13

Sediment Transfer and Siltation

IAN DOUGLAS

The dynamics of the earth surface and the lives of all people and organisms depend on flows of energy, water, and materials. These flows are profoundly modified by people to sustain both urban and rural life. The act of gathering food or fuel is a transfer of chemicals and energy. In terms of materials flows, these people-made transfers have to be compared with the geochemical circulations involved in rock weathering, erosion, transportation, and sediment deposition.

Erosion is a natural process which, although often imperceptible, can be quite extreme, even in areas remote from any disturbance by people. High, natural erosion rates occur in wet, mountain environments from the humid tropics to cool, temperate latitudes, particularly where heavy rains fall on weak, poorly consolidated rocks such as the greywackes of the west coast of the South Island of New Zealand and in the mountains of Taiwan and Japan (Aniya 1985). Some of the world's highest estimated erosion rates are for rivers draining young, tectonically active mountain regions in humid tropical and temperate regions (Table 13-1). In such areas, landsliding, often triggered by earthquakes, and stream-bank erosion and channel adjustment leave abundant spreads of debris in valley floors, which are swept downstream by runoff from major storms.

Outside these steep, tectonically active areas, natural erosion rates may be high where easily eroded, dispersable rocks occur. Despite the conventional wisdom that in tropical areas the danger of soil erosion from runoff and rain is negligible wherever dense evergreen forest is present (FAO 1978), in those places where geological conditions provide outcrops of easily erodible material, such as the mudstones and shales of the Chert-Spilite and Kuamut formations of Borneo, landslipping, bank, and channel-bed erosion often supply large quantities of mud, sand, and gravel to rivers in dense tropical forest devoid of any human disturbance. Unfortunately, the absence of permanent monitoring stations in such undisturbed areas makes it difficult to quantify natural erosion rates.

Many estimates of present-day fluvial sediment and solute loads (Table 13-2; Fig. 13.1) include both natural and people-accelerated erosion. Few estimates truly reflect the rates of erosion likely to have operated through geologic time (Douglas 1967). Many do not include all the erosion caused by human activity, as much eroded sediment is redeposited after a short movement downslope or downwind. In a simplified way, three spatial scales of sediment transfer may be envisaged (Fig. 13.2). Many soil particles are detached and carried downslope only to be held and trapped by a plant, tree, or other obstacle a little further downslope. Such retention on the hillslope leads to the buildup of colluvial deposits. The sediment reaching the valley floor may not be completely removed by the river, but may be redistributed as alluvial floodplain deposits. That sediment carried downstream may be redeposited again on another part of the floodplain or in managed rivers in reservoirs. Much of the sediment now being carried by rivers is derived from the erosion of channel banks in alluvial floodplain material.

The records of fluvial sediment loads are in the form of either the quantity of material carried past a given point on a river or the rate of deposition in a lake, reservoir, or ocean basin. Few river sediment records extend over more than a decade. All such records exhibit considerable variation from year to year (Fig. 13.3) and reveal the role of extreme events such as hurricanes (Table 13-3a). The material carried past a downstream point on a river may have been supplied to the channel upstream some years before and have been stored in the system (Table 13-3b). In many environments, over half the annual sediment load may be carried in only a few days (Table 13-3c), indicating the importance of detailed monitoring if reliable estimates of total fluvial material transfer are to be obtained. Such factors make it difficult to describe the changes in sediment transfer over the past 300 years accurately.

Lake and reservoir sediments offer an alternative, provided that accurate dating can be obtained. The recent growth of lake-catchment studies (Oldfield 1977; Petts and Foster 1985) has provided good data for several areas (Fig. 13.4). The effects of agricultural change, especially continuous cropping, hedgerow removal, subsoil drainage, and higher stocking densities, in accelerating topsoil removal, are well shown in the records of small lakes in the English midlands (Fig. 13.4, records 6 and 7).

Table 13-1 *Estimated erosion rates for mountainous areas*

River	Catchment runoff area (km²)	(mm/y)	Percentage natural vegetation	Suspended sediment yield (t/km^2y^{-1})	Source
New Guinea					
Ok Tedi	420	5,695	95	4,300–7,400	Pickup, Huggins, and Warner 1981
Aure	4,360	2,220	95	10,500	"
Fly at Kiunga	6,300	5,360	95	650–875	"
Asia					
Ching	5,700			7,150	Holeman 1968
Lo	26,000			7,300	"
Kosi	62,000			2,750	"
Amahata, Japan	97			4,900	Aniya 1985
Mt. Usu, Japan	0.21*			340,000	Chinen and Kadomura 1986
New Zealand					
Western Alps, South Island				15,000	Whitehouse 1983
Italy					
Torrente Idice	397			2,400	Ciccacci et al. 1981
Fiume Trebbia	226			1,520	Ciccacci et al. 1981
Taiwan					
Choshui	3,000	2,000		22,000	Milliman and Meade 1983
Kaoping	3,000	3,000		13,000	"
Tsengwen	1,000	2,000		28,000	"

* Rate of erosion of fresh volcanic material in the first few years after eruption.

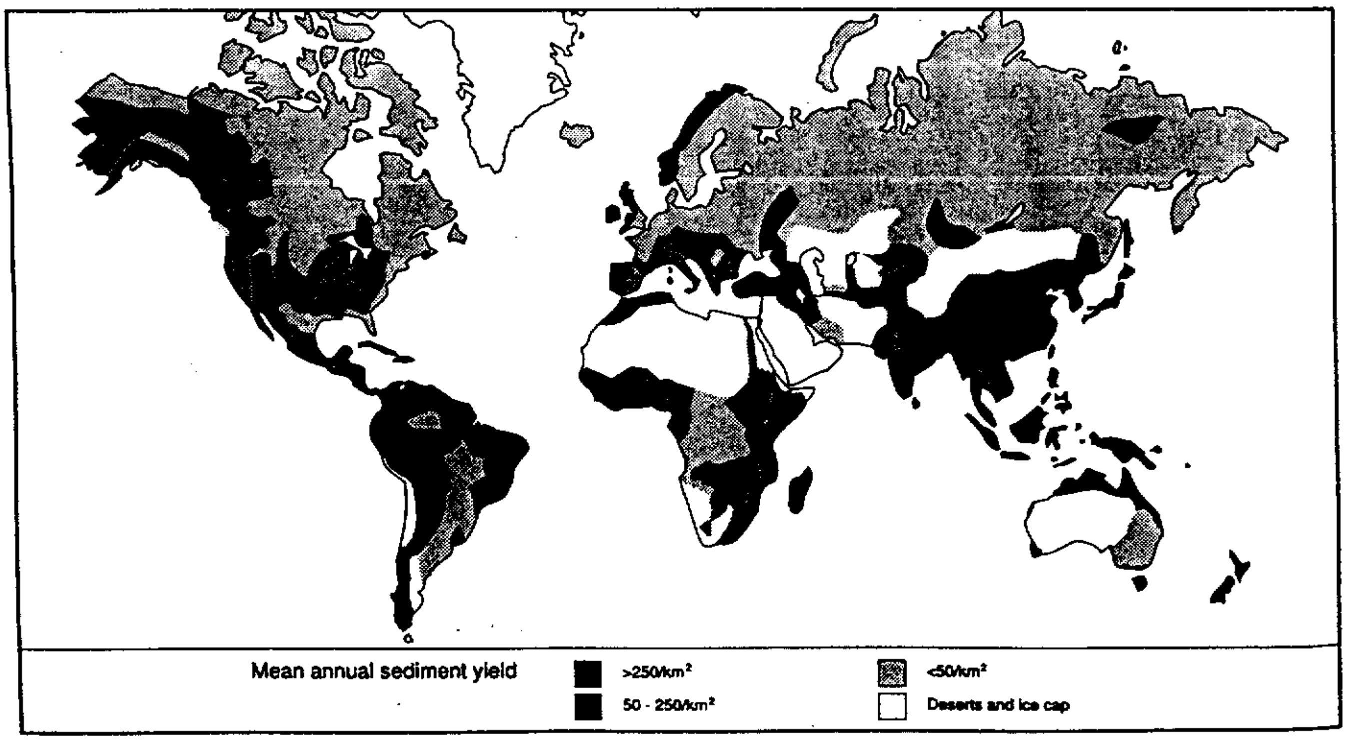

Figure 13.1 A tentative map of global variations in sediment yield.
Source: Walling and Webb 1983.

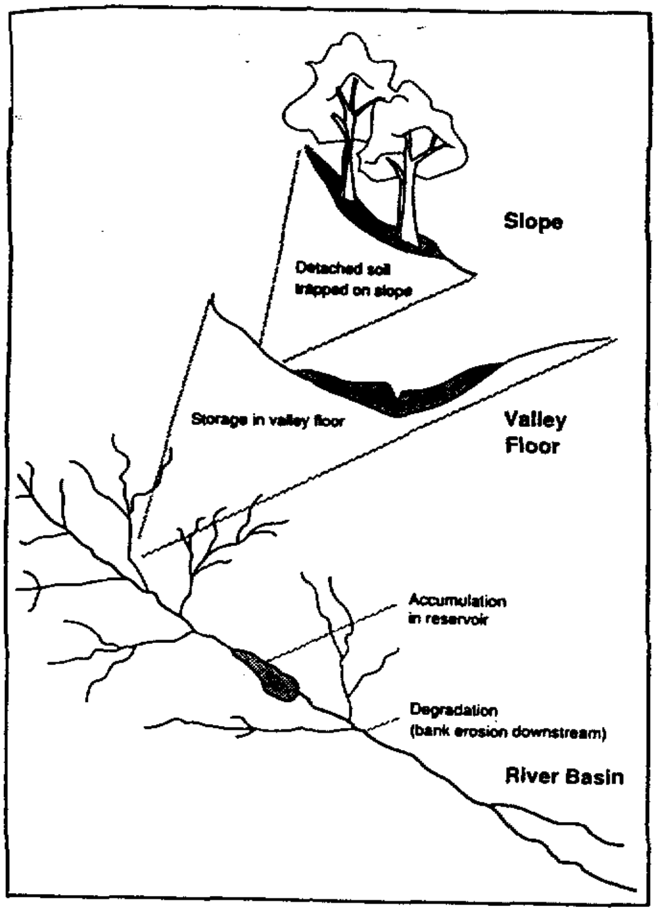

Figure 13.2 Spatial cases of sediment transfer emphasizing localities in which eroded sediment may be detained or trapped within a fluvial system.

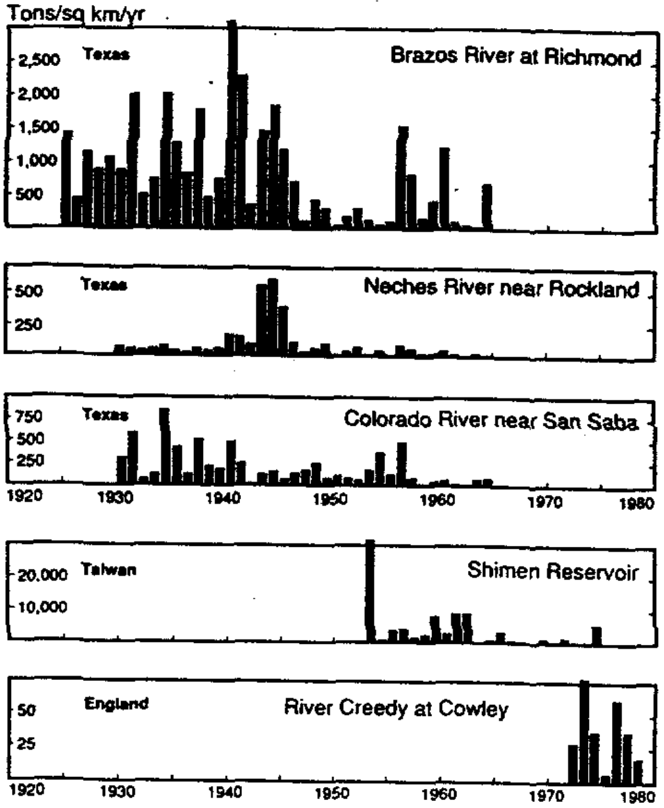

Figure 13.3 Annual fluvial sediment yields for five river systems. *Sources:* (Texas rivers) Adey and Cook 1964; Cook 1967; 1970; Mirabel 1974; (Shimen Reservoir) Shimen Reservoir Commission 1975; Stout, Bentz, and Ingram 1961; (River Creedy) Webb and Walling 1982.

Table 13-2 *Sediment and dissolved loads of major rivers*

River	Mean discharge ($10^3 m^3 s^{-1}$)	Drainage area ($10^3 km^2$)	Mean sediment load ($10^6 t/yr$)	Mean dissolved load ($10^6 t/yr$)	% of total load carried in solution
Africa					
Congo	39.2	4,000	43	47	52
Zambezi	7.1	1,340	20	15	43
Niger	6.1	1,125	40	10	20
Orange	2.9	1,000	17	12	41
Nile	2.8	3,000	0	17	100
Asia					
Ganges-Brahmaputra	19.3	1,480	1,670	151	8
Mekong	18.3	795	160	59	27
Yenisei	17.2	2,600	13	73	83
Lena	16.3	2,430	12	85	88
Huang He	1.5	752	1,080	—	—
Indus	6.7	950	100	65	39
Choshui (Taiwan)	0.14	3	66	—	—
Australia & New Guinea					
Murray-Darling	0.7	1,070	30	9	23
Purari	2.44	31	80	—	—
Europe					
Volga	8.4	1,350	26	77	77
Danube	6.4	85	19	60	76
Dnieper	1.6	500	1	11	91

Table 13-2 *(cont.)*

River	Mean discharge ($10^3 m^3 s^{-1}$)	Drainage area ($10^3 km^2$)	Mean sediment load ($10^6 t/yr$)	Mean dissolved load ($10^6 t/yr$)	Percentage of total load carrie in solution
North America					
Mississippi	18.4	3,267	210	131	38
St. Lawrence	10.7	125	4	54	93
Mackenzie	9.6	1,800	100	70	41
Columbia	8.0	670	8	35	81
Yukon	6.2	770	60	34	36
South America					
Amazon	175	6,300	900	290	24
Orinoco	30	950	225	50	18
Paraná	18	2,800	112	56	33
Magdalena	7.5	240	220	28	11

Sources: Knighton 1984, Meybeck 1976, Milliman and Meade 1983.

In Australia and the United States, the impact of agricultural expansion is shown by high late-nineteenth- and early-twentieth-century sediment yields, followed by reduced yields after better practices and soil conservation works had been established (Fig. 13.4, records 1, 2, and 3).

Deliberate trapping of sediment for land reclamation and soil conservation not only reduces the amount lost to rivers, but also yields a valuable agricultural resource. In examining the present state of the global sediment budget as affected by human action, the prehistoric and historic phases of acceleration of sediment transfer are considered first, followed next by examination of artificial sedimentation and then by assessment of the human modification of river, wind, and coastal erosion.

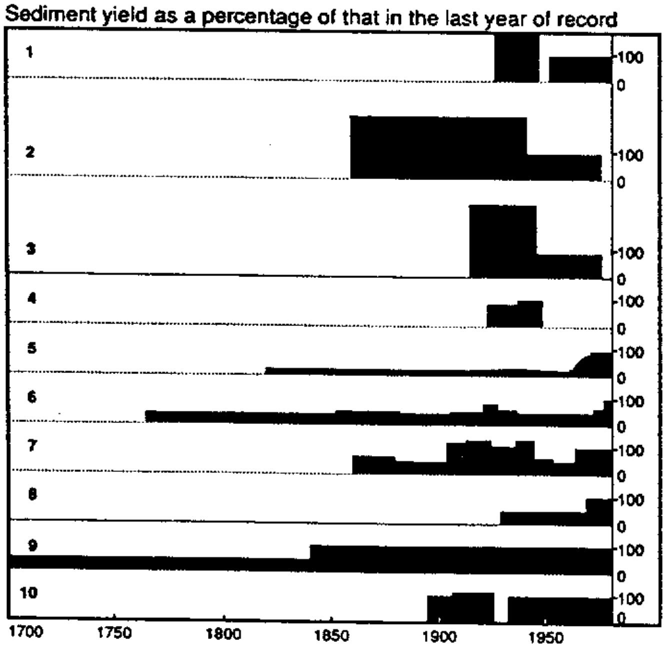

Figure 13.4 Sediment-yield reconstructions based on lake and reservoir sediment records. *Locations and sources*((1) Burrinjuck Reservoir, N.S.W., Australia: Wasson et al. 1987; (2) Coon Creek, Wisconsin: Trimble 1976; (3) Piedmont province, Maryland: Costa 1975; (4) Lake Decatur, Illinois: Brown, Stall, and DeTurk 1947; (5) Loch Grammoch, Scotland: Battarbee et al. 1985; (6) Seeswood Pool, England: Dearing and Foster 1987; (7) Merevale catchment, England: Foster et al. 1985; (8) Coombs Brook, England: Stott 1987; (9) Llangorse Lake, Wales: Jones, Benson-Evans, and Chambers 1985; (10) Montepulciano Lake, Italy: Basile and Dragoni 1987.

Prehistoric and Preindustrial Transformation of the Landscape and Increased Erosion

The process of modifying river-catchment areas goes back into prehistory, with the use of fire as a local management tool by the original people of most continents. The native tribes of the east coast of North America used fire to create the parklike aspect of the eastern forests described by early European travelers. In California, the chapparal was adapted to fires, caused both by lightning and by Indians who burned off the chapparal to encourage new growth to provide better browse for deer. The extent of the grassland areas of the Great Plains was partly a result of burning the grass either in the course of buffalo hunting or in providing new grass that would be attractive to grazing buffalo (Kidwell 1985). The Australian aborigines used fire to manipulate the extent of the dense rain forests of northeast Queensland, with pollen analysis revealing a people-induced vegetation change to sclerophyll (eucalypt) forest after 10,000 B.P., when no apparent climatic deterioration had occurred (Kershaw 1976). The role of such burning in causing erosion is not clear, but modern studies of the consequences of bush and wildfires suggest that much sediment is washed away by heavy rains before ground cover can be reestablished.

The introduction of agriculture, deforestation, and pastoralism to part of upland western Europe promoted major changes in soil character, particularly an increase in acid, podzol conditions associated with the development of peat bogs. Forest clearance by fire was at least a contributing factor, if not the prime cause, of the development of peat bogs or blanket mires, which coincides with the decline of

Table 13-3 *Examples of the irregularity of fluvial sediment transport*

a. The role of exceptional years in the mean rate of annual sediment discharge of streams draining to the Atlantic coast of the United States

River	Time period	Mean annual sediment discharge 10^3 t	Percentage of suspended sediment discharged in: 1% of time	5% of time	10% of time
Delaware River at Trenton, NJ	(a) 30 years, 1950–1979	680	49	76	85
	(b) as above excluding 1955 (the years of hurricanes Connie and Diane)	631	44	74	84
Juniata River at Newport, PA	(a) 28 years, 1952–1979	255	44	75	85
	(b) as above excluding 1972 (the year of Hurricane Agnes)	229	41	72	83

Source: Meade 1982.

b. Yearly changes in channel storage of sediment on a Californian coastal river

		Total load (1,000 million t)					
Water year	Percentage of normal runoff	Carmel at Robles	Tributary input	Bank erosion	Total inputs	Carmel at Carmel	Balance (in channel and storage change)
1980	167	50.7	14	831	896	432	+464
1981	43	1.8	1.4	negl.	3.1	44.7	−416
1982	166	26.5	14	91.2	132	317	−185
1983	413	220	65	699	985	1620	−639
1984	73	37.2	3.3	negl.	40.5	82.1	− 41.6
1985	20	0.48	0.4	negl.	0.84	12.0	− 11.1
1986	120	44.1	7.7	48.1	99.9	298	−198
Total 1980–1986		381	105	1670	2160	2810	−653

Source: Matthews and Kondolf 1987.

c. Proportion of annual sediment discharge carried in one day on the Waikele Stream at Waipahu, Oahu, Hawaii

Water year	Total annual load, tons	Maximum daily load, tons	Percentage of annual load carried in one day
1977–78	3,428.89	574	16.7
1978–79	38,211.01	31,800	83.2
1979–80	53,622.52	14,700	27.4
1980–81	3,268.67	498	15.2
1981–82	92,732.27	32,900	35.5
1982–83	5,673.72	1,880	33.1
1983–84	1,445.16	635	43.9

Source: U.S. Geological Survey Water Data Reports HI-78-1, 79-1, 80-1, 81-1, 82-1, 83-1 and 84-1.

elm in the pollen record (5,300–5,100 B.P.) (Moore 1975). The basal layers of marginal peat bogs in the southern Pennines of England contain evidence of the use of fire to clear vegetation, such as sootlike particles, charred plant fragments, and lumps of charcoal (Tallis 1975). These fires not only exposed soil to mechanical erosion, but also may have released readily soluble salts containing nutrients, thereby adding to soil degradation (Dimbleby 1974). During this upland clearance, by Neolithic and Bronze Age peoples approximately 5,300–2,500 B.P., soil disturbance was high, and alluviation occurred in nearby valleys.

Massive ground-cover changes were produced by the spread of agriculture and the intensive use of land by the great agrarian civilizations. It is unclear if the severest episodes of soil erosion coincided with the peak of agricultural activity or with the lack of maintenance of soil conservation works following the breakdown of agricultural systems, for either sociopolitical or climatic and environmental reasons. The siltation behind Roman dams in North Africa suggests that erosion occurred after agricultural development, but two other series of events are equally possible. Sedimentation could have been deliberately encouraged to ensure a deeper soil in a small area in which soil moisture retention would be much greater, or in which gradual pressure on the vegetation of catchment areas (especially in the search for fuelwood) could have led to less protection of the soil, with washing of silt into dams and irrigation systems during heavy storms.

Certainly, the advent of Berber and Arab pastoralists in North Africa led to further depletion of the vegetation cover and the later general alluviation of Mediterranean valleys, when climates became more humid (Judson 1968a; Vita-Finzi 1969). Quantifying rates of erosion during and after the early and classical civilizations of the Near East and Mediterranean is not as easy. Although the possible period of silt accumulation may be known, it is more difficult to tell if the debris was moved in a few large, rare events or if it accumulated steadily over decades and centuries. All that is known now about earth-surface processes and sedimentation suggests that the rare events may be the prime cause. This fact then raises the question: Were the classical agricultural systems under stress when a major event occurred – either through long drought, through social disruption, or through disease of crops or people?

Not all severe erosion in classical times can be explained by an extreme-event theory. Gradual soil-deterioration processes, such as salinization (today important in the Indus and Colorado valleys), were significant in the past. Salt probably played a major role in the deterioration of agriculture in Mesopotamia, and since then has been a cause of loss of ground cover and soil erosion in many arid, semiarid, and Mediterranean countries.

Before A.D. 1000, agricultural expansion led to widespread forest destruction from latitude 60°N to 40°S. Clear signs of widespread human activity after 6,200 years B.P. are detectable from the pollen record in Sumatra (Maloney 1985), with similar evidence from other parts of tropical Asia. In Europe, good climatic conditions at various times since A.D. 1000 seem to have favored the expansion of agriculture into marginal areas. However, both economic difficulties and climatic cooling caused stress at different times, leading to degradation of the marginal lands, especially where wind action affected light, sandy soils in France, Germany, and adjacent countries during the fourteenth and fifteenth centuries and again in the eighteenth century.

Industrialization, Minerals, Materials and Food Transfers over the past 300 Years

Under the small-scale agricultural civilizations, and even under those as great as the Romans, Chinese, and Incas, water control, sediment, and food transfers were essentially local. The large-scale regional and intercontinental movement of raw materials, food, and manufactured goods did not begin really until after the great age of European ocean exploration and the establishment of the colonial trading empires in the seventeenth and eighteenth centuries. It remained small until the steam age of the mid-nineteenth century.

The great acceleration in the transfer of earth-surface materials began with the rapid growth of population from the beginning of the nineteenth century. With the construction of the first industrial canals in the eighteenth century, an age of colossal earthworks started, involving the movement of huge quantities of soil and rock from cuttings to embankments. Coupled with an immense expansion of quarrying and mining, this new industrial age moved minerals, rocks, and soils on an unprecedented scale.

Urban centers of population over 100,000 grew by 76% from 1800 to 1850, outstripping the 29% increase in world population at the time and necessarily involving great quantities of building supplies and raw materials for trade and industry. Mine waste dumps, clay and gravel pits, quarries and urban rubbish dumps became new landforms around the great industrial cities. At the same time, the trade that fired the growth in markets for the products of cities like Manchester, Lille, Liège, and Pittsburgh led to the degradation of vegetation in distant tropical lands.

At the end of the eighteenth century, large-scale sugar plantations had begun to encroach inland into the rain forests of southeastern Brazil. By 1830, the expansion of coffee plantations had surpassed that of sugar, and was intensified with the ending of slavery in 1880. The general belief that coffee grew well only in virgin soil led to more extensive and sustained forest clearance than was probably necessary. In Asia, the colonial encouragement of export rice economies led to an increase in harvest from 700,000 t/y in 1860 to 4,200,000 t/y in 1914 in the Irrawaddy, Chao Phya, and Mekong deltas (Tucker and Richards 1985). When deltaic land was unavailable, adjacent lowland forest was removed. Similar clearing took place in the Western Ghats in the Bombay hinterland in India, where only designated government forest reserves retained any of the original rain forest.

This beginning of the globally interdependent, deliberate transfer of materials started the hectic phase of transformation of the earth's surface that has since accelerated as the world's urban populations expanded further. By the 1860s, the consequences of these transfers began to pose serious problems in and around major cities. In Manchester, navigation on the River Irwell became more and more difficult because of the shoals of gravel and cinders built up from the waste ashes from domestic and factory fires, which had been thrown into the river for decades. Channel cross-sections drawn up by a Royal Commission on the Pollution of Rivers in 1870 show that half of the river channel had been filled with cinders and that the capacity for floodwaters was greatly reduced. This steady deterioration of British rivers led to the famous 1910 Royal Commission 20/30 standard for sewage effluents to rivers, 20 mg/l BOD and 30 mg/l maximum for suspended sediment.

Deterioration of rivers was accompanied by the atmospheric pollution, long considered essentially a local phenomenon, which reached its peak in the severe Donora, Liège, and London smog episodes of the 1950s. Now it is realized that this smoke and sulfur dioxide pollution led to a massive transcontinental transfer of chemicals, which have affected forests and lakes hundreds of kilometers from pollutant sources. More locally, acid rain is likely to have contributed to the erosion of blanket peats on the moorlands of northwest Europe, especially in the Pennines and the Ardennes.

The machinery produced in the industrial cities in turn had its effect on agriculture. Not only was demand growing for food, but also new methods of broad-acre farming, to grow more at lower cost. By the 1930s, soil erosion had begun to be a major problem in the great wheatlands of North America, Argentina, and Australia. In the United States, the Soil Conservation Service noted an annual loss of 3,600 million t of soil in the 1930s, 2,700 million t of which came from cropland (Troeh, Hobbs, and Donahue 1980). Severe dust storms occurred, such as that of May 12, 1934, in the panhandles of Texas and Oklahoma, southeastern Colorado, and southwestern Kansas, which carried dust 2,500 km to New York City and Washington, D.C. and several hundred kilometers out to sea, shifting an estimated 185 million t of soil.

At the same time, the expanding mining industry began to have severe erosive impacts. Late-nineteenth- and early-twentieth-century tin mining in peninsular Malaysia, for example, led to many instances of valley aggradation, the most severe being that which forced the relocation of the entire town of Kuala Kubu in northern Selangor. Elsewhere mine tailings and smelter fumes denuded vegetation, creating the type of barren, eroded landscape found around Queenstown, Tasmania. Some mining, such as the "gold rushes" of the second half of the nineteenth century, lasted only two or three decades but left continuing soil-erosion and chemical-contamination problems.

Rates of expansion of mineral extraction vary through time. A doubling of *world coal production in two decades* 1860–1880 (from 200 to 400 million t) was followed by faster increases, up to almost 1,500 million t by 1914. However, world production of over 2,000 million t was not reached until 1960, after which it accelerated to 2,700 million t in 1980. Such expansion is accompanied by shifts on the places of production. Coal production in many early industrial countries has declined, but it has expanded in the southern continents, particularly in South America, Africa, and Australia. Even in old mining areas, such as Britain, the form of coal mining has altered. Open-cut, or strip, mining has become more widespread.

Above all, *the continuing growth of the urban population*, the expansion of the built-up area of cities, accelerated the volume of flows in the global resource transfer system. Between 1900 and 1950, when the world population grew by 49%, the urban population grew by 254% – with the highest urban growth rates in Asia (a 444% increase) and Africa (a 629% increase). The proportion of the world's people living in cities still is increasing in every continent, but particularly in Asia and Africa (Table 13-4). The urban population of Indonesia, which accounted for 22% of the total in 1980, will make up 40% of the total in the year 2000. Concomitant with urban growth is increased per capita consumption of earth materials. *The annual coal consumption in Britain* was about 0.5 t per capita in 1700, 1 t per capita in 1800, and 6 t per capita in 1900. Power consumption in the United States rose from just over 3 kW per capita per year in 1900 to about 12 kW in 1980.

This urban expansion requires vast areas of land. About 15,000 km^2 of Indian rural land were consumed by cities between 1955 and 1985, with another 10,000 km^2 expected to be used by the year 2000. The consumption of rock, sand, and gravel to manufacture cement and concrete is enormous. In 1961, world cement production was 383.5 million t but by 1982 it had risen to 892.1 million t – an increase of 267% (Fig. 13.5). But in newly industrializing countries and in the big nations of low latitudes, the expansion of production was far greater (Table 13-5). If most of this cement was used to make concrete, even greater quantities of sand and gravel or *of crushed rock must have been involved*, creating new depressions in the landscape and removing hills. As Sham Sani (1984) has noted around Kuala Lumpur, rock crushing is a major source of atmospheric particulates that represent an addition to the total transfer of sediment as a direct consequence of urban growth.

These demands for construction material are but part of the picture of the transformation of the earth's surface by removal, transportation, and deposition of materials. The sheer quantities of material involved in excavation, embankment, and landfill operations during civil-engineering works are great; for example, 2.5 million t had been removed for the *diversion shipping channel* during the construction of the Thames barrier in London. If these volumes are seen as part of a global sediment budget – either natural or people-accelerated – transfers of sediment must be compared with

Table 13-4 *Actual and estimated percentage of total population in urban areas*

Area	(urban as % of total) 1950	1980	2000	2025
Oceania	61.3	71.8	73.1	78.4
North America	63.9	73.8	78.0	85.8
USSR	39.3	63.2	74.3	83.4
Europe	55.9	71.1	79.0	85.9
Latin America	41.1	65.3	76.6	84.2
Africa	14.8	23.7	42.4	58.3
East Asia	17.8	28.0	34.2	51.2
South Asia	16.1	25.4	36.8	55.3

Source: United Nations, Department of Industrial, Economic, and Social Affairs 1985.

Table 13-5 *World cement production growth*

Area	1982 production as % of 1961 production	National production as % of world total 1961	1982
World	267		
Republic of Korea	3,420	0.1	2.0
China	1,744	2.4	10.5
Taiwan	889	0.5	1.5
Mexico	713	0.8	2.0
Brazil	539	1.4	2.8
Japan	341	7.4	9.4
India	272	2.5	2.5
USSR	244	15.3	13.9
U.K.	90	4.3	1.5

Source: Bureau of Mines Staff 1984.

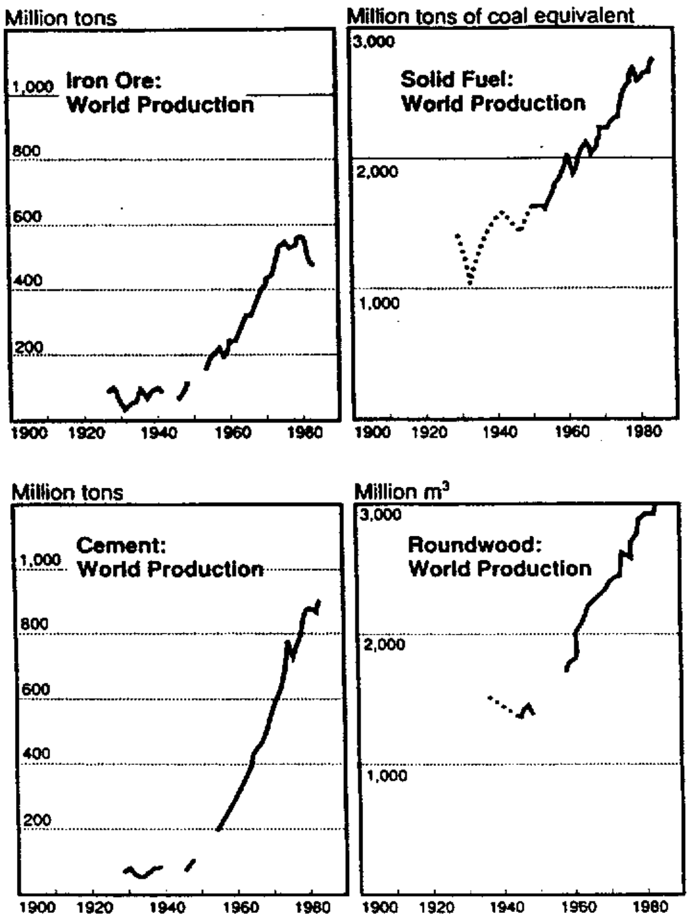

Figure 13.5 Growth in world production of iron ore, solid fuel, cement, and roundwood.

purposeful, artificial extraction and with landfill operations. Lest it be thought that all transfers of sediment and material are potentially deleterious or harmful, it is important to recall that much deposition of material by people is beneficial to human well-being. A large part of the world's population depends on land reclaimed and protected by controlled sedimentation processes for food production.

Artificial Sedimentation

Waste Disposal and Landfill Deposition of waste materials, tipping of mining spoil, disposal of power-station fly-ash, and the reclamation of land from the sea are all people-made forms of sedimentation, which, in many cases, are beneficial in human terms. Some of the building materials for the greater London area come from gravel pits along the Thames Valley in Oxfordshire and others from brick pits in Bedfordshire. The pits are reused as dumping grounds for solid wastes, wheat now being grown on former gravel pits filled with London's rubbish near Didcot, Oxfordshire. Many authorities, such as the Greater Manchester Waste Disposal Authority, have to transfer large volumes of material by rail or road to sites outside their area, Manchester depositing 0.7 million t out of a total of 1.18 million t of waste produced per year in old quarries and pits beyond its own boundaries. Still, 0.42 million t are dumped within the Authority's area, where much of the Mersey floodplain has been raised by such sanitary landfill, providing flood protection in many areas. Similar policies were adopted in San Bernardino County, California, where waste was used to construct a 430-m levee along the Santa Anna River. The compacted landfill is 76 m wide at the base and 10.7 m high, with 4 : 1 side slopes, and it has been capped with concrete to withstand erosion during floods.

Coastal and estuarine landfill has proceeded for centuries, creating new areas for industry, commerce, and residential development. Great airports, such as La Guardia in New York, Changi in Singapore, and Kai Tak in Hong Kong (Fig.

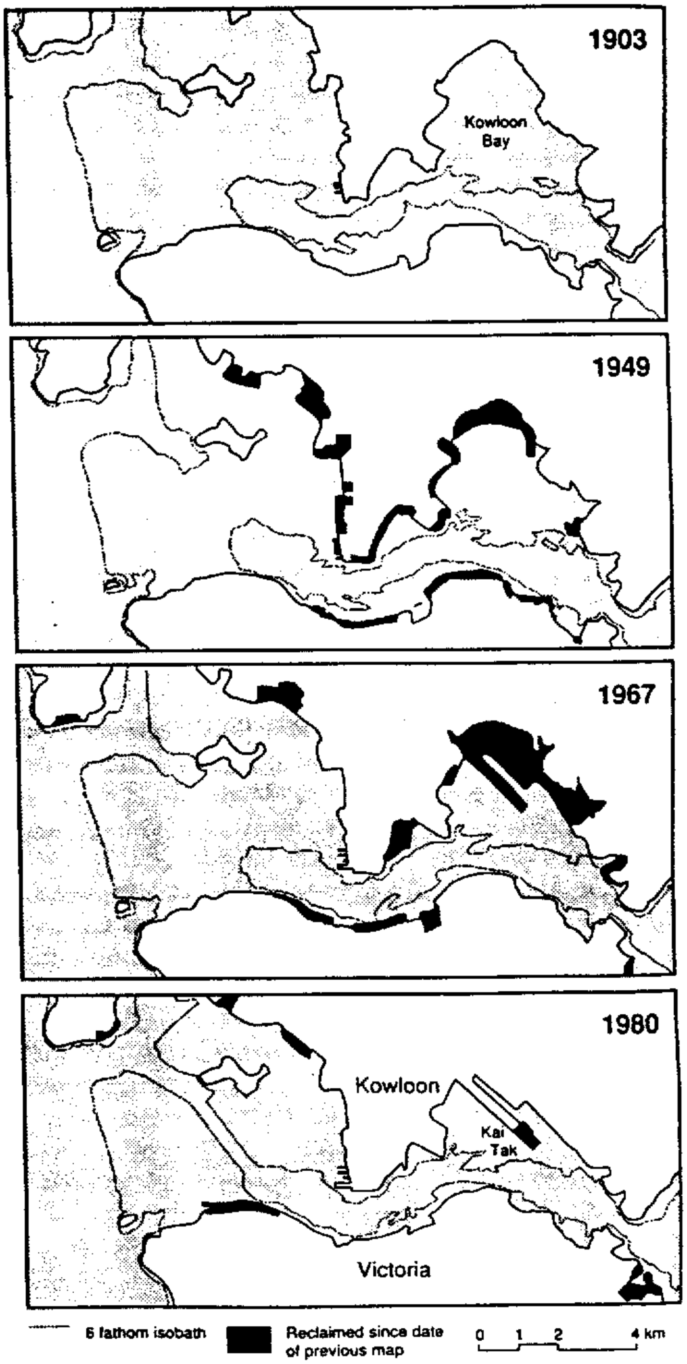

Figure 13.6 Changes in the coastline of Hong Kong harbor due to land reclamation, 1903–1980.

13.6) are built on filled areas, and many ports, such as Southampton in England, Marseille in France, and Singapore have the majority of their installations on reclaimed, filled coastal land. Such sanitary landfill has eliminated many areas of estuarine wetland to create valuable coastal real estate, such as the canal estates of Florida and Queensland.

Although many benefits accrue from such landfill operations, disadvantages also occur. The filling of swamps, estuarine wetlands, or floodplains may adversely affect flood conditions, especially when high river discharges coincide with coastal storm surges. Flood control is essentially a space-allocation problem. If the natural overflow areas, such as back swamps and marshes, are no longer available for flood storage, the space needed to accommodate floodwaters can be obtained only by raising flood heights. This in turn puts occupiers at a greater risk of inundation than before. Many immigrants within Australia and the United States move from temperate cities to subtropical coastal canal estates, only to be surprised at the cyclones and hurricanes that cause domestic flooding around their new homes.

Mining Waste Mineral extraction creates large volumes of spoil, which were traditionally dumped to form mounds on the ground surface, creating such notorious landforms as the "Wigan Alps" of greater Manchester. Since 1950, many countries have reclaimed these spoil heaps, often redesigning the landscape, reorganizing the drainage system, and re-establishing vegetation. In some cases, the spoil can be used for building material manufacture, but often it merely is bulldozed into new forms, as happened with the Wigan Alps, which have been landscaped into a country park. Spoil heaps occupied 131 km^2 of England in 1974, 43 of them associated largely with China-clay working in the Southwest (Kivell 1984), but since then much reclamation has occurred, more in the coal mining and industrial areas than in china-clay areas.

Power-Station Fuel Ash By 1979, the annual output of pulverized fuel ash (PFA) from the coalfield power stations of England and Wales was of the order of 10.5 million t (Coughlan 1979), but much of it is used as a consistent load-bearing hill and as a lightweight aggregate. Most of the 4 million t not so used went to 4 km^2 of disused clay pits at Peterborough and Gale Common, Yorkshire, where a 50-m-high mound has been landscaped as part of the reclamation of an area affected by waterlogging following mining subsidence.

In 1969, the electricity industry in the United States produced over 30 million t of PFA from burning bituminous coal and lignite – only about 20% of it finding any use (Berry and Horton 1974). The annual quantity to be dumped is now probably in excess of 32×10^6 t. The estimated annual ash production by the Liddell power station in New South Wales is 0.9 million t. The newer Bayswater power station is likely to produce 45 million t of ash during its lifetime (Day 1986), some of which can be used to fill open-cast coal workings.

Reclamation of Land from the Sea Although the deposition of urban and industrial waste is a direct, people-made sedimentation process, much sedimentation occurs by deliberate or accidental modification of natural systems. Reclamation of land from the sea is probably the most deliberate modification (Table 13-6). Areas of salt marsh usually are enclosed by banks, which are often built of material dragged from the marsh. The banks not only serve to trap fine sediment within

Table 13-6 *Land reclamation from the sea*

Country	Locality	Area (km^2)	Dates	Sources
Europe				
Northwest Europe	Overall figure	5,900	1200–1967	Smith 1967
Netherlands	Total	6,925	1200–2000	
	Zuider Zee	2,250	1930–1975	Knights 1979
	Waddensee	1,600	Since thirteenth century	"
Germany	Ems, Weser, Elbe estuaries and Schleswig-Holstein	120	Since 1900	Cole and Knights 1979
United Kingdom	Wash	310	Since eleventh century	Cole and Knights 1979
	Romney Marsh	200	Since first century	Coates 1985
France	Loire estuary, Brittany	370	Since sixteenth century	Musset 1958
Italy	Maremma	630	Since 1951	Houston 1964
Spain	Guadalquivir delta	1,362	Since 1948	Houston 1964
Asia				
China	Yangtse delta (east Shanghai)	240	721–1936	Cressey 1936
	Chongming Island	266	Since 1949	Ren et al. 1985
America				
United States	Sacramento – San Joaquin delta, California	600	Since mid-nineteenth century	Cole and Knights 1979
	Florida coastal swamps and estuaries	240	Since European settlement	Encyclopaedia Britannica

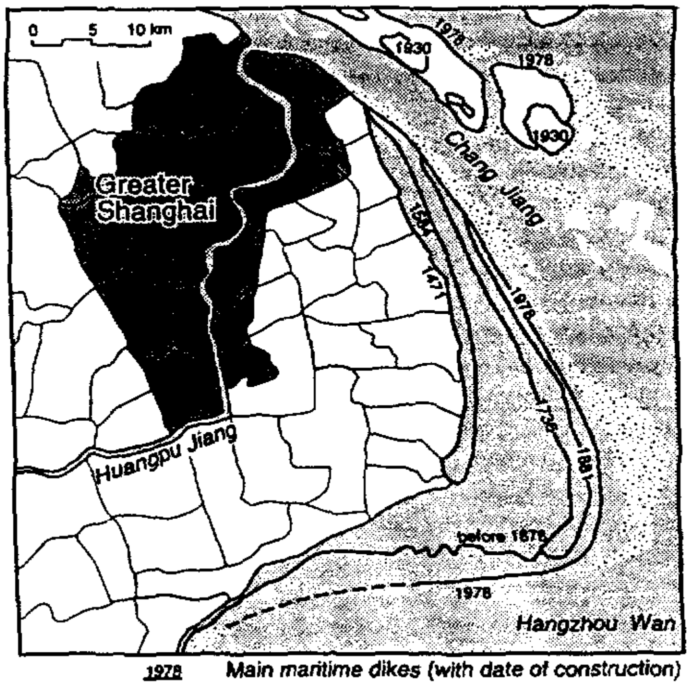

Figure 13.7 Land reclamation in the Chang Jiang (Yangtse River) estuary. (Early data after Cressey 1936.)

their confines, but also may lead to accelerated accretion on their seaward side, creating more reclaimable land, but possibly also leading to interference with drainage or shipping channels (Kestner 1979).

Construction of sea dikes in the Yangtse delta from A.D. 721 led to the growth of the foreshore east of Yangtse cape 9.5 km out to sea up to 1878 (Cressey 1936). By encouraging artificial sedimentation and by moving large quantities of material to construct dikes, some 240 km^2 have been reclaimed from the sea between the mouth of the Huang Po River and Hangchow Bay (Fig. 13.7). The famous Fangong embankment, built between A.D. 960 and A.D. 1279 for coastal protection, is now 50 to 60 km from the sea. Chinese reclamation works with nature, encouraging and directing natural sedimentation processes. The 1,083-km^2 Chongming Island in the Yangtse estuary developed as a shoal in the sixteenth century, but since 1949 some 266 km^2 have been added to it by land reclamation (Ren et al. 1985).

In prehistoric times, the Dutch or their Flemish forefathers began building mounds known as terpen, on which to place their dwellings. Some 1,500 terpen, 0.01 to 0.1 km^2 in area, can still be recognized in the Netherlands, with others in Flanders (Smith 1967). When these terpen were linked together by dikes, the possibility of permanently excluding the sea arose. However, the medieval peat diggings in the coastal swamps, as in the Norfolk marshes in England (now occupied by the Broads), and the marshes of the Loire estuary in France, merely served to increase the waterlogged areas. Most of the reclamation of these areas began in the seventeenth century, and since then, 5,090 km^2 in the Netherlands (IDG 1979) and some 370 km^2 in Brittany (Musset 1958) have been converted to agricultural land.

Gradual reclamation for urban expansion proceeds even in difficult environments such as Hong Kong (Fig. 13.6). Dredging of the sea bed for fill material often returns material deposited under past climatic conditions to the land. Care has to be taken that such operations do not lead to coastal erosion elsewhere.

Soil Conservation Efforts to impede or to draw benefit from sediment transfer processes extend back to the early history of agriculture around the Mediterranean. In the northern Negev desert, where annual rainfall averages 75 mm to 100 mm, sedentary agriculture was made possible by ingenious water-harvesting techniques. Runoff collected from the rocky upper parts of the hillslopes was directed into cultivated fields that occupied the valley floors. Soil erosion on the steep slopes was beneficial to this system because it encouraged rapid runoff into the colluvium of the valley floor and also helped to sustain the supply of sediment and nutrients to the cultivated area (De Ploey and Yair 1985; Yair 1983). Roman agriculture in North Africa, especially Tripolitania and Cyrenaica, was similarly dependent on managing water and trapping sediment in valley floors. Low dams built across valley floors impeded sediment transfer and helped to sustain the high productivity of olives and other crops required by the colonial administration.

Terracing of steep slopes has long been used to reduce erosion and increase crop production on steep slopes in environments from the semiarid to the humid tropical (Sheng 1977). Experiments at the Suide Soil and Water Conservation Experimental Station of the Huang Ho Conservatory Commission suggest that beach terracing can reduce runoff by 90% to 100% (Jiang et al. 1981). By a series of soil-conservation measures including afforestation, check dams, and terracing, 1,480 million t of sediment were retained in the 30,217-km^2 Wuding Valley in the loess plateau of northern Shaanxi in a 22-year period – equivalent to an annual retention of 2,226 t/km^2. Deliberate control of sedimentation in this highly erodible area tops 30% to 40% of the annual sediment load of almost 7000 t/km^2. Such figures, admittedly from one demonstration area, indicate the way in which artificial sedimentation can alter fluvial sediment yields.

Many areas of the United States and Australia had periods of severe soil erosion as forests were converted to agricultural land in the eighteenth and nineteenth centuries (Davis 1975). These relatively high erosion rates were followed by soil-conservation measures and better practices, which led to falls in sediment transfer, as shown in the records for the Burrinjuck Reservoir, Australia; Coon Creek, Wisconsin; and the Maryland Piedmont (Fig. 4, records 1, 2 and 3, respectively). Coon Creek was one of the first demonstration areas for the U.S. Soil Conservation Service, and the record indicates the success of the work undertaken.

Reservoir Sedimentation Not all artificial sedimentation is beneficial. The trapping of sediment in reservoirs is usually an inevitable, but unwanted, byproduct of water-storage schemes. Almost 2,000 million t of sediment accumulate each year in the reservoirs of the United States (Zachar 1982). If a reservoir is poorly sited in an area of high-sediment yields, its life may be short – restricted to ten years or so. However, many well-planned and well-sited reservoirs will take more than 1,000 years to fill.

In the past 100 years, some 135 weirs and dams were built in New South Wales. Of these, 94 were small-town water-supply reservoirs, 15 of which have sedimentation problems with capacities reduced from 25% to 100% (Morse and Outhet 1986). Overall, sedimentation of town water-supply reservoirs in New South Wales represents a cost of $A3.7 million per year. Sedimentation of reservoirs in the United States costs about U.S. $50 million a year in lost capacity in 1960. Similar problems with town water supplies occur in many areas. Lake Decatur in Illinois (Fig. 13.4, record 4) lost 26.2% of its storage capacity by sedimentation between its completion (in 1922) and 1946. Most of the incoming sediment came from sheet erosion, primarily from corn and soybean fields with slopes of 2% to 15% (Brown, Stall, and Delurk 1947). Generally, the smaller the reservoir, the faster the rate of silting and the shorter its serviceable life.

The larger, irrigation reservoirs of southeastern Australia are filling at a far slower rate, most of the sediment removed in the upper parts of their catchments being trapped within the catchment on footslopes and alluvial fans or in swamps and floodplains (Wasson et al. 1984). In semiarid areas, reservoir sedimentation may be more rapid. In Algeria, some large reservoirs became choked with sediments after 20 years, whereas others had a serviceable lives of 50 years (Zachar 1982). The Shah-Banou Farah reservoir in northern Iran, opened in 1961, lost 2.4% of its capacity annually, and the Imagi Reservoir in Kenya had its storage area reduced by 0.8% each year (Table 13-7). In the wetter area of northern Thailand, the large Bhumipol reservoir initially lost 1.5% of its capacity annually, but the rate subsequently slowed, so that useful life of the reservoir may be 600 years, compared with only another 15 years for the Kisongo Dam in Tanzania. Infilling rates in these tropical areas are four to twenty times those in temperate areas of moderate or low relief in the United States or Britain (Table 13-7). Even in England, moorland reservoirs in Northumberland and Yorkshire receive ten times the sediment yield of the Cropston Reservoir in the Midlands.

Reservoir sedimentation may be reduced, releasing the sediment from reservoirs to increase soil fertility, improve soil properties, and convert barren lands to farmland. In China, some reservoirs are operated to store water when inflow is clear, but to discharge sediment-laden water, especially in the Huang He catchment during the months of July and August (Chang et al. 1977). In this way the rate of sediment accumulation was reduced from 10.75 million t each year from 1959 to 1961, to 2 million t each year from 1962 to 1973.

People-Modified Erosion Processes

River Erosion; Sediment Yield The magnitude of erosion by rainfall and running water is difficult to express in a meaningful manner. Considerable errors may arise if records are short or if inappropriate estimation procedures are used (Walling 1977; 1979). Most measures express erosion as a volume, or weight, of material removed per unit area, and the measurements from which they are derived may be based on a small experimental plot, a hillslope, or a small catchment at a major river basin. Whatever the area supplying the sediment to a collection point, however, the volume measured represents the *net* result of all the processes that have been going on upstream. The measures do not indicate the sources of the sediment, the total volume of material detached, or the amount deposited between source areas and measurement point. On rivers, the sediment passing a measurement station may not reflect present-day erosion at all, but will be derived from erosion of river banks that may contain material deposited on the valley floor during some past phase of a different climate or during a phase of brutal land clearance, such as the removal of the forests by pioneer European settlers in North America or Australia (Douglas 1981).

Some data to indicate the scale of modification of erosion rates by people over the past 300 years are available, especially from areas in which forests have been removed (Table 13-8). Much of the extra erosion caused by human activity comes from specific localities such as forest roads, cultivated fields, construction sites, and spoil banks (Table 13-9). Llyn Peris, a lake of glacial origin in Snowdonia, Wales, received sediment at a rate of less than 5 t/km^2y^{-1} from its catchment prior to 1820. During the nineteenth century, sediment transfer increased mainly due to slate quarrying immediately adjacent

Table 13-7 *Reservoir filling rates*

Reservoir	Catchment area (km^2)	Sediment inflow ($t\,km^2/y^{-1}$)	Source
Shah-Banou Farah, northern Iran		1,900	Khodjeini and Mohammed 1973
Kisongo, Tanzania 1960–69	9.3	1,115	Murray-Rust 1972
" " 1970–71		1,600	" "
Imagi, Kenya		1,505	Christiansson 1979
Roma catchment, Lesotho	0.5	810	Chakela 1980
Bhumipol, Thailand	26,400	1,250	Chitchob and Cowley 1973
Lake Decatur, Illinois, United States	2,346	112	Brown, Stall, and DeTurk 1947
Catcleugh, Northumberland, United Kingdom		285	Douglas 1970
Strines, Yorkshire, United Kingdom		317	"
Cropston, Leicestershire, United Kingdom		30	"

Table 13-8 *Increases in sediment yield due to human activity*

Situation	Magnitude of increase	Source
In large rivers, generally	3.5 times	Dedkov and Mozzherin 1984
In small rivers, generally	8	" "
Forest clearance, Cameron Highlands, Malaysia	5	Shallow 1956
From erosion of forest roads, Idaho	200–500	Megahan 1975
Forest clearance, South Island, New Zealand	up to 100	Whitehouse 1983
Coon Creek, Wisconsin 1870–1930	10	Trimble and Lund 1982
Cultivation on forest land, Java	2	Douglas 1981
Trinidad	9	"
Ivory Coast	18	"
Tanzania	5	"
Urbanization in rainforest area, Malaysia	20	"

to the lake. In the twentieth century, rates increased to 20 t/km^2y^{-1} in the 1920s and over 50 t/km^2y^{-1} in the 1960s due to a combination of overgrazing, trampling, and construction work (Petts and Foster 1985). In Llangorse Lake (Fig. 13.4, record 9) and also in Wales, agriculture had affected sediment transfer for 2,650 years prior to 1830, but thereafter more marginal hill land was put into cultivation to supply the expanding industrial towns and cities of Britain, causing a fourfold increase in sediment input. Historical records and lake-sediment studies reveal a similar story of agricultural intensification affecting Lake Torestorpso in southern Sweden, sediment transfer reaching a peak as plowed-land expansion coincided with the historically highest sheep population in the catchment area at about 1850 (Petts and Foster 1985).

Historical records such as these show that the pattern and volume of sediment transfer vary from locality to locality. If maximum pressure on the land coincides with an exceptional extreme climatic event, then soil loss may be severe. If the pressure is in a climatically relatively calm period, the sediment transfer may not be increased greatly. The records for the Texas rivers (Fig. 13.3) show generally low sediment yields from 1947 to 1957, but it is not clear whether these reflect rainfall and runoff conditions or the trapping of sediment in newly constructed reservoirs upstream. The difference between the yields of the Neches River and those of the Brazos and Colorado rivers in the 1930s indicates the wide spatial variability in one state and emphasizes the difficulty of making regional, let alone global, statements about the trend of people-modified sediment transfers over the past 300 years.

Table 13-9 *Examples of erosion rates influenced by human activity*

Environment	t/km^2y^{-1}
Cultivated land with slope over 5%	1,000–5,000
(exceptional values up to	25,000)
Long-overgrazed mountainous area, Argentine	2,560
Fire-affected chaparral rangeland, Arizona	8,308
Unreclaimed strip-mine spoil banks, Kentucky	10,425
Urban construction sites	1,614–22,640

Source: After Jansson 1982.

However, human activity also increases the frequency of mass movements, which in turn increase river-sediment loads. Two hundred years ago, forests covered more than 70% of the Liusha basin in western Sichuan, China, and mudflows occurred about once in 10 years in some 15 mudflow gullies. By 1968, the population had increased fivefold and the forest cover was reduced to 17% of the area, with mudflows now occurring several times a year in up to 42 mudflow-generating gullies (Du Ronghuan and C. Bifan 1985). Clearance of forests in the South Island of New Zealand increased landslide densities from 0.5–1 per km^2 to 12–30 per km^2 and slope denudation rates from 100 to 1,100–400 $m^3/km^2/y$ (Williams 1980).

Sediment supplied from the slopes does not always enter the river, and much entering the river is stored in the floodplain and valley floor. The net output to the ocean may be only a small part of the total sediment transfer within a drainage basin. Of 0.02 km^3 of material eroded since 1700 off the upland soils of a 155-km^2 drainage basin in the Maryland Piedmont in the United States, 34% was removed by the river, 14% has been stored in the floodplains of the basin, and over half – 52% – has been held in colluvium and sheetwash deposits and at the junctions of headwater tributaries (Costa 1975). In the driftless area of Wisconsin, the 1930s saw sediment accumulated in alluvial deposits at almost 3,000 $t/km^2/y$, but only 160 $t/km^2/y$ left the basin, 95% of the eroded soil being retained. Following soil conservation measures, the supply from the slopes is now less than the amount removed by rivers, the difference being made up by removal from valley deposition (Trimble 1983). Elsewhere, as indicated earlier, reservoirs trap sediment; further erosion may occur downstream of reservoirs and much material is deposited in coastal estuaries, salt marshes, mangrove swamps, and deltas (Meade 1982). During all these phases of removal, transportation, deposition, and remobilization, elements are removed from solid particles and are added to the total solute loads of streams. However, solute loads do not reflect merely erosion within the catchment area, but include atmospheric inputs, volcanic eruptions, and chemical elements added by human activity. Possibly 15% of the worldwide dissolved load is derived from the atmosphere, and 12% from human activity (Meybeck 1979), but the effects on particular rivers vary greatly. Some 85% of the dissolved load of the Rio Tete, an Amazon tributary 1,700 km inland from the Atlantic, is derived from the atmosphere (Gibbs 1970), whereas the bulk of the solutes in many urban streams is derived from pollutant discharges.

Both sediment and solute loads may be reduced by land and waste-water treatment. The efficiency of soil-conservation measures is well documented (Trimble 1983). The decrease in sediment yield to the Shimen Reservoir, Taiwan (Fig. 13.3) since 1963 is largely due to the construction of check dams upstream and erosion-control works on the steep, unstable shale and sandstone slopes of the typhoon-affected catchment area. Afforestation is not always as effective in reducing sediment yields, conversion of moorland pasture to pine forest in Britain actually leading to increased sediment discharges (Newson 1979). Construction of drainage ditches leads to increases in sediment yields from highly erodible soils beneath British pine plantations, as in the Macclesfield Forest (Fig. 13.4, record 8). Plowing of land prior to afforestation has led to tenfold increases in sediment transfer into some southern Scottish lakes (Fig. 13.4, record 5). Removal of pollutants from waste discharges may be only an alteration to the location and pathway of material transfers. For example, treatment of municipal sewage wastes may lead to discharge of clean water to rivers but have a residual sludge which has to be dumped, often into coastal waters.

Human Impact on the Chemical Elements Carried by Some Major Rivers If nineteenth-century estimates of fluvial solute loads are compared with modern calculations, the loads of some rivers, such as the Danube (Table 13-10), show pronounced increases, which may be a result of urban and industrial dicharges of chemical elements in waste waters. In other areas, the sodium chloride loads of rivers have increased as a result of the mobilization of salt through agricultural operations, as on the rivers Murray in Australia, Indus in Pakistan, and Colorado in the United States. The salt load of the River Murray increases from 0.14 million t/yr at Albury to 1.4 million t/yr at Morgan, South Australia, with at least 0.41 million t/yr of that increase being due to human activity. Chloride concentrations at Morgan have increased by an average of 1.4% per year since 1940 (Peck, Thomas, and Williamson 1983).

Industrial and urban activity have also increased major solute loads significantly. Mining effluent plays a major part in this process, with acid mine drainage affecting streams in many coal-mining areas, such as the Appalachians of the United States. However, one of the most marked increases has been in the chloride load of the Rhine (Table 13-11), largely due to waste discharge from potash mines (Van Haaren 1963). Meybeck (1979) attributes increases in major solute contents of rivers to urban and industrial activity, calculating that some 450 million t/yr of dissolved matter are carried to the oceans as a direct result of waste discharges.

Table 13-10 *Nineteenth- and twentieth-century estimates of fluvial solute loads*

River	Total load (million t/y) Russell 1898	Meybeck 1976
Danube	22.97	60.38
Nile	17.29	17.40
Mississippi	115.9	130.68
Rhone	8.45	18.24

Table 13-11 *Temporal changes in the solute loads of major rivers*

(a) *Mean Concentrations* (mg/l)

River	Ca		Na		K		Cl		SO_4	
	ca.1900	ca.1970	ca.1900	ca.1970	ca.1900	ca.1970	ca.1900	ca.1970	ca.1900	ca.1970
Mississippi	34	39	11	17	2.8	2.8	10.3	19.3	25.5	50.3
St. Lawrence	30	50	5.5	12.6	1.35	1.35	7.5	27.5	14	29.4
Rhine	50	100	5	120	5	8.5	20	133	35	96
Seine	74	97	7.3	39.7	2.2	6.9	7.5	4	21.8	75
Oder and Vistula	42	65	3.8	44	2.1	17.4	4.9	6.1	18.5	58

(b) *Increase in total land (million t/y) and increase in load (waste discharge) per inhabitant (kg/yr)*

River	Ca		Na		K		Cl		SO_4	
	Increase	Per capita	Increase	Per capita	Increase	Per capita	Increase	Per capita	Increase	Per capita
Mississippi	2.3	34	3.5	52	0	0	5.2	77	14.5	215
St. Lawrence	2.1	90	1.45	65	0	0	4.15	185	3.2	143
Rhine	3.5	86	8	200	0.24	6	5.5	137	4.15	103
Seine	0.15	10	0.25	16	0.04	2.5	0.27	18	0.42	28
Oder and Vistula	1.1	34	2.0	62	0.77	24	2.8	87	1.95	61

Source: After Meybeck 1979.

Some heavy metals, especially copper, molybdenum, bromine, antimony, lead, and zinc, occur in river waters in much greater quantities than would be expected from natural weathering and sediment and solute transfer processes (Martin and Meybeck 1979). Not all the increased abundance of these elements in rivers can be attributed to industrial activity, but at least some of it is. Many specific cases of heavy-metal pollution highlight the importance of these transfers. Sediments from the Elbe River in and upstream of the German port of Hamburg have concentrations of mercury that exceed natural background values by 8 to 85 times (Table 13-12). The scale of increases in the fluxes of heavy metals may be gauged from estimates that the amount of mercury carried to the oceans by rivers has increased by four times; that of cadmium released by mining compared to the natural flux, by thirty times; and that of lead in the open ocean, by three to five times (Ehrlich et al. 1977).

Wind erosion Natural movements of dust on a global scale reflect the transport of material out of the world's deserts into the oceans and across the continents. About 500 million t of wind-blown dust are lifted from the continental surfaces each year – primarily from the great deserts (McCauley et al. 1981). Falls of Saharan dust in the countries of northwest Europe occur about once every seven to eight years (Pitty 1968; Goudie 1978), while dust from the Chinese deserts regularly reaches Beijing (Liu et al. 1981) and is occasionally carried to northern Alaska (Rahn, Borys, and Shaw 1981).

On the other hand, transport of dust on a continental scale is often associated with the blowing of fine particles from cultivated fields. The blowing of soil from the plains of parts of Texas, New Mexico, Colorado, Oklahoma, and Kansas in the 1930s seriously damaged 28,000 km^2 in the heart of the affected zone (Lockeretz 1978). Although the terrible people- and climate-induced erosion of the 1930s Dust Bowl was never supposed to happen again, wind erosion remains a problem, albeit less severe, in this area. More land in the Great Plains was damaged annually by wind in the 1950s than in the 1930s, although the earlier dust storms were more spectacular. In February 1977, strong winds in the first winter storm to hit the drought-stricken high plains eroded plowed fields locally to depths exceeding 1 m, depositing the eroded material in locate sheets from several to more than 100 cm thick, extending several kilometers downward of the source areas and blowouts (McCauley et al. 1981). The dust was swept across the southern states out into the Atlantic, thereby adding to the sedimentary record of the ocean floors.

This people-enhanced wind erosion from cultivated fields often involved the remobilization of ancient aeolian deposits that had accumulated under previous climatic conditions. Many areas of Quaternary loess in mid- to high latitudes or of former desert dunes in lower latitudes become unstable when the vegetation is removed and cultivation commenced. Some areas, such as the Great Plains of the United States, had not become completely stable before European settlement. During 21 five-year droughts in the 748 years before 1950, windstorms carried dust from areas in which vegetation had died. However, clearance of vegetation and plowing aggravated the situation. Now wind erosion removes 907 million t of soil a year from the United States, mainly in exceptional storms, such as that of February 1977, which removed as much as 1,100 t/km^2 from parts of eastern Colorado (McCauley et al. 1981). Dust deposition rates vary greatly; in Tempe, Arizona, dust accumulates at a rate of 54 t/km^2 y^{-1} as a result of dust storms (haboobs) bring material mainly from cultivated, desert areas and dry stream courses within 50 to 200 km of Tempe, (Péwé et al. 1981). Harmattan dust is deposited at Kano, Nigeria at a rate of 99 t/km^2 y^{-1}, where it adds beneficial phosphorous and potassium to local soils (Wilke et al. 1984).

Remobilization of physical wind-blown material and loess is common in areas close to such sources, as in China and Iceland, but it is also significant in once-forested agricultural regions in Europe. In Britain, the danger of wind erosion when the surface soil is dry, particularly in flat areas with few windbreaks such as the Fens, is widely recognized by many farmers (Observer 1967). Accounts of such erosion in the vales of Pickering and York (Brade-Birks 1944; Briggs and France 1982; Radley and Simms 1967), parts of the West Midlands (Fullen 1985; Reed 1979), south Lancashire (Wilson and Cooke 1980), Nottinghamshire (Stamp 1948; Wilkinson, Broughton, and Parker-Sutton 1969), Lincolnshire (Robinson 1968), and the Fenland and Breckland areas of East Anglia (Brade-Birks 1944) point to four conditions favoring wind erosion: (1) the paucity of binding materials (clay or humus) in the surface soil; (2) the paucity of rain, with consequent drying of the surface soil; (3) level topographic surfaces devoid of windbreaks; and (4) wind of sufficient velocity (about 14 m/s in the Fens and 12 m/s in Shropshire) (Douglas 1970).

Blowing of soil occurs in many parts of continental Europe. The well-sorted sands of agricultural areas of Denmark and southern Sweden are particularly prone to wind erosion (Mattsson 1984; Moller 1985). Since 1539, Danish govern-

Table 13-12 *Heavy-metal concentrations in sediments from the Elbe River and its tributaries near Hamburg: enrichment in relation to background values*

Element	Background	Range of concentrations (mg/l) Minimum	Maximum	Range of enrichment of four highly polluted sites compared to background
Zinc	94	136	2,717	4.1–29
Copper	16	16	529	3.1–34
Chromium	59	5	369	1.0–6.3
Lead	30	33	110	3.1–37
Arsenic	10	8	183	1.1–19
Nickel	21	19	89	0.9–4.2
Cobalt	8	7.2	23.7	1.1–3.1
Calcium	0.4	0.3	19.4	4.5–56
Mercury	0.2	0.4	17.0	8.0–85

Source: After Lichtfuss and Brummer 1981.

ments have sought to curtail sand drift, but present farming practices, with large, carefully cultivated and rolled fields that are bare in spring, contribute to soil erosion (Moller 1986). Although the total area of the USSR potentially affected by wind erosion is unknown, about 35,000 km^2 of the Ukraine, approximately 20% of the arable and pasture land of that republic, are at risk from deflation (Silvestrov 1971). Dust storms that affected the southern and southwestern parts of European Russia in the spring of 1960 damaged 4,000 km^2 of newly sown crops. In eastern Georgia in 1953, deflation caused the loss of 1,450 km^2 of crops.

Wind erosion is not divorced from water erosion. Frequently, wind-blown deposits are degraded by raindrop splash and water runoff, whereas fluvial deposits, especially from floodwaters, may be deflated by wind. In the Kairouan area of Tunisia, the great floods of 1969 deposited material that has produced 200 km^2 of shifting dunes. Polymer soil stabilizers are needed to assist dune stabilization by planting vegetation (De Kesel and De Vleeschauwer 1981).

Coastal Erosion Coastal change is a spatially differentiated pattern of erosion and accretion. Land is lost in some places and gained in others. Some eroded sediment is transferred out to the sea floors, but other sediment is delivered to the coastlines by the discharge of rivers. For many stretches of coastline, a series of natural compartments with their own sediment budgets may be recognized. The southern Californian coast may be divided into four discrete sedimentation cells, each containing a complete cycle of littoral transport and sedimentation. Rivers are the principal sources of sediments for the cells, and the chief sinks are the series of submarine canyons, which bisect the continental shelf and intercept the sand as it moves southward along the coast (Komar 1983). Any discussion of coastal erosion ought to be in this sediment budget framework, examining the destination of the eroded sediment and the sources of replenishment. Beaches and cliffs offer somewhat different situations, but the erosion of both depends on wave action and may be drastically affected by storm surges. When Hurricane Frederic hit the sandy barrier Dauphin Island, Alabama in 1979, the shoreline retreated an average of about 25 m both on the Gulf and Sound sides, reducing the width of the island by about 10% (Nummedal 1983). On the north shore of Long Island, New York, a hurricane in 1944 cut back the cliff at Shoreham 12 m in one day (Sunamura 1983). A low cliff in East Anglia, England, was driven back more than 30 m overnight during the 1953 North Sea storm surge (King 1980).

The exposure and nature of coastlines affects their resistance to erosion (Table 13-12), but many coastal landforms reflect the delicate balance of their sediment budget. Reduction or augmentation of the sediment supply may lead to considerable changes in erosion or deposition. At Hallsands, south Devon, England, about 0.5 million m^3 of shingle were removed for building materials between 1897 and 1902 from the foreshore of a micaschist cliff. As a result, the whole beach was lowered by 3.6 m, and rapid cliff erosion followed, ruining the fishing village (Sunamura 1983). The dumping in 1963 of some 2.9 million m^3 of mud, sand and pebbles dredged from Oceanside Harbor, California, on beaches south of the San Luis Rey River led to severe erosion during storms. Waves lifted pebbles as much as 6 m in the air, throwing them against nearby buildings and using them to undermine the beach road (Kuhn and Shepard 1983). Harbor construction frequently disrupts coastal sediment budgets, often leading to accumulation of sand where it is unwanted and producing severe erosion of tourist beaches, which have to be replenished at great cost, as on the Belgian coast near Zeebrugge (Douglas 1971).

The exploitation of the coastline and nearshore environment as a resource, for transportation, aggregates, industry, residential development, and recreation, has profound impacts on aquatic and wetland ecosystems. Coastal sediment budgets are modified drastically by these human activities, with severe off-site impacts. Delta progradation may be accelerated by land reclamation, as in the Wanqingsha and Denglongsha areas of the Zhujiang (Pearl River) deltas of China, which are now advancing at 63.6 and 121.7 m/y, respectively, compared with an average rate of around 15 m/y in previous centuries (Huang 1987). Reduction of sediment yield, on the other hand, may cause drastic coastal erosion. While Holeman (1968) estimated the sediment discharge of the Nile to be 111 million t/y, Milliam and Meade (1983) argued that since the closing of the Aswan High Dam, the Nile transports virtually no sediment to the sea (Table 13-2). The 245-km-long Nile Delta coastline, no longer augmented by Nile sediment, is now subject to aggravated erosion (Table 13-13), some 1.8 km^2/y being lost from the Damiette and Rosette promontories (Paskoff 1981). Erosion has been a problem in this area for a long time, but it is now worsened by subsidence due to groundwater abstraction and to lack of replenishment. Modification of the transfer of water to benefit irrigation and power generation has led to an unwanted change in the sediment budget, with deposition in the reservoir and erosion of the delta.

Coastal protection works may actually aggravate erosion, as near Bournemouth, England. Harbor works often produce deposition on one side and erosion on the other. Breakwaters at Lagos Harbor, Victoria Island, Nigeria have accelerated the natural erosion rate from a tolerable 2–4 m/y to a disastrous and worrying 20 m/y (Chidi 1987). So great is the variation in these effects from place to place, and at any given site, through time as a result of extreme events, that it is difficult to estimate the net global effect of coastal changes caused directly or indirectly by people. However, they are most severe where coastlines are most modified, and such places are usually where coastal population densities are greatest. Sand replenishment to make up for the losses caused by human action is a common remedy from Lagos to Zeebrugge to Santa Barbara. It is a sediment transfer that will have to be repeated again and again, however, as the beaches are pounded relentlessly by the waves, which drag away material to be carried down the coast by longshore drift.

Conclusion

When the volumes of the deliberate, people-made transfers of material are compared with some of the people-

Table 13-13 *Rates of coastal erosion*

Catergory or locality	Long-term rate (m/y)	Maximum rate in extreme event	Source
Global orders of magnitude			
Granitic rocks	0.001		Sunamura 1983
Limestone	0.001–0.01		"
Flysch and shale	0.01		
Chalk and Tertiary sedimentary rocks	0.1–1		"
Quaternary deposits	1–10	12	"
Unconsolidated volcanic ejecta	10	140	"
Quaternary deposits			
Wolin Island, Poland	0.81		Kostrzewski and Zwolinski 1987
Holderness, England			
Volcanic islands			
Krakatoa, Indonesia	33		Sunamura 1987
Surtsey, Iceland	25–38		
Nishinoshima, Japan	80		
Barrier islands			
Chandleur islands, Louisiana	2–12	30	Kahn and Dolan 1985
Mid-Atlantic coast, U.S.			Dolan and Lins 1987
General U.S. rates			
Atlantic coast	0.8	(loss) 24.6 to 25.5 (gain)	Dolan, Hayden, and May 1983
Gulf Coast	1.8	(loss) 8.8 to 15.3 (gain)	
Pacific coast	0.0	(loss) 5.0 to 10.0 (gain)	
Nile delta			
Rosette Point	60		Paskoff 1981
Damiette Point	30–40		"

affected fluvial sediment loads (Table 13-14), the similarities of the orders of magnitude of both deliberate and inadvertent transfers is apparent. Clearly, both sets of figures fail to tell the whole story. Much sediment eroded on hillslopes merely accumulates at the base of the slopes or in valley floors and is not evacuated by major rivers. In some places, the volume of such locally moved material may be several times the net load exported by major rivers. Equally, the figures for mineral production do not take into account the overburden, waste products, and mining residues involved in the mineral-extraction process.

Comparison of the historic trends of growth in resource exploitation, as indicated by cement, iron ore, solid fuel, and roundwood production (Fig. 13.5) with historic trends in sediment transfer (Figs. 13.3 and 13.4) reveals an exponential growth in the deliberate transfer of materials, with threefold to tenfold increases since the 1920s, but only a slight increase in the sediment yields of some rivers. At present the deliberate and accidental transfer of materials by people's activities is of approximately the same order of magnitude (Table 13-15). The deliberate transfer accelerates the accidental transfer. Both transfers are episodic, but the deliberate transfer is increasing more rapidly. Long recognized as a major geological agent, human action will soon account for most of the transfer of earth-surface materials. The scale of this human action is illustrated by the area of the United States disturbed for bituminous coal mining from 1930 to 1971, a total of 5,880 km^2, or approximately twice the area of the Grand Duchy of Luxembourg. With growing world population, the loss of land to agricultural uses for fuel, for mineral and construction-material extraction, and for residential development may soon become a factor limiting the

Table 13-14 *Comparison of mineral production and fluvial sediment yields*

Process	Million tons per year
World lime production, 1982	112
Mean annual sediment yield of the Mackenzie River	100
World phosphate rock production, 1982	122
Mean annual sediment yield of the Red River	130
World salt production, 1982	169
Mean annual sediment yield of the Mekong River	160
World iron-ore production, 1982	795
Mean annual sediment yield of the Amazon River	900
World bituminous coal production, 1982	2,718
Mean annual sediment yield of the Ganges, Brahmaputra, and Yangtse rivers	2,750

Sources: Mineral production: Bureau of Mines Staff 1984; and sediment yields: Milliman and Meade 1983.

Table 13-15 *Global sediment transfer estimates*

	Date	Million tons per year	Source
Transfers by natural processes			
Average denudation rate for the ice-free land surface	1983	33,127*	Saunders and Young 1983
Loss of topsoil	1984	25,700	Brown 1984
River sediment yield to the oceans (a)	1968	24,000	Judson 1968b
(b)	1968	18,300	Holeman 1968
(c)	1983	13,505	Milliman and Meade 1983
Yield of dissolved matter to the oceans	1976	3,250	Meybeck 1976
People-made transfers			
Total mineral production			
(a) nonmetallic minerals	1982	6,339†	Bureau of Mines Staff, 1984
(b) metals	1982	926	" " " "
(c) oil and natural gas	1984	4,255	World Resources Institute 1986
U.S. production of nonmetallic construction materials	1972	1,875‡	Ehrlich et al. 1977
Total cereal production	1984	1,780	World Resources Institute 1986
Total grain exports	1984	153	" " " "
Total carbon dioxide emissions from anthropogenic sources	1984	153	" " " "
Total fluvial solute load from anthropogenic sources	1979	450	Meybeck 1979

* Based on the authors' statement that average denudation rates for all climates are 10–1,000 m^3/km^2y^{-1}.

† Does not include the amount of overburden and mine waste involved in mineral production, and neglects sand and gravel and similar, but includes 892 million t of cement.

‡ Includes approximately 100×10^6 t of cement production.

choice of energy-generation techniques. At present the deliberate transfers reflect economic and political conditions, the accidental, more closely climatic extremes. However downturns in economic activity lead to stress in land management and aggravation of the work of natural processes. In times of recession, environmental issues take a back seat.

Some areas suffer a relatively short period of sediment removal and then are stabilized by careful management, as the U.S. Soil Conservation Service demonstration area at Coon Creek, Wisconsin has shown (Trimble 1983). In other circumstances, a change in land use is the cause of temporary instability, as during land development for urban construction (Douglas 1985; Wolman 1967). Nevertheless, the overwhelming impression is that transfer of materials is changing the face of the earth at a faster rate than that at which the world's population is growing.

Sediment transfer may be deliberate or the accidental by-product of some other form of resource use or land management. Many successful techniques to minimize the detrimental effects of erosion and sedimentation are available but often all that the technology can do is to transfer the problem to another location. If waste cannot be disposed of on land, it may be dumped at sea. Retention of sediment upstream may lead to further erosion downstream. Further transformation of the global geochemical budget is inevitable, but many of the present problems of erosion and sedimentation could be reduced by careful land management and better choice of alternative sources of energy and strategies for water use.

References

Adey, E. A., and H. M. Cook. 1964. Suspended-sediment load of Texas streams. Compilation Report October 1959–September 1961. *Texas Water Commission Bulletin 6410*.

Aniya, M. 1985. Contemporary erosion rate by landsliding in Amahata River basin, Japan. *Zeitschrift fur Geomorphologie NF 29*: 301–14.

Basile, G. F., and W. Dragoni. 1987. Geomorphology and erosion of the southern Chiana Valley, Italy. In *International Geomorphology 1986*. Part I, ed. V. Gardiner, 843–52. Chichester: Wiley.

Battarbee, R. W., P. G. Appelby, K. Odell, and R. J. Flower. 1985. ^{210}Pb dating of Scottish lake sediments, afforestation and accelerated soil erosion. *Earth Surface Processes and Landforms 10*: 137–42.

Berry, B. J. L., and F. E. Horton. 1974. *Urban Environmental Management: Planning for Pollution Control*. Englewood Cliffs, NJ: Prentice-Hall.

Brade-Birks, S. G. 1944. *Good Soil*. London: English Universities Press.

Briggs, D. J., and J. France. 1982. Mapping soil erosion by wind for regional planning. *Journal of Environmental Management 15*: 159–68.

Brown, C. B., J. B. Stall, and E. E. DeTurk. 1947. The causes and effects of sedimentation in Lake Decatur. *Illinois State Water Survey Bulletin 37*.

Brown, L. R. 1984. The global loss of topsoil. *Journal of Soil and Water Conservation 39* (3): 162–65.

Bureau of Mines Staff. 1984. *Minerals Yearbook 1982*. Washington, D.C.: U.S. Department of the Interior.

Chakela, Q. K. 1980. Reservoir sedimentation within Roma Valley and Maliele catchments in Lesotho. *Geografiska Annaler 62A*: 157–69.

Chang Hao, Hsia Mai-Ting, Chen Shih-Chi, Li Chen-Wu, Hsia Heng-Pin, Chiang Nai-Sen, and Lin Pin-Wen 1977. Regulation of sediments in some medium-sized and small reservoirs on the heavily silt-laden streams in China. *Scientia Sinica 20*: 89–105.

Chidi, I. A. 1987. Harbor-development-related erosion at Victoria Island, Lagos. In *International Geomorphology 1986*, Part I, ed. V. Gardiner, 165–81. Chichester: Wiley.

Chinen, T., and H. Kadomura. 1986. Posteruption sediment budget of a small catchment on Mt. Usu, Hokkaido. *Zeitschrift fur Geomorphologie* NF Suppl-Bd 60: 217–31.

Chitchob, S., and J. E. Cowley. 1973. Bhumibol reservoir-sediment status after eight years of operation. *International Association for Hydraulic Research International Symposium on River Bangkok 1*: 35–45.

Ciccacci, S., P. Fredi, E. Lupia Palmieri, and F. Pugliese. 1981. Contributo dell'analisi geomorfica quantitativa alla valutazione dell'entita dell'erosione nai bacini fluviali. *Bolletino Societa Geologica Italiana 99*: 455–516.

Coates, D. R. 1985. *Geology and Society*. New York: Prentice-Hall.

Cole, G., and B. Knights. 1979. An introduction to estuarine and coastal land reclamation and waste storage. In *Estuarine and Coastal Land Reclamation and Water Storage*, ed. B. Knights and A. J. Phillips, 3–20. Farmborough: Saxon House.

Cook, H. M. 1967. Suspended-sediment load of Texas streams. Compilation Report October 1959–September 1961. *Texas Water Development Board Report 45*.

———. 1970. Suspended-sediment load of Texas streams. Compilation Report October 1963–September 1965. *Texas Water Development Board Report 106*.

Costa, J. E. 1975. Effects of agriculture on erosion and sedimentation in the Piedmont province, Maryland. *Geological Society of America Bulletin 86*: 1281–86.

Coughlan, J. 1979. Aspects for reclamation in Southampton Water. In *Estuarine and Coastal Land Reclamation and Water Storage*, ed. B. Knights and A. J. Phillips, 99–124. Farnborough: Saxon House.

Cressey, G. B. 1936. The Fengshien landscape: A fragment of the Yangtse Delta! *Geographical Review 26*: 396–413.

Davis, M. B. 1975. Erosion rates and land use history in southern Michigan. *Environmental Conservation 3*: 139–48.

Day, D. G. 1986. *Water and Coal*. Canberra: Center for Resource and Environmental Studies, Australian National University.

Dearing, J. A., and I. D. L. Foster. 1987. Limnic sediments used to reconstruct sediment yields and sources in the English midlands since 1765. In *International Geomorphology 1986*. Part I, ed. V. Gardiner, 853–68. Chichester: Wiley.

Dedkov, A. P., and V. I. Mozzherin. 1984. *Erosion and Sediment Yield on the Earth*. Kazan: Kazan University Press. (In Russian.)

De Kesel, M., and D. De Vleeschauwer. 1981. Sand dune fixation in Tunisia by means of polyurea polyalkylene oxide (Uresol). In *Tropical Agricultural Hydrology*, ed. R. Lal and E. W. Russell, 273–81. Chichester: Wiley.

De Ploey, J., and A. Yair. 1985. Promoted erosion and controlled colluviation: A proposal concerning land management and landscape evolution. *Catena 12*: 105–110.

Dimbleby, G. W. 1974. The legacy of prehistoric man. In *Conservation in Practice*, ed. A. Warren and F. B. Goldsmith, 279–89. London: Wiley.

Dolan, R., B. Hayden, and S. May. 1983. Erosion of the U.S. shorelines. In *CRC Handbook of Coastal Processes and Erosion*, ed. P. D. Komar, 285–99. Boca Raton, FL: CRC Press.

Dolan, R., and H. Lins. 1987. Beaches and barrier islands. *Scientific American 257* (1): 52–59.

Douglas, I. 1967. Man, vegetation, and the sediment yields of rivers. *Nature 215*: 925–28.

———. 1970. Sediment yields from forested and agricultural lands. In *The Role of Water in Agriculture*, ed. J. A. Taylor, 57–88. Oxford: Pergamon.

———. 1971. Dynamic equilibrium in applied geomorphology – two case studies. *Earth Science Journal 5*: 29–35.

———. 1981. Soil conservation measures in river basin planning. In *River Basin Planning: Theory and Practice*, ed. S. K. Saha and C. J. Barrow, 49–73. Chichester: Wiley.

———. 1985. Urban sedimentology. *Progress in Physical Geography 9*: 255–80.

Du Ronghuan, and C. Bifan. 1985. Distribution of mudflows and landslides and examples against them in China.

Ehrlich, P. R., A. H. Ehrlich, and J. P. Holdren. 1977. *Ecoscience: Population, Resources, Environment*. San Francisco: W.H. Freeman.

FAO. 1978. The state of natural resources and the human environment for food and agriculture. *The State of Food and Agriculture 1977*. FAO Agriculture Series 8, 3-1-3-65.

Foster, I. D. L., J. A. Dearing, A. Simpson, A. D. Carter, and P. G. Appleby. 1985. Lake catchment based studies of erosion and denudation in the Merevale catchment, Warwickshire. *Earth Surface Processes and Landforms 10*: 45–68.

Fullen, M. A. 1985. Wind erosion of arable soils in east Shropshire (England) during spring 1983. *Catena 12*: 111–20.

Gibbs, R. J. 1970. Mechanisms controlling world water chemistry. *Science 170*: 1088–90.

Goudie, A. S. 1978. Dust storms and their geomorphological implications. *Journal of Arid Environments 2*: 105–12.

Holeman, J. N. 1968. Sediment yield of major rivers of the world. *Water Resources Research 4*: 737–47.

Houston, J. M. 1964. *The Western Mediterranean World*. London: Longman.

Huang Zhenguo, Li Pingri, Zhang Zhonqying, and Li Konghong. 1987. The geomorphological evolution of the Zhujiang delta. In *International Geomorphology 1986*. Part I, ed. V. Gardiner, 989–97. Chichester: Wiley.

IDG. 1979. Information and Documentation Centre for the Geography of the Netherlands. *Compact Geography of the Netherlands*. Utrecht: IDG.

Jansson, M. B. 1982. *Land Erosion by Water in Different Climates* (UNGI Rapport No. 57). Uppsala: Department of Physical Geography, Uppsala University.

Jiang Dequi, Qi Leidi, and Tan Jieshang. 1981. Soil erosion and conservation in the Wuding River Valley, China. In *Soil Conservation: Problems and Prospects*, ed. R. P. C. Morgan, 461–79. Chichester: Wiley.

Jones, R., K. Benson-Evans, and F. M. Chambers. 1985. Human influence on sedimentation in Llangorse Lake, Wales. *Earth Surface Processes and Landforms 10*: 227–36.

Judson 1968a. Erosion rates near Rome, Italy. *Science 160*: 1444–46.

———. 1968b. Erosion of the land. *American Scientist 56*: 356–71.

Kahn, J. H., and R. Dolan. 1985. Longhsore bars and shoreline erosion along the Chandeleur Islands, Louisiana. *Zeitschrift fur Geomorphologie NF 29*: 89–97.

Kershaw, A. P. 1976. A late Pleistocene and Holocene pollen diagram from Lynch's Crater, north eastern Queensland, Australia. *New Phytologist 77*: 469–98.

Kestner, F. J. T. 1979. Loose boundary hydraulics and land reclamation. In *Estuarine and Coastal Land Reclamation and Water Storage*, ed. B. Knights and A.J. Phillips, 23–47. Farnborough: Saxon House.

Khodjeini, V., and A. Mohammed. 1973. Etude de l'engravement et de l'envasement de la retenue du barrage de Shah-Banou Farah. *International Association for Hydraulic Research International Symposium on River Mechanics Bangkok 1*: 23–34.

Kidwell, C. S. 1985. Science and ethnoscience: Native American world views as a factor in the development of native technologies. In *Environmental History: Current Issues in Comparative Perspective*, ed. K. E. Bailes, 277–87. Lanham and London: University Press of America.

King, C. A. M. 1980. *Physical Geography*. Oxford: Blackwell.

Kivell, P. T. 1984. Environmental management through derelict land reclamation. In *Environmental Management: British and Hungarian Case Studies* (Studies in Geography in Hungary 16), ed. P. A. Compton and M. Pecsi, 75–90. Budapest: Akademiai Kiado.

Knighton, A. D. 1984. *Fluvial Forms and Processes*. London: Edward Arnold.

Knights, B. 1979. Reclamation in the Netherlands. In *Estuarine and Coastal Land Reclamation and Water Storage*, ed. B. Knights and A. J. Phillips, 209–33. Farnborough: Saxon House.

Komar, P. D. 1983. Beach processes and erosion – An introduction. In *CRC Handbook of Coastal Processes and Erosion*, ed. P. D. Komar, 1–20. Boca Raton, FL: CRC Press.

Kostrzewski, A., and Z. Zwolinski, 1987. Operation and morphologic effects of present-day morphogenetic processes modeling the cliffed coast of Wolin Island, NW Poland. In *International Geomorphology 1986*. Part I, ed. V. Gardiner, 1231–52. Chichester: Wiley.

Kuhn, G. G., and F. P. Shepard. 1983. Beach processes and sea cliff erosion in San Diego County, California. In *CRC Handbook of Coastal Processes and Erosion*, ed. P. D. Komar, 267–84. Boca Raton, FL: CRC Press.

Lichtfuss, R., and G. Brummer. 1981. Naturlicher Gehalt und anthropogene Anreicherung von Schwermetallen in den Sedimenten von Elbe, Eider, Trace, und Schwentine. *Catena 8*: 251–64.

Liu Tungsheng, Gu Xiongfei, An Zhisheng, and Fan Yongxiang. 1981. The dust fall in Beijing, China on April 18, 1980. *Geological Society of America Special Paper 186*, 149–57.

Lockeretz, W. 1978. The lessons of the dust bowl. *American Scientist 66*: 560–71.

Maloney, B. K. 1985. Man's impact on the rainforests of West Malaysia. *Journal of Biogeography 12*: 537–58.

Martin, J.-M., and M. Meybeck. 1979. Elemental mass-balance of material carried by major world rivers. *Marine Chemistry 7*: 173–206.

Matthews, W. V. G., and G. M. Kondolf. 1987. Changes in sediment storage over time in a coastal Californian river. *International Association of Hydrological Sciences Publication* 165: 413–14.

Mattsson, J. O. 1984. Erosionsprobleme i Svergie. I Vinderosionsproblem med sarskild hansyn till de skanska odlingsomradena. *Kungliga Soogs-och Lantbruksabademiens Tidskrift 123 (5–6)*: 371–81.

McCauley, J. F., C. S. Breed, M. J. Crolier, and D. J. Mackinson. 1981. The U.S. dust storm of February 1977, 123–47. *Geological Society of America Special Paper 186*.

Meade, R. H. 1982. Sources, sinks, and storage of river sediment in the Atlantic drainage of the United States. *Journal of Geology 90*: 235–52.

Megahan, W. F. 1975. Sedimentation in relation to logging activities in the mountains of central Idaho. In *Present and Prospective Technology for Predicting Sediment Yields and Sources*. ARS-S-40, 74–82. U.S. Department of Agriculture: Agricultural Research Service.

Meybeck, M. 1976. Total mineral dissolved transport by world major rivers. *Hydrological Sciences Bulletin 21*: 265–84.

———. 1979. Concentrations des eaux fluviales en elements majeurs et apports en solution aux oceans. *Revue de geologie dynamique et geographie physique 21*: 215–46.

Milliman, J. D., and R. H. Meade. 1983. World-wide delivery of river sediment to the ocean. *Journal of Geology 91*: 1–21.

Mirabel, J. 1974. Suspended-sediment load of Texas streams. Compilation Report October 1965–September 1971. *Texas Water Development Board Report 184*.

Moller, J. T. 1985. Soil and sand-drift in Denmark. *GeoSkrifter* 22.

———. 1986. Soil degradation in a north European region. In *Desertification in Europe*, ed. R. Fantechi and N. S. Margaris, 214–30. Dordrecht: Reidel.

Moore, P. D. 1975. Origin of blanket mires. *Nature 256*: 267–69.

Morse, R. J., and D. N. Outhet. 1986. Sediment management on a total catchment basis. *Journal of Soil Conservation New South Wales 42*: 11–14.

Murray-Rust, D. H. 1972. Soil erosion and reservoir sedimentation in a grazing area west of Arusha, northern Tanzania. *Geografiska Annaler* 54A: 325–43.

Musset, R. 1958. *La Bretagne*. Paris: Armand Colin.

Newson, M. D. 1979. The results of ten years' experimental study on Plynlimon, Mid-Wales, and their importance for the water industry. *Journal of the Institution of Water Engineers and Scientists 33*: 321–33.

Nummedal, D. 1983. Barrier islands. In *CRC Handbook of Coastal Processes and Erosion*, ed. P. D. Komar, 77–121. Boca Raton, FL: CRC Press,

Observer, The. 1967. Farmers' Dust Bowl fears. January 29, 1967.

Oldfield, F. 1977. Lakes and their drainage basins as units of sediment-based ecological study. *Progress in Physical Geography 1*: 460–501.

Paskoff, R. 1981. *L'erosion des cotes*. Paris: Presses Universitaires de France.

Peck, A. J., J. F., Thomas, and J. R. Williamson. 1983. *Salinity Issues: Effects of Man on Salinity in Australia* (Water 2000: Consultants Report 8). Canberra: Australian Government Publishing Service.

Petts, G., and I. Foster. 1985. *Rivers and Landscapes*. London: Arnold.

Pewe, T. L., E. A. Pewe, R. H. Pewe, A. Journaux, and R. M. Slatt. 1981. Desert dust: characteristics and rates of deposition in central Arizona, USA. *Geological Society of America Special Paper 186*: 169–90.

Pickup, G., R. J. Huggins, and R. F. Warner. 1981. Erosion and sediment yield in Fly River drainage basins, Papua New Guinea. *International Association Hydrological Sciences Publication 132*: 438–56.

Pitty, A. F. 1968. Particle size of the Saharan dust which fell in Britain in July 1968. *Nature 220*: 364–65.

Radley, J., and C. Simms. 1967. Wind erosion in East Yorkshire. *Nature 216*: 19–22.

Rahn, K. A., R. D. Borys, and G. E. Shaw. 1981. Asian desert dust over Alaska: anatomy of an Arctic haze episode. *Geological Society of America Special Paper 186*: 37–70.

Reed, A. H. 1979. Accelerated erosion of arable soils in the United Kingdom by rainfall and runoff. *Outlook on Agriculture 10*: 41–48.

Ren Mei'E, Yang Renzhang, and Bao Haosheng. 1985. *An Outline of China's Physical Geography*. Beijing: Foreign Language Press.

Robinson, D. N. 1968. Soil erosion by wind in Lincolnshire, March 1968. *East Midland Geographer 4*: 351–62.

Russell, I. C. 1898. *River Development As Illustrated by the Rivers of North America*. London: John Murray.

Saunders, I., and A. Young. 1983. Rates of surface processes on slopes, slope retreat, and denudation. *Earth Surface Processes and Landforms 8*: 473–501.

Shallow, P. G. D. 1956. River flow in the Cameron Highlands. *Hydroelectric Board Technical Memorandum 3*.

Sham Sani. 1984. Inadvertent atmospheric modifications through urbanization in the Kuala Lumpur area. In *Urbanization and Ecodevelopment with Special Reference to Kuala Lumpur* (Institut Pengajian Tinggi Prosiding Seminar PRO 2), ed. Yip Yat Hoong and Low Kwai Sim, 155–69. Kuala Lumpur: Universiti Malaya.

Sheng, T. C. 1977. Protection of cultivated slopes – terracing, steep slopes in humid regions. *FAO Conservation Guide 1*: 147–69.

Shimen Reservoir Authority. 1975. *Shimen Reservoir Catchment Management Work Report*. Taipei: The Authority. (In Chinese.)

Silvestrov, S. I. 1971. Efforts to combat the process of erosion and deflation of agricultural land. In *Natural Resources of the Soviet Union: Their Use and Renewal*, ed. I. P. Gerasimov, D. L. Armand, and K. M. Yefron, 161–83. San Francisco: Freeman.

Smith, C. T. 1967. *An Historical Geography of Western Europe before 1800*. London: Longman.

Stamp, L. D. 1948. *The Land of Britain: Its Use and Misuse*. London: Longman.

Stott, A. P. 1987. Medium-term effects of afforestation on sediment dynamics in a water-supply catchment: A mineral magnetic interpretation of reservoir deposits in the Macclesfield forest,

N. W. England. *Earth Surface Processes and Landforms 12*: 619–30.

Stout, I. M., L. C. Bentz, and H. W. Ingram (compilers). 1961. Silt load of Texas streams: a compilation report June 1889–September 1959. *Texas Board of Water Engineers Bulletin, 6108*.

Sunamura, T. 1983. Processes of sea cliff and platform erosion. In *CRC Handbook of Coastal Processes and Erosion*, ed. P. D. Komar, 233–65. Boca Raton, FL: CRC Press.

———. 1987. Coastal cliff erosion in Nii-jima Island, Japan: Present, past and future – an application of mathematical model. In *International Geomorphology 1986*. Part I, ed. V. Gardiner, 1199–1212. Chichester: Wiley.

Tallis, J. H. 1975. Tree remains in southern Pennine peats. *Nature 256*: 483–84.

Trimble, S. W. 1976. Sedimentation in Coon Creek Valley, Wisconsin. *Proceedings, Third Federal Interagency Sedimentation Conference*, 5: 100–112.

———. 1983. A sediment budget for Coon Creek Basin in the driftless area, Wisconsin, 1853–1977. *American Journal of Science 283*: 454–74.

Trimble, S. W., and S. W. Lund. 1982. Soil conservation in the Coon Creek Basin, Wisconsin. *Journal of Soil and Water Conservation 37*: 355–56.

Troeh, F. R., J. A. Hobbs, and R. L. Donahue. 1980. *Soil and Water Conservation for Productivity and Environmental Protection*. Englewood Cliffs, NJ: Prentice-Hall.

Tucker, R., and J. F. Richards. 1985. The global economy and forest clearance in the nineteenth century. In *Environmental History: Critical Issues in Comparative Perspective*, ed. K. E. Bailes, 577–85. Lanham and London: University Press of America.

United Nations. Department of Industrial, Economic, and Social Affairs. 1985. *World Population Prospects: Estimates and Projections as Assessed in 1982* (Population Studies No. 86). New York: United Nations.

Van Haaren, F. W. J. 1963. The River Rhine as a source of drinking water. *Proceedings of the Society for Water Treatment and Examination 12*: 177–96.

Vita-Finzi, C. 1969. *The Mediterranean Valleys: Geological Changes in Historical Times*. Cambridge: Cambridge University Press.

Walling, D. E. 1977. Assessing the accuracy of suspended-sediment rating curves for a small basin. *Water Resources Research 13*: 531–38.

———. 1979. Reliability considerations in the evaluation and analysis of river loads. *Zeitschrift fur Geomorphologie NF Supp-Bd 29*: 29–42.

Walling, D. E., and B. W. Webb. 1983. Patterns of sediment yield. In *Background to Palaeohydrology*, ed. K. J. Gregory, 69–100. Chichester: Wiley.

Wasson, R. J., R. L. Clark, I. R. Willett, J. Waters, B. L. Cambell, and D. N. Outhet. 1984. Erosion history from sedimentation in Burrinjuck Reservoir, N. S. W. *Proceedings Drainage Basin and Sedimentation Conference, University of Newcastle, Australia*.

Wasson, R. J., R. L. Clark, P. M. Nanninga, and J. Water. 1987. ^{210}Pb as a chronometer and tracer, Burrinjuck Reservoir, Australia. *Earth Surface Processes and Landforms 12*: 399–414.

Webb, B. W., and D. E. Walling. 1982. The magnitude and frequency characteristics of fluvial transport in a Devon drainage basin and some geomorphological implications. *Catena 9*: 9–24.

White, B. M., B. J. Duke, and W. L. O. Jimoh. 1984. Mineralogy and chemistry of Harmattan dust in northern Nigeria. *Catena 11*: 91–96.

Whitehouse, I. E. 1983. Erosion in the eastern South Island high country – a changing perspective. *Tussock Grasslands and Mountain Lands Institute Review 42*: 3–23.

Wilkinson, B., W. Broughton, and J. Parker-Sutton. 1969. Survey of wind erosion on sandy soils in the East Midlands. *Experimental Husbandry 18*: 53–59.

Williams, P. W. 1980. From forest to suburb: The hydrological impact on man in New Zealand. In *The Land Our Future: Essays on Land Use and Conservation in New Zealand*, ed. A. G. Anderson, 103–24. Auckland: Longman Paul/New Zealand Geographical Society Inc.

Wilson, S. J., and R. U. Cooke. 1980. Wind erosion. In *Soil Erosion*, ed. M. J. Kirkby and R. P. C. Morgan, 217–51. Chichester: Wiley.

Wolman, M. G. 1967. A cycle of sedimentation and erosion in urban river channels. *Geografiska Annaler 49A*: 385–95.

World Resources Institute. 1986. *World Resources 1986: An Assessment of the Resource Base That Supports the Global Economy*. New York: Basic Books.

Yair, A. 1983. Hillslope hydrology, water harvesting, and areal distribution of some ancient agricultural systems in the northern Negev Desert. *Journal of Arid Environments 6*: 283–301.

Zachar, D. 1982. *Soil Erosion*. (Development in Soil Science 10) Amsterdam: Elsevier.