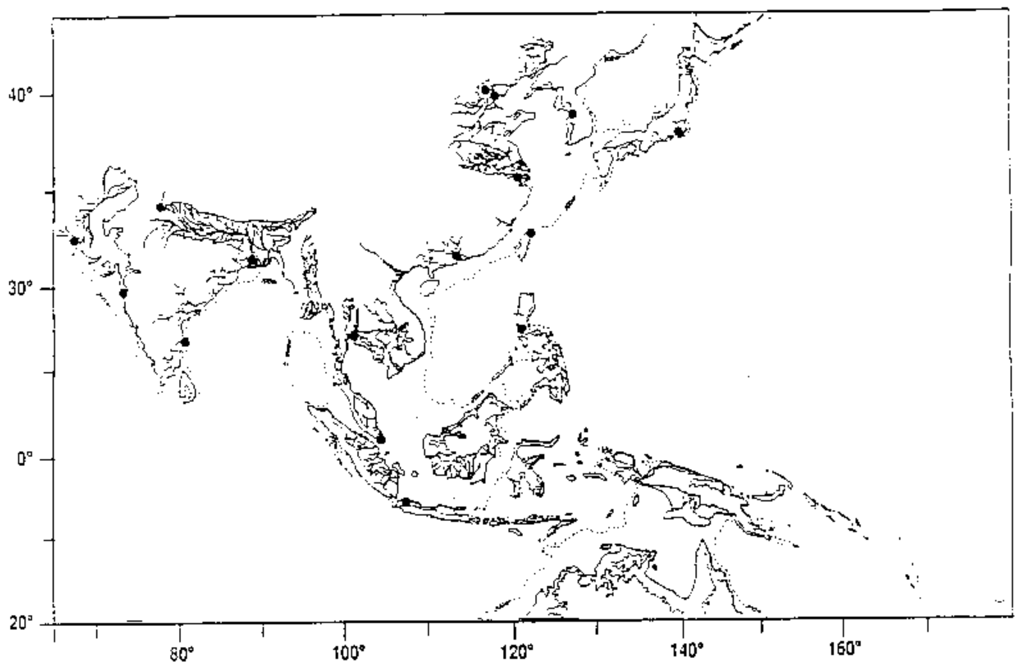

Figure 16. Major urban (megapolis) centers in Asia and the Pacific in relation to rivers and coastal lowlands (shaded areas).

world (Table 5). The results of such calculations indicate clearly that in developed regions of the world such as North America, Europe and Japan, there are *ca.* 18 to 24 dams per million people whereas in developing countries there are only 1.4 to 3.3 dams per million people. This suggests that as countries develop increased needs for hydroelectric power, flood control and water resource control, inevitably there will be increased dam construction. The rapid development in China provides a good example of this scenario. Prior to 1950 there were only eight dams in China (reported in the World Register of Dams). As of 1982 the number had increased to over 18,000.

Perhaps of greater importance than the number of dams that exist worldwide is the amount of regional discharge controlled by dams. Petts (1984) estimates that about 20% of the stable (average ?) runoff from Africa and North America is contributed by impoundments. For Europe and Asia the values are 15 and 14%, respectively and about 4.1 for South America and 6.1% for Australia. The value for Africa is quite high considering the relatively small number of dams there. The relatively high percentage of controlled discharge from Asia is clearly influenced by the large number of dams constructed in China.

Another consideration to be made when evaluating the effect of damming on sediment discharge from rivers is the geometry of the river. Milliman and Syvitski (1992) point out the importance of watershed size and elevation (which serves as a surrogate for relief and/or tectonic instability of the watershed). Generally, small watersheds with high maximum elevation have greater sediment yields than do those that are larger and of lower relief.

5.3. Areas at risk

Combining the tectonic and anthropogenic factors, we can differentiate various regions and their potential risks related to changes in their river systems. In some areas, such as southern Asia, a major drift in erosional patterns together with an increased rate in local sea level rise could effect a number of major urban centers (Fig. 16). As can be seen in Table 6, some regions, particularly West Africa, are drained by rivers with generally low sediment yields, the result of low tectonic influence and relatively low impact from human activity. Damming these rivers, therefore, can reduce sediment flux to the coastal areas to levels below natural inputs.

In contrast, East Africa is drained by rivers that erode tectonically active areas, meaning that the yields of these rivers are far greater than those of West Africa, and it is possible that over grazing by cattle has increased the erosion of these mountainous and hilly barriers (e.g., Dunne, c.f. Milliman and Meade, 1983). Damming these East African rivers may bring sediment discharge levels back to pre-human levels. Although reducing the turbidity of coastal waters (thus locally enhancing reef growth), this also runs the risk of coastal erosion. North Africa, particularly the Morocan mountains, is drained by short, highly tectonic rivers. Local overgrazing, combined with periodically very heavy rains on a normally arid to semi-arid landscape, has created highly erodible conditions, resulting in high sediment discharge.

One of the complicating factors in assessing the morphologic and related biogenic impacts from changes in sediment delivery is that sediments are both an asset and a liability. For example, a continuous supply of sand is not only desirable, but essential for maintenance of recreational beaches. Approximately 90% of U.S. beaches, and perhaps 70% worldwide (including many along the west coast of Africa), are eroding through a combination of decreased sediment supply, sea level rise, and overdevelopment (Bird, 1981; Leatherman and Gaunt, 1989). Artificial beach nourishment is widely practiced in many countries, but at an average cost (in U.S. dollars) of $8 per cubic meter of sediment (Figure 7). On the other hand, these same sands become a liability if transported to, and trapped in, navigable waters, such as rivers, tidal inlets, harbors, and turning basins (Sheall, 1991)

Sand is also essential for supplying sediments to subsiding deltas, where much of the coastal population in developing countries resides. The common attribute shared by all deltas, regardless of environmental setting, has been the ability to accumulate river-derived sediment more rapidly than it can be removed by marine processes. However, as river channels extend seaward, building new land, they also become inefficient and loose their gradient advantage; it is rare that a delta progrades continuously seaward without some lateral shift or without changing its depositional site. Thus the same sands that provide new land also set into motion the processes that ultimately lead to abandonment of deltas and local land loss through erosion (Figure 8).

In contrast to the sands, fine-grained sediments are often an unseen and apparently passive component in coastal waters. Sediment distribution and properties are slow to change, and their role in water-column events is not always apparent. Yet, these sediments play a critical role in some of the more pervasive long-term coastal problems. For example:

1) Shoaling is more than just a hazard to navigation. It reduces the volume of estuaries and coastal embayments, thereby increasing the impact of storm tides on coastal property; it alters the size and distribution of habitats available to important fish and shellfish; it can change over time the distribution of water-column turbidity, affecting, through light penetration, primary productivity.

2) Heavy metals, pesticides and other "particle-reactive" toxic substances adsorb from the water column onto surfaces of fine-grained sediment particles and move thereafter with the sediments. Thus they may be initially concentrated in a water-column turbidity maximum, then briefly deposited beneath the turbidity maximum, before finally accumulating in the long-term loci of mud accumulation.

3) Decomposition of organic matter in the sediments represents an oxygen demand which, when combined with physical stratification, can lead to bottom-water anoxia and fish kills. Nutrient elements which are remineralized in the decomposition process make the sediments a nutrient bank for the water column; withdrawals may be gradual and continuous, due to diffusion, or abrupt, due to major sediment-resuspension events. Primary productivity in the water column responds to these nutrient inputs.

4) High concentrations of suspended sediment can smother benthic communities and prevent recruitment. Coral reef and oyster communities are perhaps the most susceptible.

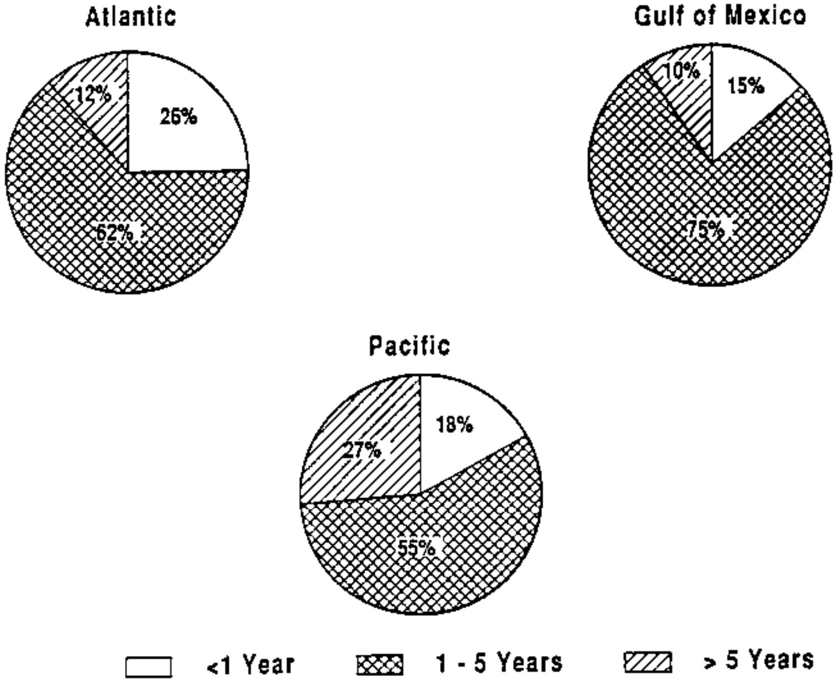

Figure 7. A comparison of the duration of renourished beaches on the Atlantic, Gulf of Mexico, and Pacific coasts of the United States. Most last fewer than 5 years.

TABLE 4.

Projected Deforestation Rate (Assuming Direct Relation to Population Size) by the year 2005:

Region	Rate (ha/yr)
Tropical America	7.4×10^6
Tropical Africa	7.8×10^6
Tropical Asia	2.2×10^6

TABLE 5.

Number of Dams Relative to Population of Various Regions of the World*

Region	Dams/Million People
North America	22.5
South America	3.3
Europe	10.0
Africa	1.4
Oceania	2.9
China	17.5
Japan	17.7

*Number of dams as of 1982 (van der Leeden, 1990) and population as of 1985 (Demeny, 1987)

TABLE 2.

Net Deforestation Rate[1] by Region (1981-85)[2]

Region	Rate (ha/yr)	% of Productive Forest
Tropical America	5.1 X 10^6	0.77
Tropical Africa	3.6 X 10^6	0.67
Tropical Asia	1.6 X 10^6	0.60

[1] Deforestation - reforestation

[2] From Arnold (1987). Net deforestation rates for temperate regions are small compared to those in tropical regions.

TABLE 3.

Projected Population Growth Rate 1985-2005[1]

Region	1985 Population (Millions)	2005 Population Increase (Millions)
Tropical America	405	189
Tropical Africa	432	383
Tropical Asia	1,525	618

[1] From Demeny

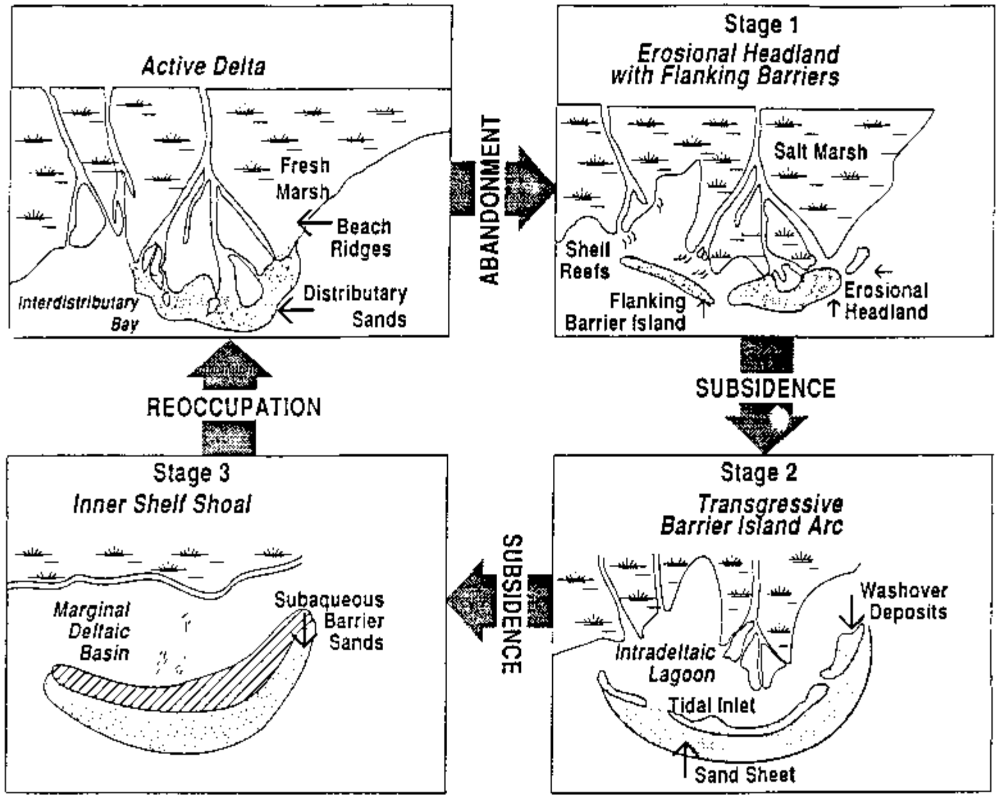

Figure 8. Evolutionary stages of a delta cycle showing abandonment and reoccupation (Coleman, 1988; originally from Penland and Boyd, 1981).

Although few studies have quantified these effects, there is general agreement that remobilized muds and sands that make their way to the coast can be physically detrimental to survival, growth, abundance, and net productivity.

3.2.2. The Problem of Prediction. One of the chief problems in predicting shoreline response to changes in sediment delivery is that there is no universally applicable model. Shorelines of the world can be broadly and simplistically divided into deltas, beaches and barriers, wetlands and tidal flats, estuaries, cliffed coasts, and reefs and atolls. However, it is no more reasonable to expect that a single model can apply to this wide range of shoreline types than it is to expect that a single model can explain global economics or global politics.

A second problem is that application of different approaches to morphologic change leads to different results on the same section of shoreline. For example, Dolan *et al.* (1991) found that fitting a linear model to shoreline erosion would only approximate the average rate of change from shorelines with non linear response, but that linear fits may be more representative of trends over long time periods (Figure 9). They noted that trends in shoreline movement, from which predictions might be made, can be unidirectional and constant, or cyclic with accelerations and decelerations. Figure 9 illustrates this concept and shows the difficulty of predicting changes from past performance by using different approaches.

Another problem concerns accuracy and precision. Estimates of past morphologic change can be used to predict future changes, but reliability depends on the particular method utilized, the time between measurements, the total length of the measurements, and the magnitude of shoreline position errors (Dolan *et al.*, 1980; Leatherman, 1983; Foster *et al.*, 1989; Smith and Zarillo, 1990). The overwhelming need for highly accurate shoreline maps and prediction models has unfortunately shifted emphasis away from processes that actually cause the morphologic changes. To be effective, predictions from observed shoreline changes must always be used in conjunction with basic principles of water and sediment movement.

Finally, there is the problem of sea level rise. Deglaciation has led to a 100+ m rise in ocean level during the past 15,000-20,000 years. Effects of this rise during the past few thousand years are likely to be confounded with variations in sediment delivery during the same period. Because of the slow, gradual rise, there is a lag time in response. We are not at all certain as to what the short-term response is to slow rates of sea level rise since it appears to differ from that produced by very rapid rates (Kraft *et al.*, 1987; National Research Council, 1987). Separating the effects of this weak long-term sea level signal from the noisy short-term storm record, and from the variations in sediment delivery, is exceedingly difficult.

3.3.3. The Role of Sea Level. As sea level rises, shorelines throughout the world will respond by flooding or eroding, unless offset by increases in sediment delivery. Each response is a type of marine transgression that leads to rapid recession or migration of the shoreline. Whereas flooding is the inundation of low-lying coastal land which is unable to build upward or outward at a rate sufficient to keep pace with sea level rise, erosion is the physical removal of sedimentary materials which form the shoreline. Erosion accounts for most of the net shoreline

areas in a delicate state of balance.

5.2. Regional trends in anthropogenic activities that pose greatest global threat.

Anthropogenic activities that can subject watersheds to greater risk of altered sediment discharge to the coastal zone, and for which regional trends can be assessed, are the construction of dams and deforestation. While these are not the only activities that effect sediment yields of watersheds (see section 2.2), they are probably two of the more important ones. It is also possible to predict trends that might be expected regarding dam building and deforestation because these activities can be related to regional population growth patterns as is discussed below.

5.2.1. Regional Trends in Deforestation. As of about 1980 the world's forest covered about 4,320 million hectares and is about equally distributed between the temperate and tropical zones (Arnold, 1987). Although deforestation followed by row cropping in temperate regions led to widespread accelerated soil erosion in the past (see for example, Meade, 1988), most of the accessible temperate forests are managed so that there is insignificant annual net loss (i.e., deforestation-reforestation) although there are clearly regions where losses are significant (e.g., N.W. North America). According to Arnold (1987), "the main threats to the temperate forests are fire, disease and pests, and more recently, atmospheric pollution."

In contrast to forest in the temperate zone those in the tropics are being removed at an alarming rate (Table 2). Deforestation in the tropics is in response to the needs for more agricultural land to support growing populations, whereas deforestation in temperate regions is generally followed by reforestation. As a consequence, essentially all deforestation in the tropics is followed by row crop agriculture and/or development of pasture lands, both of which are particularly conducive to soil erosion in the tropics given their low fertility and their general poor structure (Arnold, 1987). Given the trends in population growth expected in the tropics (Table 3) and the apparent association of deforestation with this growth, it can be reasonably assumed that this activity will increase in the near future. While at the present time deforestation in the tropics removes about 0.7% per year of the existing forest, the rate will probably increase to over 1% by the year 2005 (Table 4).

The above is not meant to suggest that in certain regions of the temperate zone rapid deforestation is not occurring. There are clearly regions such as the Canadian Pacific Northwest where rapid deforestation is probably resulting in increased sediment delivery to the oceans even though, globally, reforestation of temperate forest offset the deforestation.

5.2.2. Regional trends in the construction of dams and water diversions. As of 1982 there existed *ca.* 34,000 dams (as listed in the World Register of Dams, International Commission on Large Dams) of which about 53% (i.e., 18,600) were located in China, 15% (i.e., 5,340) located in the USA and 6% (i.e., 2,140) located in Japan. Using world population data for 1985 (Demeny, 1987) and statistics on the worldwide distribution of dams as of 1982 (van der Leeden *et al.*, 1990), the number of dams per million people can be calculated for various regions of the was eroded from steep hillslopes and deposited as alluvium in the stream valleys. During intervening periods of less intense rainfall, the alluvial deposits were degraded, leaving behind terraced valleys. These valleys were then refilled with sediments during the next episode of heavier rainfall. In tectonically less active regions of the world, such episodes of erosion and sedimentation may proceed more slowly (Leopold and Miller, 1954; Judson, 1963).

5. ENVIRONMENTAL FACTORS AND ANTHROPOGENIC ACTIVITIES WHICH INCREASE RISK OF COASTAL DEGRADATION AS A RESULT OF ALTERED SEDIMENT DELIVERY

This section summarizes the most important characteristics of watersheds and coastlines that increase their susceptibility to detrimental change in response to anthropogenic activities. In addition, this section also emphasizes those anthropogenic activities that will result in the greatest response, and presents data on recent and projected regional trends in these activities.

5.1. Natural Features That Increase Risk

5.1.1. Watershed Characteristics. Regional tectonism is the most pervasive of the natural factors that determine the sediment yields of watersheds and their responses to anthropogenic changes. The combination of bedrock that has been contorted and broken by tectonic forces and its exposure on rapidly uplifted and tectonically oversteepened slopes makes these regions especially susceptible to massive erosion, both natural and anthropogenic. Natural erosion of steep slopes, especially by massive failures such as landslides, is intensified and accelerated by human activities such as logging and farming. Where tectonic regions correspond to areas of heavy rainfall (southeastern Asia, Oceania), erosion is rapid. Where tectonic regions correspond to areas of lesser rainfall (Atlas region of northwestern Africa, western slopes of the Andes), average erosion rates are only slightly diminished; the difference is that sediments are delivered during sporadic large runoff events rather than at more uniform rates. Areas of high tectonism and low rainfall yield considerably more sediment than areas of low tectonism and high rainfall (such as lowland Amazonia and west Africa).

5.1.2. Coastlines. The two types of coastal areas at greatest risk as a result of their natural environmental setting are 1) low-lying regions, especially those subject to high subsidence rates, such as deltas, and 2) environments that are already in a delicate state of physical and ecological balance, such as mangrove forests. Subsiding deltas are particularly vulnerable because their very existence requires the continued input of river-derived sediments. With land elevations already at or near sea level, natural subsidence rates of 1-10 cm/yr cannot go uncompensated, even for time periods as short as a single decade.

Shorelines in tropical latitudes that are already in delicate balance are also at severe risk. Not only can very small changes in sediment delivery alter the balance between supply and loss to the ocean, but the changes can occur rapidly. Perhaps the best examples are in mangrove ecosystems, where decreasing freshwater input creates an ecological stress at the same time that decreasing sediment loads create a physical stress. Often, low-lying deltas are also the coastal

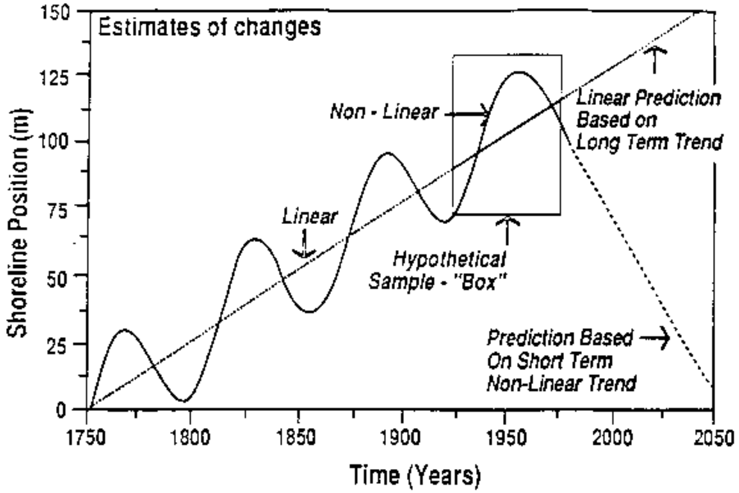

Figure 9. Example of a hypothetical change in shoreline position that is cyclic over a period of hundreds of years. Estimates for predicting the future trend from the 50-yr sample box illustrates the difference in linear and non-linear models: the quadratic fit is a better short-term model but the linear fit is better long-term predictor (modified from Dolan, *et al.*1991).

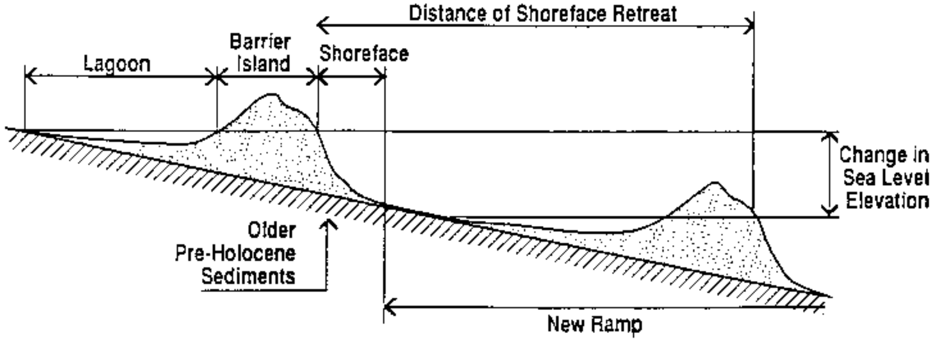

Figure 10. Intact migration of a barrier island across the inner continental shelf. Such idealized movement under conditions of rising sea level requires a continuous supply of sediment (modified from Everts, 1987).

recession on beaches and barrier islands, such as the east coast of the U.S. and the west coast of Africa; flooding accounts for most of the loss in wetlands and subsiding deltas such as the Mississippi, Ganges, and Niger.

Although, to a first approximation, shorelines can be divided into those that will flood and those that will erode, the processes of flooding and erosion are closely related to each other and to changes in sediment delivery. For example, some barrier island shorelines will initially erode, perhaps in a stepwise fashion, then flood or "drown in place" during periods of low sediment supply. Other barriers may erode on both the seaward and landward sides until efficient overwash can take place, allowing the islands to begin migrating intact (Figure 10). Still other shorelines initially may be submerged, then begin eroding when embayments and shallow bodies of open water become large enough to accommodate storm waves, as appears to have happened during the widespread internal fragmentation of some wetlands in the Gulf of Mexico.

Flooding and erosion are responses that also are related temporally. Sea level, which has undergone huge climatically-induced excursions, is clearly responsible for large-scale marine transgressions (Curray, 1964; Swift, 1968; Posamentier *et al.*, 1988). Retreat of the shoreface for great distances (10-100 km) has been driven by the potential for flooding over geologic time scales, irrespective of changes in sediment supply. Without sea level rise, these transgressions would not occur. Yet, it is the seasonal storm waves that produce the widespread erosion and redistribution of sediment. Storms, fortnightly tides, and seasonal wind patterns work on the shoreline at higher frequencies and are the agents of short-term sea level changes. Regardless of greenhouse-induced climatic changes, nearly all of the world's shorelines have been, and will continue to be, subject to episodic "crescendo" events that produce far greater short-term hazards than secular sea level rise (Fairbridge, 1989). Changes in sediment supply will simply change the magnitude of short-term erosional events.

3.3. Effects of Increased Sediment Delivery

The effects of an increase in sediment delivery to the coast will be highly site-specific and depend on: the type of sediment delivered (mud, sand, or gravel, and organic content); relative magnitude of increase (percent of existing input), shoreline configuration (embayed or open), wave energy and offshore slope, tectonic setting and rate of local sea level rise, types of benthic habitats and their susceptibility to sedimentation, and the potential for sediment dispersal (types of water motion). The most likely general responses will be:

3.3.1. Higher Water Column Turbidity and Increased Sediment Trapping in Estuaries. In terms of sediment dynamics, the most important feature of many estuaries is the broad zone of abnormally high suspended sediment concentration in the "turbidity maximum," where light is severely limited. Numerous investigators have found that a relationship exists between light attenuation and submerged macrophyte distribution (Carter and Rybicki, 1990). Light attenuation by suspended sediment can limit photosynthesis (Spence, 1976; Dennison and Alberte, 1982) as well as depth distribution and rate of growth in aquatic plant populations in estuaries (Buesa, 1975; Chambers and Prepas, 1988). Increases in suspended sediments would accentuate these

advanced, it raised the levels of the channel beds, much as an ocean swell raises the level of the sea as it passes through. Bed levels rose 5 m in the tributary Yuba River at Marysville and nearly 3 m in the Sacramento River at Sacramento. The river beds at these towns reached their highest elevations 10 to 20 years after the mining was stopped, and then they declined steadily during the next 30 to 40 years to their previous elevations. All in all, the great wave of hydraulic-mining debris took nearly a century to pass through the channels of the Sacramento River system and finally to reach San Francisco Bay (Meade, 1982, p. 243-244; Smith, 1965).

4.2. Storage on Century to Millennium Time Scales

The pattern of storage and remobilization described in the preceding paragraph, however, applies only to the sediment in and near the river channels. It does not apply to the debris that overflowed onto the flood plains. The hydraulic-mining debris that was carried out of the river channel during floods and deposited on the flood plains was sufficient in many places to cover entire houses and orchards (Kelley, 1959, p. 134-135, 203-204). Most of that debris still remains where it was deposited a century ago: In some tributary basins of the Sacramento River, about 90 percent of the hydraulic-mining debris still remains stored on flood plains (Adler, 1980; James, 1989, 1991). The time required to remove sediment from storage on the flood plain is much longer than the century that was required to remove the debris from the main river channels. Flood-plain deposits are removed mainly by erosion of channel banks as streams slowly migrate laterally, a process that proceeds at a substantially slower pace than the vertical removal of material stored in the bottom of the river channel. The complete remobilization of flood-plain deposits may require time periods of an order of a millennium or more (Leopold *et al.*, 1964, p. 328).

Many of the problems associated with the prediction of storage and remobilization of sediment on time scales of 100 to 1000 years were demonstrated in a study carried out on Coon Creek, a small tributary of the Mississippi River that drains 360 km^2 of southwestern Wisconsin. Originally covered by forests, Coon Creek basin was settled by European immigrants and cleared for farming about 1850. As the forests were cleared and the land was plowed, a cycle of erosion and sedimentation began, the consequences of which are still strongly in effect today. Sediments were eroded at a greatly accelerated rate from upland and tributary areas, and were transferred to the lower hillslopes and valleys of the creek basin. Much less than 10 percent (5 x 10^6 tons) of the sediment eroded from the uplands during the years since 1850 was exported out of the basin by the creek. More than 90 percent (80 x 10^6 tons) of the sediment was deposited along the way, on hillslopes and flood plains, where most of it still remains in storage. Upland erosion rates, therefore, are not reflected in the sediment yields at the mouth of Coon Creek (Trimble, 1983).

In tectonically active regions of the world, cycles of erosion, storage, and remobilization of sediment in river valleys may be greatly accelerated. Grant (1985) presents evidence for 8 major episodes of erosion and alluvial sedimentation in New Zealand during the last 1,800 years. He believes that the major episodes of erosion and sedimentation were related to fluctuating magnitudes of major rainstorms and floods. During periods of more intense rainfall, sediment river systems. Sediment is stored in large river systems at many different time scales, and this storage severely obscures the linkage between the erosion of uplands and the discharges of sediment at the mouths of rivers. In the conterminous United States, for example, upland erosion rates exceed the rates of river-sediment discharge into the coastal zones by a factor of ten (Curtis *et al.*, 1973; Holeman, 1981). Said another way, ninety percent of the sediment presently being eroded off the land surface of the United States is being stored somewhere in the river systems between the uplands and the sea, most likely on hillslopes and floodplains. Furthermore, the time lags between erosion and sediment transport are such that the sediments carried by large rivers today may represent episodes of erosion that occurred decades, centuries, or even millennia ago. Excellent summaries of the problems involved in understanding the linkage (or lack of it) between soil erosion and river-sediment transport have been prepared by Schumm (1977) and Walling (1983).

4.1. Storage on decade to century time scales

Perhaps our perceptions of sediment storage in river systems are biased toward the time scale of 10 to 100 years which is, after all, the secular scale, or the scale of a human life span. Any direct sensory perceptions we may have of changes in rivers are confined to processes that operate over periods of 100 years or less.

On the basis of suspended-sediment discharges measured in the Brahmaputra River and its tributaries in the Assam province of northeastern India, Goswami (1985) calculated a sediment budget for a 607-km reach of the river during the period 1971-1979. Some 2.1 x 10^9 tons of sediment, or 70 percent of the total sediment brought into the reach during the period 1971-1979, remained stored in the reach at the end of the period. This quantity of stored sediment must have aggraded the river bed by an average of 10-30 cm during the period 1971-1979. Goswami (1985, p. 977) speculates that the river channel "is currently experiencing a secular period of rapid aggradation", perhaps triggered by the great earthquake of 1950 in the Himalayas, which should be followed in due time by a period of relatively slower removal. Such an episode of remobilization and degradation of the river bed would send a large pulse of sediment out of Assam and into Bangladesh and the delta at the head of the Bay of Bengal. Because only 8-9 years of sediment data were available here, we can only speculate on the period of such a cycle of aggradation and degradation, but it is perhaps most easily visualized at a time scale somewhere between several decades and a century.

The classic case study of the movement and storage of sediment in a river system on time scales of 10 to 100 years is that of the hydraulic-mining debris in the Sacramento River valley of California (Gilbert, 1917; Kelley, 1959). Between 1855 and 1885, enormous quantities of coarse sediment were washed into some of the tributaries of the Sacramento River during hydraulic mining for gold. The resulting problems that developed downstream (flooding, filling of navigation channels, destruction of flood-plain farms) became so serious that hydraulic mining was curtailed by a court decision in 1884. By that time, however, the large mass of sediment, characterized as a "wave" by Gilbert (1917), was already in the stream channels and was moving slowly down the tributaries and in the Sacramento River. As the mass of sediment

limitations and perhaps magnify the role of the turbidity maximum as a particle distribution center for the rest of the estuary. The clear connection between transport of sediments and transport of toxic and nontoxic substances on their surfaces is an important reason to be concerned about increased sediment loads when issues of eutrophication, habitat loss, agricultural impact, and fisheries are being considered. Further, in shallow water estuarine systems, the water column and bottom sediments interact continually, exchanging and redistributing particles and solutes. Any focal point in the water column will likely be related to sediment storage on the bottom (Figure 11). Since estuaries are known to be natural sediment traps (Meade, 1972; Biggs and Howell, 1984), it is logical to conclude that higher levels of sediment delivery will lead to higher rates of short-term deposition and long-term accumulation. Highest rates of sedimentation (1-10 cm/yr) can be expected in less energetic zones near the head where fine-grained sediments are entrapped in estuarine circulation (Nichols *et al.*, 1991).

3.3.2. Shoaling and Increased Navigational Hazards in Tidal Inlets and River Entrances. The intersection of estuarine tidal flow and wave-induced transport in the littoral zone creates a sink for sand storage (Swift, 1976). This intersection (and sink) often occurs in tidal inlets, which are simply openings between adjacent barrier island segments. Many inlets serve as navigable passage through these barrier island chains as well as past spits that front bar-built estuaries. The size of an inlet and its permanency are determined by two forces: wave action, which causes transport of sand into the inlet, and tidal currents, which tend to scour the channel. Thus inlets open and close in response to changes in coastal conditions and in sediment delivery. Sediment trapped in inlets accumulates as massive shoals referred to as flood tidal deltas (landward side) and ebb tidal deltas (seaward side). Increased sediment delivery could be critical in that tidal inlets are inherently unstable; long-term observations show that most inlets eventually close (Leatherman, 1982). Although inlet sands are generally derived from the adjacent beaches, increases in sediment delivery will be most important when river channels connect directly to inlets, thus supplying them from the landward side.

Deceleration of flow as rivers widen or enter larger receiving basins also create conditions favorable for shoaling. In the United States alone, the U.S. Army Corps of Engineers spends $400 million per year for dredging inlets, rivers, and estuaries (Sheall, 1991). One particularly troubling aspect of increased sediment delivery is the formation of low density fluid mud deposits. Fluid muds already pose extreme dredging problems in ports and turning basins, perhaps most notably in the U.K., The Netherlands, and numerous tropical Asian countries (NEDECO, 1964; Kirby and Parker, 1973). Not only are these muds hard to dredge because of their low density, but it is hard to make objective decisions as to what even constitutes the bottom for navigational purposes.

3.3.3. Locally Lower Rates of Beach Erosion. If sediments are of the correct size and available, then beaches can build, even under modest rates of sea level rise (Figure 12). This is especially true when large flood tidal deltas serve briefly as additional sediment reservoirs during barrier island migration. However, beach accretion and/or slower rates of beach erosion will probably be important only locally for two reasons. First, it is unlikely that additional sediments will be of the proper size to remain on beaches. Fine-grained sediments will be unstable and

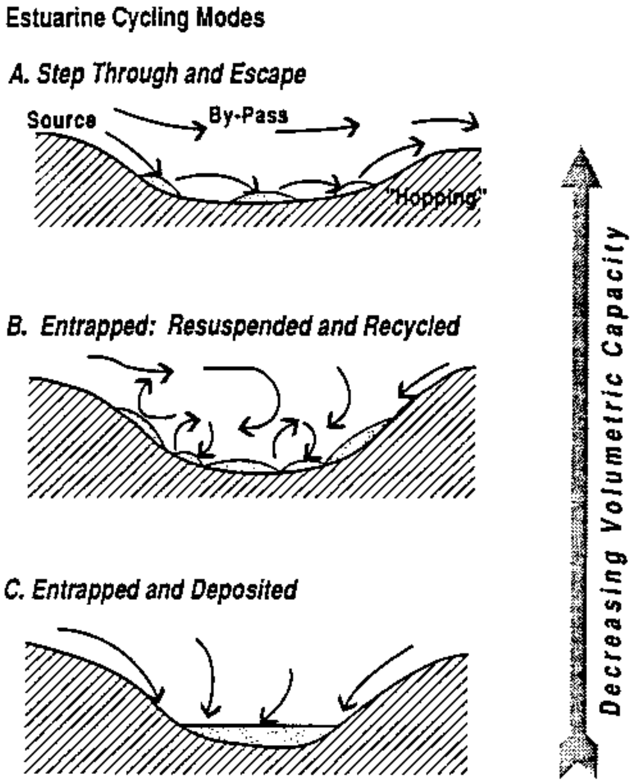

Figure 11. Diagram showing cycling modes and entrapment of sediments in estuaries, as related to volumetric capacity (modified from Nichols and Biggs, 1985).

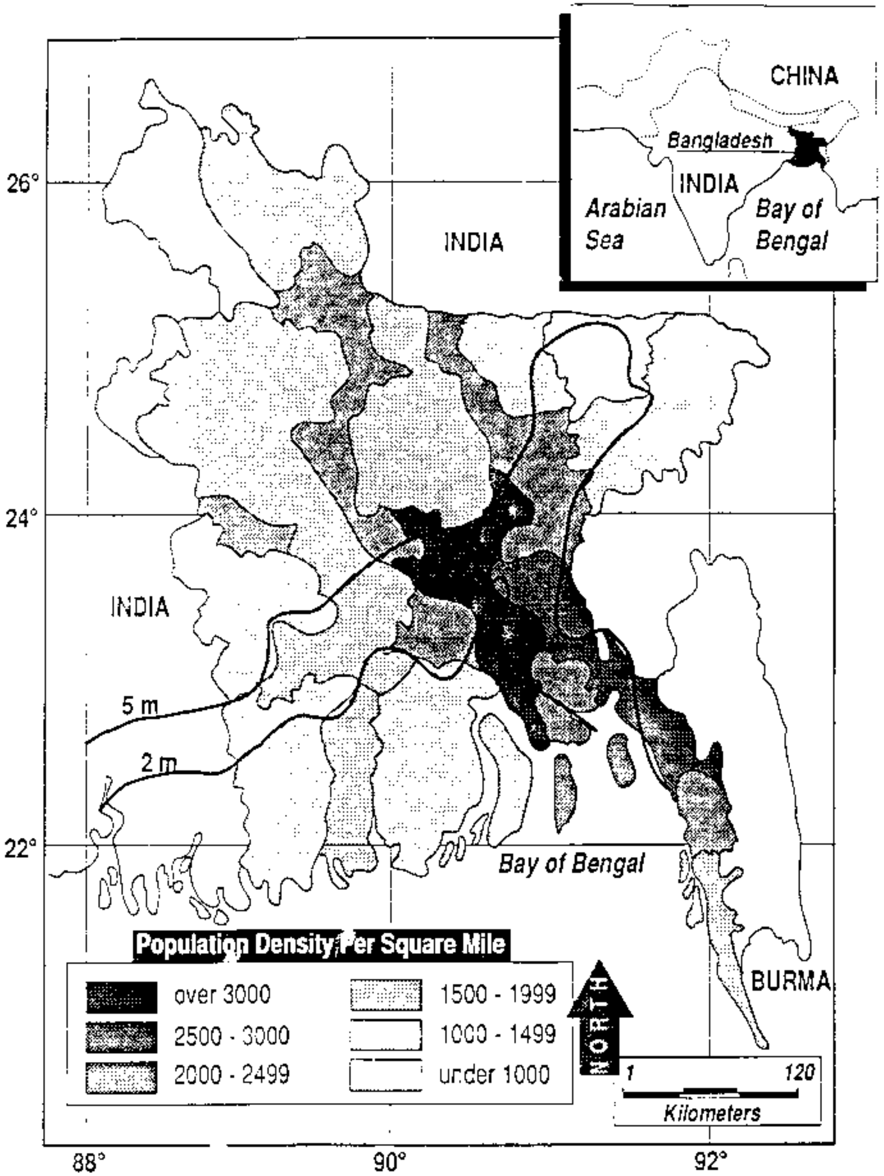

Figure 15. Population densities and topographic elevations in Bangladesh. Various global and local environmental changes could see a local sea level rise between 2 and 4 meters in the next 100 years, greatly impacting one of the world's most populated countries. (After Milliman *et al.*, 1989).

accentuates the sediment disparity problem. Even a slight loss of mangrove forests can result in accelerated coastal erosion (see, for example, Ormond, 1985).

Different deltas will respond in different ways to loss of sediments. Deltas that are on relatively stable geologic platforms (e.g. the Senegal in Africa, Ord in Australia, and Yangtze in China) will transgress through erosion at the seaward margins. Sandy deltas in extremely high wave energy environments, such as the Indus in Pakistan, will experience reworking of delta front sands in such a way as to actually create a transgressing beach environment (Wells and Coleman, 1984). In arid climates, loss of any already-sparse vegetation through salt water penetration, which is often associated with loss of sediments, is likely to increase wind-blown sands and form a landscape dominated by dune fields (Coleman *et al.*, 1981). Case studies of the Mississippi and Nile (Wells and Coleman, 1987; Coleman *et al.*, 1981), both subsiding deltas that have lost much of their sediment load only within the last 30-40 years, reveal some of highest rates of land loss in the world. In the case of the Yellow River in China, 1.1 billion tons of sediment ceased to reach the delta front on the Jiangsu coast after the major diversion of 1854. Except for local erosion around the abandoned river mouth, the Jiangsu coast continued to prograde for the next 90 years, after which the coast began eroding rapidly (average loss of 68 km^2/yr). Presumably this lag in delta-wide erosion reflects the time required for nearshore waters to reach a new wave-base equilibrium and during which time sediment was transported landward from offshore regions. In a small but fortunate way, some of the sediment lost through processes of deltaic erosion will be a source for replenishing downdrift environments.

Decreased sediment delivery, because of dams and channel-stabilization structures (such as embankments and levees) also may mean less deposition on to flood plains during seasonal flooding. In this way, local subsidence may be uncompensated, resulting in a net sinking of land, and in low-lying coastal areas a corresponding rise in sea level. Where increased water needs (in part perhaps due to decreased downstream delivery of river water) require utilization of ground water, subsidence could accelerate substantially, resulting in local sea level rise in excess of 1-2 cm/yr. In such low-lying countries as Egypt and Bangladesh, such a loss of coastal low lands could be disastrous (Fig. 15).

Decreased freshwater discharge also means diminished nutrient flux to coastal waters, which adversely affects biological productivity. The lack of influx of nutrient-rich Nile waters after the completion of the High Aswan Dam in 1964, for example, corresponded with a 95 percent decrease in the offshore sardine fisheries; the estimated loss of income in 1970 alone was 14 million dollars (Abdel-Aal, 1985; Wahby and Bishara, 1981). Even the construction of irrigation barrages can lead to decreased coastal productivity and thus affect regional fisheries, as seen in the 3-fold decrease in fish-catch per boat off the Indus River after completion of the Kotri Barrage in 1956 (Milliman *et al.*, 1984).

4. TIME SCALES RELATING CAUSE AND EFFECT

The most confounding factor in trying to relate anthropogenic influences in watersheds to the actual delivery of sediments to the coastal zones is the large-scale storage of sediment in

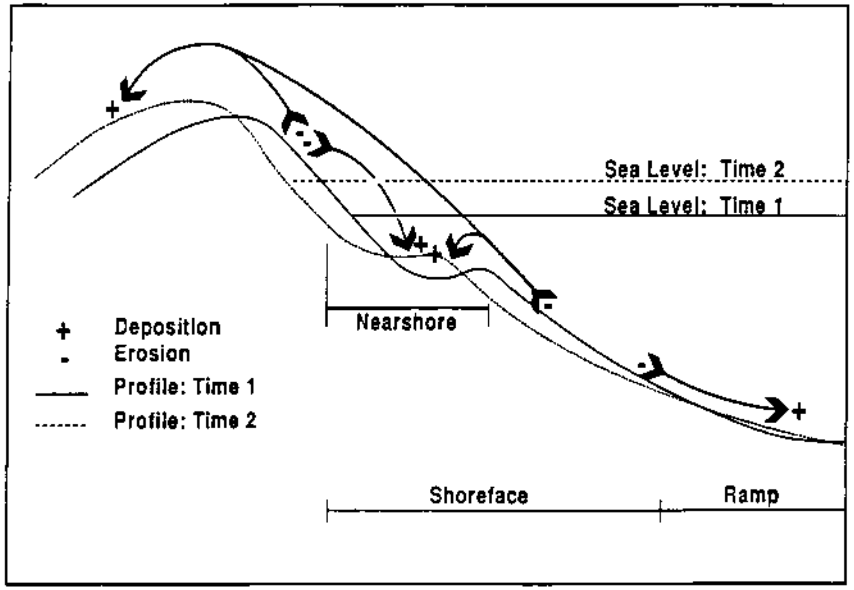

Figure 12. Diagram showing in two dimensions the directions of sediment transport on a beach. Sands move both onshore and offshore in response to a rising sea level (modified from Dubois, 1992). The longshore sand transport is not shown.

quickly removed in a wave-dominated environment. Second, the volume of new sediments, relative to what is needed, will likely be small. Even when new sediments are introduced by rivers, much of this material is first trapped in estuaries or in tidal inlets, thus never making its way to the beaches. The small impact of adding even large amounts of sand to the beach can be appreciated by examining the short life of beach renourishment projects (Figure 7). For example, seven beach renourishment projects since 1958 at Victoria Beach, Lagos, Nigeria, have failed to abate the rapid rates of erosion estimated at 25 to 30 m annually along the beach (Ibe *et al.*, 1984). One exception is where additional beach sand is supplied by cliffs. Beaches and cliffs are part of a coupled system. Accelerated delivery from cliffs will go directly to the beach, increasing the littoral budget with properly sized sediment.

3.3.4. Lower Susceptibility to Flooding and Less Wetland Fragmentation from Sea Level Rise. Although marshes are usually considered sites where vertical accumulation of sediment easily keeps pace with sea level rise (Redfield, 1972; McCaffrey and Thompson, 1980; Stumpf, 1983; Allen and Rae, 1988), there is a net loss in many parts of the world (Stevenson *et al.*, 1986; Allen and Pye, 1992). When rates of sediment accumulation at 15 marsh sites in the U.S. (1.4 mm/yr to 14 mm/yr) were compared to rates of apparent sea level rise, only 75% had positive rates of accretionary balances (Stevenson *et al.*, 1986). This at first may seem surprising in that marsh vegetation absorbs energy and alters patterns of sedimentation by trapping particles, with roots helping secure the substrate beneath the sediment-water interface. However, many marshes are in a state of delicate balance and are considered to be on the borderline of submergence. Slight changes in sediment supply or rates of relative sea level rise (order of 1 mm/yr) can change the accretionary balance (Figure 13). Thus increased sediment delivery to the coast has the potential for replenishing these wetlands, provided the sediments are available to and can be uniformly dispersed across, the marsh surfaces. Additional sediments will be especially valuable in subsiding basins (e.g., deltas) since here the problems are most severe, but the processes which deposit sediment on the marsh surface remain very active (Reed, 1989).

As tropical analogues to temperate salt marshes, mangrove swamps show many of the same adaptations. They are restricted to favorable energy conditions, rarely occur outside the intertidal zone, and are most extensive where shore gradients are low. Mangroves have proved a valuable economic resource in the tropics. Indonesia alone has nearly four million hectares of mangrove forest (e.g., UNEP, 1985; Gomez, 1988). Mangroves act as nurseries for many commercially valuable fish and shellfish, serve as sources of wood and food for local inhabitants as well as forming a rich and diverse ecosystem and refuge. For example, local fishing from and around mangroves provides 20 to 60 percent of the income for households in several village communities along the west coast of Sri Lanka (Amarasinghe, 1988). Moreover, the mangrove community acts as a sediment trap, thereby retarding coastal erosion (e.g., Ormond, 1988).

The primary danger to mangrove forests is sea level rise in the absence of sedimentation. On the other hand, where sediment supply is abundant mangroves show rapid advance, e.g., on the shores of prograding deltas (10s to 100s m/yr; Macnae, 1968). Therefore, the primary impact on mangrove shorelines from increased sediment delivery will be opportunistic colonization, especially on Pacific islands where sedimentation has accelerated by anthropogenic soil erosion

sedimentation patterns; a decrease in sediment accumulation could be critical in those ecosystems already in delicate balance.

One such example is near Bangkok, Thailand, where regional subsidence has effectively drowned a formerly productive mangrove system; in places the mangroves have retreated more than 500 m in less than 30 years. Unfortunately, however, mangroves are under even more immediate pressures, particularly from logging. The Philippines, for example, have only about 25 percent of their original mangrove forests still remaining (Gomez, 1988), and the ability of these mangroves to survive the next century must be considered problematic (Ormond, 1988). Declining health of mangrove forests will have particularly deleterious effects on tropical deltas (Snedaker, 1984). Damming of rivers means that the necessary brackish water conditions no longer are present. For instance, mangrove communities in the Indus River delta have declined dramatically since damming of the river in the early 1960's, resulting in the displacement of many of the indigenous villages that depended on the forests for their food, shelter and fuel. Decreased delivery of river sediment will almost certainly have a deleterious effect on the Sundarban mangrove forest, upon which no less than 30 percent of the Bangladeshi population presently depends (UN/ESCAP, 1986). But as we have little idea of the transfer or fate of fluvial sediment in this delta area, nor do we know rates of subsidence, we are at a loss to predict the extent to which engineering projects would alter the environment, other than to say almost certainly the effects would be negative and quite probably (at least locally) disastrous.

3.4.4. Loss of Deltaic Environments. Most deltas are actually composite features, made up variously of beaches, spits, dune fields, tidal flats, wetlands, and active and abandoned distributaries. Under natural conditions, delta subsidence from consolidation and dewatering of underlying sedimentary sequences is offset by the deposition of river-borne sediment, particularly that sediment deposited by flood overspill of river banks. Sediment reaching the coastal environment can accumulate in a seaward progradation of the shoreward and/or delta front. Some low-lying areas experience natural subsidence rates as great as 1 to 10 cm/yr, 10 to 100 times the present eustatic rate of sea level rise. The future need to pump ground waters in the Nile Delta, whose natural subsidence rates (5 mm/yr; Stanley, 1988) are about three times the current rate of sea-level rise, could increase subsidence rates considerably. Using the most pessimistic scenario (maximum sea-level rise, maximum subsidence rates), Milliman *et al.* (1989) calculated that by the year 2100, more than 25 percent of Egypt's presently habitable land could be inundated by rising sea level. With a national population that is doubling every 20-30 years, such a prediction is gloomy indeed.

Even at the present modest rates of worldwide sea level rise, many large marine deltas have entered a transgressive phase because of subsidence, and other factors such as decreasing sediment loads, natural channel switching and lobe abandonment, and leveeing and related human activities. Because many deltas exist either in high wave energy environments or support large populations (e.g. Ganges-Brahmaputra, Indus, Niger, Nile), additional loss of sediments, especially the selective loss of sand, will be devastating: tropical marine deltas will probably be the most seriously impacted of all the coastal environments. The fact that many temperate and tropical deltas are covered by a fragile living surface of salt marsh or mangrove swamp engineering solution to local erosion problems produces a tradeoff of unwanted downdrift effects (Pilkey, 1989).

3.4.2. Changes in Offshore Profile and Shelf Transport Processes. Beach erosion and barrier island migration in the absence of an ample sediment supply will lead to changes in the offshore profile. Beach sediments are part of a sand sharing system in which the upper beach face and even the dunes are removed during storms and temporarily stored offshore in a system of ridges and runnels (Davis *et al.*, 1972). Following each storm, most of the sand returns to the beach face. However, decreased sediment delivery to the nearshore zone, together with a modest sea level rise, will result in redistribution of sand on the shoreface, thus leading to net offshore transport of valuable beach sand.

3.4.3. Greater Susceptibility to Flooding and Increases in Wetland Loss. Reasons behind present-day marsh loss can be broadly grouped as 1) loss of substrate upon which marshes are built, as in the case of subsiding deltas, 2) landward barrier island migration which forces the marshes behind them to be displaced and eventually buried or eroded, 3) loss of sediment input through upstream engineering works such as dams and levees, 4) direct removal by man from dredge and fill activities and construction of pipeline and navigation canals, and 5) construction of bulkheads and revetments at the coast, preventing landward translation as sea level rises. The overall resistance of marsh substrate to direct erosion by waves suggests that submergence (insufficient sediment accumulation) will be the leading cause of marsh loss in the future. Decreases in sediment delivery will have the greatest impact in highly subsiding areas where marshes receive their sediments from large point sources. The most common type of loss by submergence will be from the formation of interior ponds that occur as marsh vegetation deteriorates from effects of anoxia.

Contrary to a substantial body of earlier literature, mangrove margins are now thought to be a response to sedimentation and unable to actually control landform evolution (Woodroffe, 1983). Therefore, decreases in sediment delivery could have substantial impacts because of the wide distribution of these environments: Ganges-Brahmaputra Delta; coasts of Sumatra, Borneo, and Papau New Guinea; Queensland and Northern Territory of Australia; coasts of French Guiana, Surinam, and Guyana in northeast South America; and, in similar locations in east and west Africa. In fact, few ecosystems are as important to the coastal community but also as fragile as the mangrove forests. Many of more than 200 plant species within the mangrove ecosystem require brackish waters and relatively low rates of sedimentation and subsidence (i.e., water depths must be within a narrow range, deeper than which the mangroves will ceases colonization).

A recent review by Ellison and Stoddart (1991) found that, in the absence of terrigenous sediment input, mangrove ecosystems could keep pace with rates of sea level rise of 8-9 mm/yr, but would be under severe stress and could not survive at rates exceeding 12 mm/yr. A scenario of ecosystem collapse from sea level alone during the next 100-200 years is especially realistic in the case of low-lying carbonate shorelines where sediment input is very low. However, as in the case of salt marshes, mangroves ultimately will respond to large-scale geomorphology and

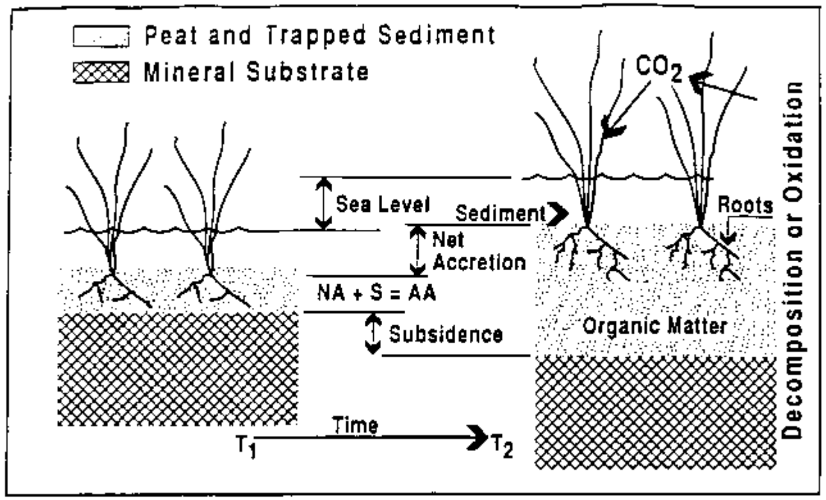

Figure 13. Schematic diagram of processes that govern marsh accretion (NA = net accretion; S = subsidence; AA = absolute accretion; modified from Delaune, *et al.* 1989).

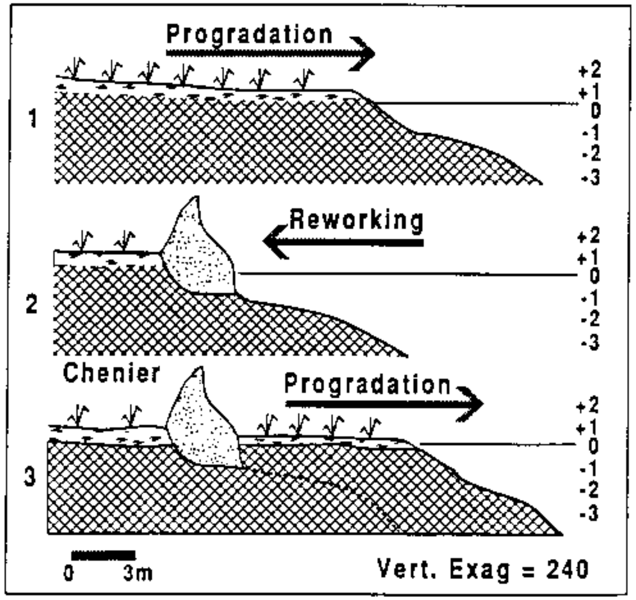

Figure 14. Episodic shoreline development of a chenier plain. Growth is dependent on sediment supply (modified from Elliott, 1978).

(Ellison and Stoddart, 1991). In extreme cases, massive sediment input can bury pneumatophores and kill mangroves (Stoddart and Pethick, 1984).

3.3.5. Smothering of Benthic Habitats, and Effects on Growth Rates from Changes in Intensity and Spectral Quality of Light. Coral reefs, which often occur in association with mangroves, are dependent on the ability to produce their own sedimentary calcium carbonate required for vertical growth. The sediment budget depends entirely on biogenic production, and growth capacity of individual reef-building organisms sets absolute limits on reef growth. Since most reefs appear able to keep up with present and modest increases in rates of sea level rise (Neumann *et al.*, 1985; Lidz and Shinn, 1991), sedimentation poses one of the greatest threats on a timescale of centuries. Harbor dredging and unprecedented development along tropical shorelines are the two factors presently causing severe degradation from increased sedimentation (Rogers, 1990). Although some coral species can remove modest amounts of sediment using tentacles and excretion of mucus, heavy sedimentation results in fewer viable species, less live coral, lower growth rates, reduced recruitment from larval settlement, and slower rates of reef accretion (Dodge *et al.*, 1974; Dodge and Vaisnys, 1977; Babcock and Davis, 1991). Excessive sedimentation can kill not only corals, but also sponges which serve as food and habitats for tropical fisheries. Widespread degradation of coral reefs from siltation occurs along the entire east African coastal region from Somalia in the north to Inlaca Island, Mozambique and several oceanic islands. In Kenya, silt carried by the Tana River has adversely affected catches of both finfish and prawns in Ungwana Bay (UNEP, 1989). The impacts of reduced light, while difficult to separate quantitatively from the effects of smothering, lead to lower rates of photosynthesis and to metabolic stress. According to Rogers (1990), chronic sedimentation rates greater than 10 mg/cm^2/day should be considered as "high."

3.3.6. Renewed Growth in Deltas and on "Downdrift" Coasts. If sediment delivery is substantially increased through river diversion, farming and deforestation, or from major remobilization of upstream sources, then new deltas will build. Delta growth from increased river discharge in Asia over the past millennia has brought populations closer to the coast. In fact, people in Asia are occupying some land areas that probably would not have existed if not for the increased land erosion upstream. For example, the city of Shanghai, which presently has a metropolitan population of nearly 20 million, was a low-lying tidal flat deposited as recently as 2-3 thousand years ago.

Two classic examples which attest to the importance of river diversion and delta growth are the Yellow River in China and the Atchafalaya River in the Gulf of Mexico of the U.S. (Ren, 1983; Wells, 1987). The Yellow River episodically shifted depositional sites in the mid-1800s from the Yellow Sea to the Gulf of Po Hai, building a major delta some 500 km to the north. The Mississippi Delta, of which the Atchafalaya is the newest lobe, has switched depositonal sites at least seven times in the past 5,000 years. Although rates of growth in new deltas can be 1-10 km^2/yr, there is a substantial tradeoff: associated with each river diversion is a period of coastal erosion as sediments are diverted to a new site. It may take decades or centuries before the amount of land being added to a new delta lobe offsets the amount of land being lost from an abandoned delta lobe. Barring episodic shifts in depositonal site, increases in sediment delivery probably will not produce significant morphologic effects unless 1) new sediment contains a high percentage of sand, 2) subsidence rates are low, 3) new sediment is not being discharged directly into deep water, and 4) the potential for removal by marine processes, such as waves and tides, is low.

Major rivers often supply sediments to "downdrift" coasts which are morphologically and genetically tied to processes in updrift deltas. These coastlines, referred to as chenier-plain coasts, include northeastern South America, northwest Gulf of Mexico, as well as parts of China, Australia, and New Zealand. Since the same sediment sources that supply deltas provide sediments to their downdrift coasts, increased sediment delivery will provide an opportunity for renewed chenier plain growth (Figure 14). This will be possible even in the absence of delta growth since 1) new sediments that fail to be incorporated into deltas will still be available for transport within the receiving basin, and 2) many downdrift coasts are mangrove swamp or salt marsh and can effectively incorporate large volumes of fine-grained sediments.

3.4. Effects of Decreased Sediment Delivery

The effects of decreased sediment delivery to the coast will be most pronounced in low lying coastal areas, especially those subject to high subsidence rates, and in environments that are already in a delicate state of balance. Low-lying deltas may be particularly vulnerable in the near future, as their rapid buildup over the past several millennia appears to have been due in part to anthropogenically enhanced terrestrial erosion and river discharge, which soon will be negated by constructed of dams and other river diversions. Uncompensated (or even accelerated) subsidence of low-lying deltas will be one effect of river/sediment diversion, but accentuated coastal erosion may lag considerably. In contrast, biological effects from the decreased flux of fresh water, such as shrinking mangrove forests and decreased coastal fisheries, probably will be felt immediately.

3.4.1. Increased Beach Erosion. Beaches exist wherever there is a sufficient supply of sediment for accumulation at the shoreline. Most are composed of sand, gravel, or abraded shell and are broadly classified as either mainland or barrier beaches. Although most sand that supplies beaches has been derived from rivers, there is considerable longshore flux (up to 10^6 m^3/yr) that serves simultaneously as a source and sink, and there is significant onshore-offshore exchange. A decrease in sediment supply to the coast, regardless of cause, will almost surely lead to faster erosion, assuming other factors remain constant (SCOR, 1991). The obvious exception is in the case where the lost sediment would have been either too coarse or too fine to be in general equilibrium with the existing coastal environment.

Loss of sediment will also increase frequency of overwash processes. Barrier islands will thin more rapidly from accelerated erosion on both landward and seaward sides; eventually, when some critical width is reached (300-500 m), the rate of shoreline movement will increase sharply as all available sand begins moving across the island. To stem erosion and protect backshore features, many beaches are highly engineered systems that include massive seawalls, revetments, groins, and jetties. Since there is virtually no excess sand in most beach systems, every