6 HUMAN AGENCY IN GEOMORPHOLOGY

Introduction

The human role in creating landforms and modifying the operation of geomorphologic processes such as weathering, erosion, and deposition is a theme of great importance, though one that, particularly in the Western world, has not received the attention it deserves.

The range of the human impact on both forms and processes is considerable. For example, in Table 6.1 there is a list of some anthropogenic landforms together with some of the causes of their creation. There are very few spheres of human activity which do not, even indirectly, create landforms (Haigh, 1978). It is, however, useful to recognize that some features are produced by *direct* anthropogenic processes. These tend to be more obvious in their form and origin and are frequently created deliberately and knowingly. They include landforms produced by constructional activity (such as tipping), excavation, travel, hydrologic interference, and farming. Hillsides have been terraced in many parts of the world for many centuries, notably in the arid and semi-arid highlands of the New World (Donkin, 1979; Denevan, 2001), but examples are also known from southern England where in Roman and Medieval times *strip lynchets* have been produced by plowing on steep slopes (Figure 6.1).

Landforms produced by *indirect* anthropogenic processes are often less easy to recognize, not least because

Table 6.1 Some anthropogenic landforms

Feature	*Cause*
Pits and ponds	Mining, marling
Broads	Peat extraction
Spoil heaps	Mining
Terracing, lynchets	Agriculture
Ridge and furrow	Agriculture
Cuttings and sunken lanes	Transport
Embankments	Transport, river and coast management
Dikes	River and coast management
Mounds	Defense, memorials
Craters	War, *qanat* construction
City mounds (*tells*)	Human occupation
Canals	Transport, irrigation
Reservoirs	Water management
Subsidence depressions	Mineral and water extraction
Moats	Defense
Banks along roads	Noise abatement

Figure 6.1 Strip lynchets (terraces) in Dorset, southern England, produced by plowing on steep slopes.

they tend to involve, not the operation of a new process or processes, but the acceleration of natural processes. They are the result of environmental changes brought about inadvertently by human technology. Nonetheless, it is probably this indirect and inadvertent modification of process and form that is the most crucial aspect of **anthropogeomorphology**. By removing natural vegetation cover – through the agency of cutting, burning, and grazing (see Trimble and Mendel, 1995) – humans have accelerated erosion and sedimentation. Sometimes the results will be obvious, for example when major gully systems rapidly develop; other results may have less immediate effect on landforms but are, nevertheless, of great importance. By other indirect means humans may create subsidence features and hazards, trigger off mass movements such as landslides, and even influence the operation of phenomena such as earthquakes.

Finally there are situations where, through a lack of understanding of the operation of processes and the links between different processes and phenomena, humans may deliberately and directly alter landforms and processes and thereby set in train a series of events which were not anticipated or desired. There are, for example, many records of attempts to reduce coast erosion by expensive engineering solutions, which, far from solving erosion problems, only exacerbated them.

Landforms produced by excavation

Of the landforms produced by direct anthropogenic processes those resulting from excavation are widespread, and may have some antiquity. For example, Neolithic peoples in the Breckland of East Anglia in England used antler picks and other means to dig a remarkable cluster of deep pits in the chalk. The purpose of this was to obtain good-quality nonfrost-shattered flint to make stone tools. In many parts of Britain chalk has also been excavated to provide marl for improving acidic, light, sandy soils, and Prince (1962, 1964) made a meticulous study of the 27,000 pits and ponds in Norfolk that have resulted mainly from this activity – an activity particularly prevalent in the eighteenth century. It is often difficult in individual cases to decide whether the depressions are the results of human intervention, for solutional and periglacial depressions are often evident in the same area, but pits caused by human action do tend to have some distinctive features: irregular shape, a track leading into them, proximity to roads, etc. (see the debate between Prince (1979) and Sperling et al. (1979)).

Difficulties of identifying the true origin of excavational features were also encountered in explaining the Broads, a group of 25 freshwater lakes in the county of Norfolk. They are of sufficient area, and depth, for early workers to have precluded a human origin. Later it was proposed instead that they were natural features caused by uneven alluviation and siltation of river valleys which were flooded by the rapidly rising sea level of the Holocene (Flandrian) transgression. It was postulated by Jennings (1952) that the Broads were initiated as a series of discontinuous natural lakes, formed beyond the limits of a thick estuarine clay wedge laid down in Romano-British times by a transgression of the sea over earlier valley peats. The waters of the Broads were thought to have been impounded in natural peaty hollows between the flanges of the clay and the marginal valley slopes, or in tributary valleys whose mouths were blocked by the clay.

It is now clear, however, that the Broads are the result of human work (Lambert et al., 1970). Some of them have rectilinear and steep boundaries, most of them are not mentioned in early topographic books, and archival records indicate that peat cutting (*turbary*) was widely practiced in the area. On these and other grounds it is believed that peat-diggers, before AD 1300, excavated 25.5×10^6 m^3 of peat and so created the depressions in which the lakes have formed. The flooding may have been aided by sea-level change. Comparably extensive peat excavation was also carried on in The Netherlands, notably in the fifteenth century.

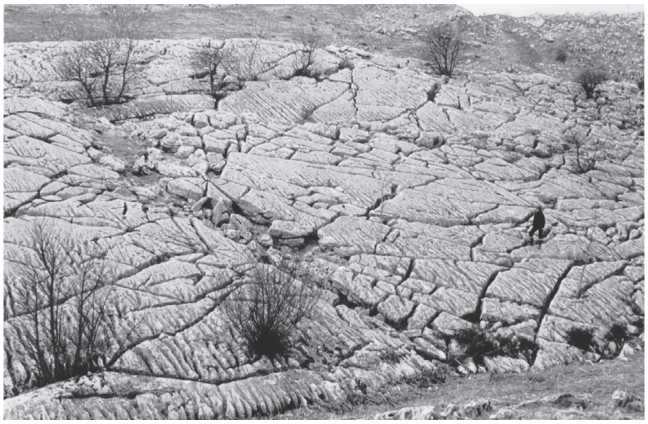

Figure 6.2 A limestone pavement at Hutton Roof Crags in northwest England. Such bare rock surfaces may result in part from accelerated erosion induced by the first farmers in prehistoric times. Many of them are now being damaged by quarrying and removal of stone for garden ornamentation.

Figure 6.3 The Rössing uranium mine near Swakopmund in Namibia, southern Africa. The excavation of such mines involves the movement of prodigious amounts of material.

Other excavational features result from war, especially craters caused by bomb or shell impact. Regrettably, human power to create such forms is increasing. It has been calculated (Westing and Pfeiffer, 1972) that between 1965 and 1971, 26 million craters, covering an area of 171,000 hectares, were produced by bombing in Indo-China. This represents a total displacement of no less than 2.6×10^9 m^3 of earth, a figure much greater than calculated as being involved in the peaceable creation of The Netherlands.

Some excavation is undertaken on a large scale for purely aesthetic reasons, when Nature offends the eye (Prince, 1959), while in many countries where land is scarce, whole hills are leveled and extensive areas stripped to provide fill for harbor reclamation. One of the most spectacular examples of this kind was the deliberate removal of steep-sided hills in the center of Brazil's Rio de Janeiro, for housing development.

An excavational activity of a rather specialized kind is the removal of limestone pavements (Figure 6.2) – areas of exposed limestone in northern England which were stripped by glaciers and then molded into bizarre shapes by solutional activity – for ornamental rock gardens. These pavements which consist of arid, bare rock surfaces (clints) bounded by deep, humid fissures (grikes) have both an aesthetic and a biological significance (Ward, 1979).

One of the most important causes of excavation is still mineral extraction (Figure 6.3), producing open-pit mines, strip mines, quarries for structural materials, borrow pits along roads, and similar features (Doerr and Guernsely, 1956). Of these, 'without question, the environmental devastation produced by strip mining exceeds in quantity and intensity all of the other varied forms of man-made land destruction' (Strahler and Strahler, 1973: 284). This form of mining is a particular environmental problem in the states of Pennsylvania, Ohio, West Virginia, Kentucky, and Illinois. Oil shales, a potential source of oil that at present is relatively untapped, can be exploited by open-pit mining, by traditional room and pillar mining, and by underground *in situ* pyrolysis. Vast reserves exist (as in Canada) but the amount of excavation required will probably be about three times the amount of oil produced (on a volume basis), suggesting that the extent of both the excavation and subsequent dumping of overburden and waste will be considerable (Routson et al., 1979). Some of the waste, produced by the retorting of the shale to release the oil, contains soluble salts and potentially harmful trace elements, which limit the speed of ground reclamation (Petersen, 1981).

An early attempt to provide a general picture of the importance of excavation in the creation of the landscape of Britain was given by Sherlock (1922). He estimated (see Table 6.2) that up until the time in which he wrote, human society had excavated around 31×10^9 m^3 of material in the pursuit of its economic activities. That figure must now be a gross underestimate, partly because Sherlock himself was not in a position to appreciate the anthropogenic role in creating features such as the Norfolk Broads, and partly

Table 6.2 Total excavation of material in Great Britain until 1922. Source: Sherlock (1922: 86)

Activity	*Approximate volume (m^3)*
Mines	15,147,000,000
Quarries and pits	11,920,000,000
Railways	2,331,000,000
Manchester Ship Canal	41,154,000
Other canals	153,800,000
Road cuttings	480,000,000
Docks and harbors	77,000,000
Foundations of buildings and street excavation	385,000,000
Total	30,534,954,000

Table 6.3 Humans as earthmovers. Source: Hooke (1994)
(a) Deliberate human earthmoving actions in the USA, omitting the indirect effects of actions such as deforestation and cultivation

Activity	*(10^9 tonnes year^{-1})*
Excavation for housing and other construction	0.8
Mining	3.8
Road work	3.0
Total USA	7.6
World total (roughly four times the USA total)	30.0

(b) Estimated world totals due to natural earthmoving processes

Activity	*(10^9 tonnes year^{-1})*
River transport	
(a) to oceans and lakes	14
(b) short-distance transport within river basins	40
Tectonic forces lifting continents	14
Volcanic activity elevating sea floor	30
Glacial transport	4.3
Wind transport	1.0

because, since his time, the rate of excavation has greatly accelerated. Sherlock's 1922 study covers a period when earth-moving equipment was still ill-developed. Nonetheless, on the basis of his calculations, he was able to state that 'at the present time, in a densely peopled country such as England, Man is many times more powerful, as an agent of denudation, than all the atmospheric denuding forces combined' (p. 333). The most notable change since Sherlock wrote has taken place in the production of aggregates for concrete. Demand for these materials in the UK grew from 20 million tonnes per annum in 1900 to 202 million tonnes in 2001, a tenfold increase.

For the world as a whole, the annual movement of soil and rock resulting from mineral extraction may be as high as 3000 billion tonnes (Holdgate et al., 1982: 186). By comparison it has been estimated that the amount of sediment carried into the ocean by the world's rivers each year amounts to 24 billion tonnes per year (Judson, 1968). More recently, Hooke (1994) has tried to produce some data on the significance of deliberate human earthmoving actions in the USA and globally and these are shown in Table 6.3.

Landforms produced by construction and dumping

The process of constructing mounds and embankments and the creation of dry land where none previously existed is longstanding. In Britain the mound at Silbury Hill dates back to prehistoric times, and the pyramids of Central America, Egypt, and the Far East are even more spectacular early feats of landform creation. Likewise in the Americas Native Indians, prior to the arrival of Europeans, created large numbers of mounds of different shapes and sizes for temples, burials, settlement, and effigies (Denevan, 1992: 377). In the same way, hydrologic management has involved, over many centuries, the construction of massive banks and walls – the ultimate result being the present-day landscape of The Netherlands. Transport developments have also required the creation of large constructional landmarks, but probably the most important features are those resulting from the dumping of waste materials, especially those derived from mining (see Figure 6.4). It has been calculated that there are at least 2000 million tonnes of shale lying in pit heaps in the coalfields of Britain (Richardson, 1976). In the Middle East and other areas of long-continued human urban settlement the accumulated debris of life has gradually raised the level of the land surface, and occupation mounds (*tells*) are a fertile source of information to the archaeologist. Today, with the technical ability to build that humans have, even estuaries may be converted from

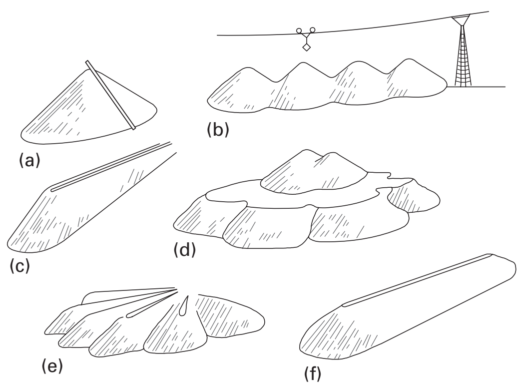

Figure 6.4 Some shapes produced by shale tipping: (a) conical, resulting from MacClaine tipping; (b) multiple cones tipped from aerial ropeways; (c) high fan-ridge by tramway tipping over slopes; (d) high plateau mounds topped with cones; (e) low multiple fan ridges by tramway tipping; (f) lower ridge by tramway tipping (after Haigh, 1978, figure 2.1).

ecologically productive environments into suburban sprawl by the processes of dredging and filling. Indeed, one of the striking features of the distribution of the world's population is the tendency for large human concentrations to occur near vast expanses of water. Many of these cities have extended out on to land that has been reclaimed from the sea (e.g., Hong Kong, Figure 6.5), thereby providing valuable sites for development, but sometimes causing the loss of rich fishing grounds and ecologically valuable wetlands (Hudson, 1979).

The ocean floors are also being affected because of the vast bulk of waste material that humankind is creating. Disposal of solid waste by coastal cities is now sufficiently large to modify shorelines, and it covers adjacent ocean bottoms with characteristic deposits on a scale large enough to be geologically significant. This has been brought out dramatically by Gross (1972: 3174), who undertook a quantitative comparison of the amount of solid wastes dumped into the Atlantic by humans in the New York metropolitan region with the amount of sediment brought into the ocean by rivers:

> The discharge of waste solids exceeds the suspended sediment load of any single river along the U.S. Atlantic coast. Indeed, the discharge of wastes from the New York metropolitan region is comparable to the estimated suspended-sediment yield (6.1 megatons per year) of all rivers along the Atlantic coast between Maine and Cape Hatteras, North Carolina.

Not only are the rates of sedimentation high, but the anthropogenic sediments tend to contain abnormally high contents of such substances as carbon and heavy metals (Goldberg et al., 1978).

Many of the features created by excavation in one generation are filled in by another, since phenomena such as water-filled hollows produced by mineral extraction are often both wasteful of land and also suitable locations for the receipt of waste. The same applies to natural hollows such as **karstic** or ground-ice depressions. Watson (1976), for example, has mapped

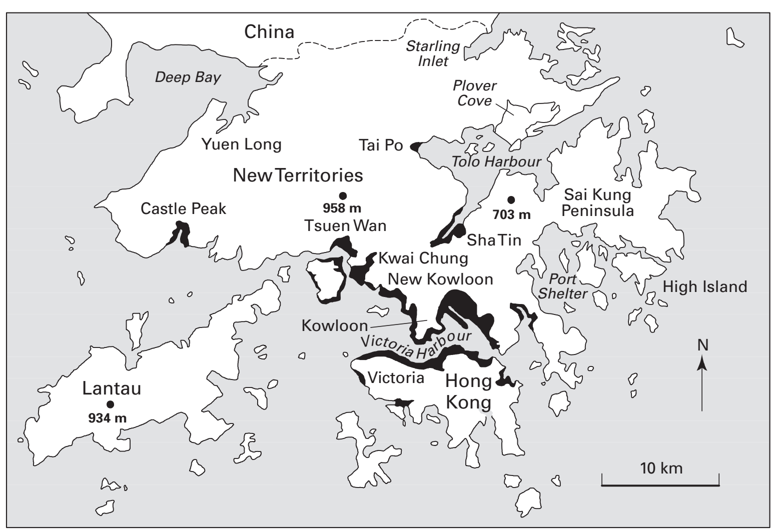

Figure 6.5 Map of Hong Kong showing main urban reclamation areas shaded black (reprinted from Hudson, 1979, figure 1, in *Reclamation review*, 2, 3–16, permission of Pergamon Press Ltd © Pergamon Press Ltd).

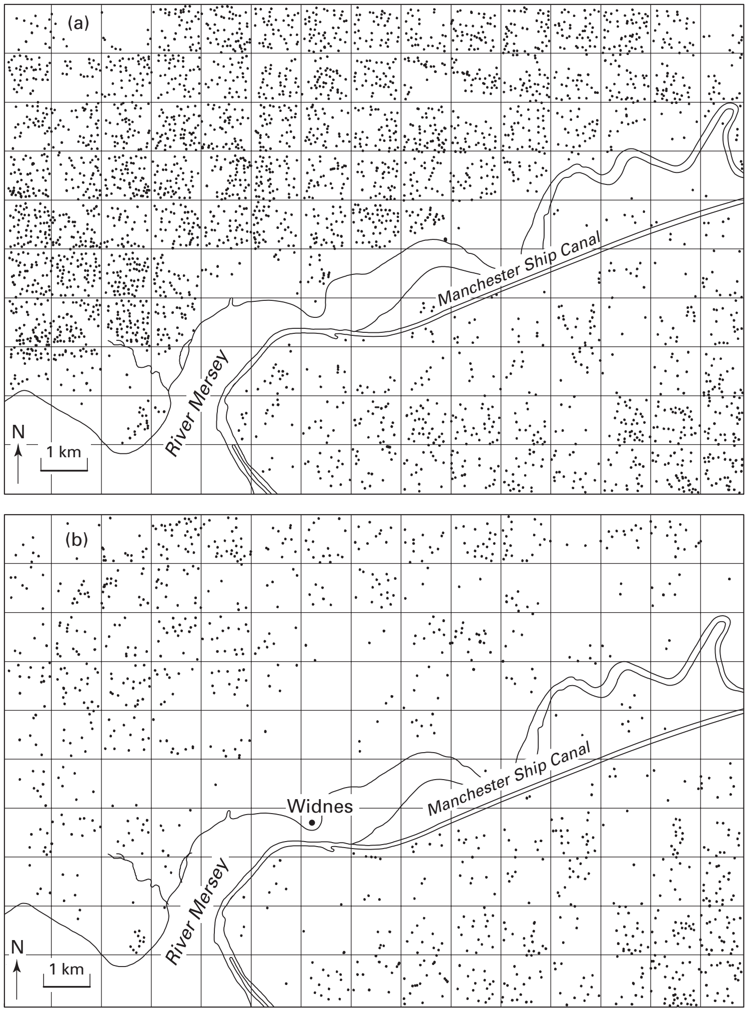

Figure 6.6 The distribution of pits and ponds in a portion of northwestern England: (a) in the mid-nineteenth century; (b) in the mid-twentieth century (after Watson, 1976).

the distribution of hollows, which were largely created by marl diggers in the lowlands of southwest Lancashire and northwest Cheshire, as they were represented on mid-nineteenth-century topographic maps (Figure 6.6a). When this distribution is compared with the present-day distribution for the same area (Figure 6.6b), it is evident that a very substantial proportion of the holes has been infilled and obliterated by humans, with only 2114 out of 5380 remaining. Hole densities have fallen from 121 to 47 km^{-2}.

At the present time, large quantities of waste are sent to landfill sites. In 1995, member states of the European Union landfilled more than 80% of their waste, but under the EU Landfill Directive this figure should be reduced substantially in coming decades.

Accelerated sedimentation

An inevitable consequence of the accelerated erosion produced by human activities has been accelerated sedimentation (see, e.g., Komar et al.'s 2004 study of sedimentation in Tillamook Bay, Oregon). This has been heightened by the deliberate addition of sediments to stream channels as a result of the need to dispose of mining and other wastes.

In a classic study, G. K. Gilbert (1917) demonstrated that hydraulic mining in the Sierra Nevada mountains of California led to the addition of vast quantities of sediments into the river valleys draining the range. This in itself raised their bed levels, changed their channel configurations and caused the flooding of lands that had previously been immune. Of even greater significance was the fact that the rivers transported vast quantities of debris into the estuarine bays of the San Francisco system, and caused extensive shoaling which in turn diminished the tidal prism of the bay. Gilbert calculated the volume of shoaling produced by hydraulic mining since the discovery of gold to be 846×10^6 m^3.

Comparably serious sedimentation of bays and estuaries has also been caused by human activity on the eastern coast of America. As Gottschalk (1945: 219) wrote:

> Both historical and geologic evidence indicates that the pre-agricultural rate of silting of eastern tidal estuaries was low. The history of sedimentation of ports in the Chesapeake Bay area is an epic of the effects of uncontrolled erosion since the beginning of the wholesale land clearing and cultivation more than three centuries ago.

He has calculated that at the head of the Chesapeake Bay, 65×10^6 m^3 of sediment were deposited between 1846 and 1938. The average depth of water over an area of 83 km^2 was reduced by 0.76 m. New land comprising 318 hectares was added to the state of Maryland and, as Gottschalk remarked, 'the Susquehanna River is repeating the history of the Tigris and Euphrates'. Much of the material entrained by erosive processes on upper slopes as a result of agriculture in Maryland, however, was not evacuated as far as the coast. Costa (1975) has suggested, on the basis of the study of sedimentation, that only about one-third of the eroded material left the river valleys. The remainder accumulated on floodplains as alluvium and colluvium at rates of up to 1.6 cm per year. Similarly, Happ (1944), working in Wisconsin, carried out an intensive augering survey of floodplain soil and established that, since the development of agriculture, floodplain aggradation had proceeded at a rate of approximately 0.85 cm per year. He noted that channel and floodplain aggradation had caused the flooding of low alluvial terraces to be more frequent, more extensive and deeper. The rate of sedimentation has since declined (Trimble, 1976), because of less intensive land use and the institution of effective erosion control measures on farmland (see also Magilligan, 1985).

Such valley sedimentation is by no means restricted to the newly settled terrains of North America. There is increasing evidence to suggest that silty valley fills in Germany, France, and Britain, many of them dating back to the Bronze Age and the Iron Age, are the result of accelerated slope erosion produced by the activities of early farmers (Bell, 1982). Indeed, in recent years, various studies have been undertaken with a view to assessing the importance of changes in sedimentation rate caused by humans at different times in the Holocene in Britain. Among the formative events that have been identified are: initial land clearance by Mesolithic and Neolithic peoples; agricultural intensification and sedentarization in the late Bronze Age; the widespread adoption of the iron plow in the early Iron Age; settlement by the Vikings; and the introduction of sheep farming (Table 6.4).

A core from Llangorse Lake in the Brecon Beacons of Wales (Jones et al., 1985) provides excellent long-term data on changing sedimentation rates:

Period (years BP)	*Sedimentation rate (cm 100 years^{-1})*
9000–7500	3.57
7500–5000	1.0
5000–2800	13.2
2800–AD 1840	14.1
c. AD 1840–present	59.0

The thirteenfold increase in rates after 5000 years BP seems to have occurred rapidly and is attributed to initial forest clearance. The second dramatic increase of more than fourfold took place in the past 150 years and is a result of agricultural intensification.

In the past two centuries rates of sedimentation in lake basins have changed in different ways in different basins according to the differing nature of economic activities in catchments. Some data from various sources are listed for comparison in Table 6.5. In the case of the Loe Pool in Cornwall (southwest England) rates of sedimentation were high while mining industry was active, but fell dramatically when mining was curtailed. In the case of Seeswood Pool in Warwickshire, a dominantly agricultural catchment area in central England, the highest rates have occurred since 1978 in response to various land management changes, such as larger fields, continuous cropping, and increased dairy herd size. In other catchments, pre-afforestation plowing may have caused sufficient disturbance to cause accelerated sedimentation. For example, Battarbee et al. (1985b) looked at sediment cores in the Galloway area of southwest Scotland and found that in Loch

Table 6.4 Accelerated sedimentation in Britain in prehistoric and historic times

Location	*Source*	*Evidence and date*
Howgill Fells	Harvey et al. (1981)	Debris cone production following tenth century AD introduction of sheep farming
Upper Thames Basin	Robinson and Lambrek (1984)	River alluviation in the late Bronze Age and early Iron Age
Lake District	Pennington (1981)	Accelerated lake sedimentation at 5000 years BP as a result of Neolithic agriculture
Mid-Wales	Macklin and Lewin (1986)	Floodplain sedimentation (Capel Bangor unit) on Breidol as a result of early Iron Age sedentary agriculture
Brecon Beacons	Jones et al. (1985)	Lake sedimentation increase after 5000 years BP at Llangorse due to forest clearance
Weald	Burrin (1985)	Valley alluviation from Neolithic onwards until early Iron Age
Bowland Fells	Harvey and Renwick (1987)	Valley terraces at 5000–2000 years BP (Bronze or Iron Age settlement) and after 1000 years BP (Viking settlement)
Southern England	Bell (1982)	Fills in dry valleys: Bronze and Iron Age
Callaly Moor (Northumberland)	Macklin et al. (1991)	Valley fill sediments of late Neolithic to Bronze Age

Table 6.5 Data on rates of erosion and sedimentation in lakes in the last two centuries

Location	*Dates*	*Activity*	*Rates of erosion in catchment (R. Cober) as determined from lake sedimentation rates (t km^{-2} year^{-1})*
Loe Pool (Cornwall) (from O'Sullivan et al., 1982)	1860–1920	Mining and agriculture	174
	1930–6	Intensive mining and agriculture	421
	1937–8	Intensive mining and agriculture	361
	1938–81	Agriculture	12
Seeswood Pool (Warwickshire) (from Foster et al., 1986)	1765–1853		7.0
	1854–80		12.2
	1881–1902		8.1
	1903–19		9.6
	1920–5		21.6
	1926–33		16.1
	1934–47		12.7
	1948–64		12.0
	1965–72		13.9
	1973–7		18.3
	1978–82		36.2

Grannoch the introduction of plowing in the catchment caused an increase in sedimentation from 0.2 cm per year to 2.2 cm per year.

The work of Binford et al. (1987) on the lakes of the Peten region of northern Guatemala (Central America), an area of tropical lowland dry forest, is also instructive with respect to early agricultural colonization. Combining studies of archaeology and lake sediment stratigraphy, they were able to reconstruct the diverse environmental consequences of the growth of Mayan civilization (Figure 6.7). This civilization showed a dramatic growth after 3000 years BP, but collapsed in the ninth century AD. The hypotheses put forward to explain this collapse include warfare, disease, earthquakes, and soil degradation. The population has remained relatively low ever since, and after the first European contact (AD 1525) the region was virtually depopulated. The period of Mayan success saw a marked

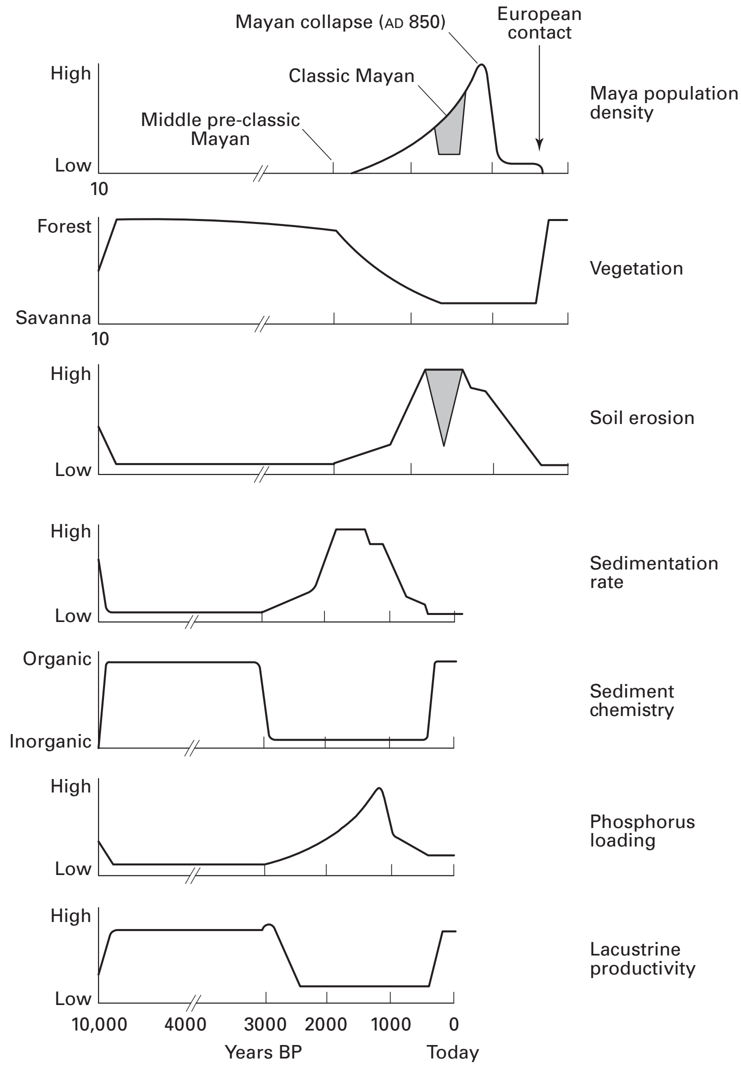

Figure 6.7 The human and environmental history of the Peten Lakes, Guatemala. The shaded areas indicate a phase of local population decline (modified after Binford et al., 1987).

reduction in vegetation cover, an increase in lake sedimentation rates and in catchment soil erosion, an increased supply of inorganic silts and clays to the lakes, a pulse of phosphorus derived from human wastes, and a decrease in lacustrine productivity caused by high levels of turbidity.

Sedimentation has severe economic implications because of the role it plays in reducing the effective lifetime of reservoirs. In the tropics capacity depletion through sedimentation is commonly around 2% per year (Myers, 1988: 14), so that the expected useful life of the Paute hydroelectric project in Ecuador (cost US$ 600 million) is 32 years, that of the Mangla Dam in Pakistan (cost US$ 600 million) is 57 years, and that of the Tarbela Dam, also in Pakistan, is just 40 years.

Ground subsidence

Not all ground subsidence is caused by humans. For example, limestone solutional processes can, in the absence of humankind, create a situation where a cavern collapses to produce a surface depression or sinkhole, and permafrost will sometimes melt to produce a **thermokarst** depression without human intervention. Nonetheless, ground subsidence can be caused or accelerated by humans in a variety of ways: by the transfer of subterranean fluids (such as oil, gas, and water); by the removal of solids through underground mining or by dissolving solids and removing them in solution (e.g., sulfur and salt); by the disruption of permafrost; and by the compaction or reduction of sediments because of drainage and irrigation (Johnson, 1991; Barends et al., 1995).

Some of the most dangerous and dramatic collapses have occurred in limestone areas because of the dewatering of limestone caused by mining activities. In the Far West Rand of South Africa, gold mining has required the abstraction of water to such a degree that the local water table has been lowered by more than 300 m. The fall of the water table caused miscellaneous clays and other materials filling the roofs of large caves to dry out and shrink so that they collapsed into the underlying void. One collapse created a depression 30 m deep and 55 m across, killing 29 people. In Alabama in the southern USA, water-level decline consequent upon pumping has had equally serious consequences in a limestone terrain; and Newton (1976) has estimated that since 1900 about 4000 induced sinkholes or related features have been formed, while fewer than 50 natural sinkholes have been reported over the same interval. Sinkholes that may result from such human activity are also found in Georgia, Florida, Tennessee, Pennsylvania, and Missouri. In 1904, near Tampa (Florida), overpumping of an artesian aquifer caused 64 new sinkholes to form within a one-month period.

In some limestone areas, however, a reverse process can operate. The application of water to overburden above the limestone may render it more plastic so that the likelihood of collapse is increased. This has occurred beneath reservoirs, such as the May Reservoir in central Turkey, and as a result of the application of wastewater and sewerage to the land surface. Williams (1993) provides a survey of the diverse effects of human activities on limestone terrains.

The process can be accelerated by the direct solution of susceptible rocks. For example, collapses have occurred in gypsum bedrock because of solution brought about by the construction of a reservoir. In 1893 the MacMillan Dam was built on the Pecos River in New Mexico, but within 12 years the whole river flowed through caves which had developed since construction. Both the San Fernando and Rattlesnake Dams in California suffer severe leakage for similar reasons.

Subsidence produced by oil abstraction is an increasing problem in some parts of the world. The classic area is Los Angeles, where 9.3 m of subsidence occurred as a result of exploitation of the Wilmington oilfield between 1928 and 1971. The Inglewood oilfield displayed 2.9 m of subsidence between 1917 and 1963. Some coastal flooding problems occurred at Long Beach because of this process. Similar subsidence has been recorded from the Lake Maracaibo field in Venezuela (Prokopovich, 1972) and from some Russian fields (Nikonov, 1977).

A more widespread problem is posed by groundwater abstraction for industrial, domestic, and agricultural purposes. Table 6.6 presents some data for such subsidences from various parts of the world. The ratios of subsidence to water level decline are strongly dependent on the nature of the sediment composing the aquifer. Ratios range from 1:7 for Mexico City, to 1:80 for the Pecos in Texas, and to less than 1:400 for London, England (Rosepiler and Reilinger, 1977). The extent of subsidence that has taken place in the USA as a result of groundwater abstraction has recently been assessed by Chi and Reilinger (1984). In Japan subsidence has also now emerged as a major problem (Nakano and Matsuda, 1976). In 1960 only 35.2 km^2 of the Tokyo lowland was below sea level, but continuing subsidence meant that by 1974 this had increased to 67.6 km^2, exposing a total of 1.5 million people to major flood hazard. Shanghai in China is another low-lying Asian city that has suffered from subsidence, with as much as 2 to 3 m since 1921 (Chai et al., 2004).

The subsidence caused by mining (which led to court cases in England as early as the fifteenth century as a consequence of associated damage to property) is perhaps the most familiar, although its importance varies according to such factors as the thickness of seam removed, its depth, the width of working, the degree of filling with solid waste after extraction, the geologic structure, and the method of working adopted (Wallwork, 1974). In general terms, however, the vertical displacement by subsidence is less than the thickness of the seam being worked, and decreases with an increase in the depth of mining. This is because the overlying strata collapse, fragment, and fracture, so that the mass of rock fills a greater space than it did when naturally compacted. Consequently the surface expression of deep-seated subsidence may be equal to little more than one-third of the thickness of the material removed. Subsidence associated with coal mining may disrupt surface drainage and the resultant depressions then become permanently flooded.

Coal-mining regions are not the only areas where subsidence problems are serious. In Cheshire, northwest England, rock salt is extracted from two major

Table 6.6 Ground subsidence. Source: data in Cooke and Doornkamp (1974); Prokopovich (1972); Rosepiler and Reilinger (1977); Holzer (1979); Nutalaya and Ran (1981); Johnson (1991)

Cause	*Location*	*Amount (m)*	*Date*	*Rate (mm year^{-1})*
Ground subsidence produced by oil and gas abstraction	Azerbaydzhan, USSR	2.5	1912–62	50
	Atravopol, USSR	1.5	1956–62	125
	Wilmington, USA	9.3	1928–71	216
Ground subsidence produced by groundwater abstraction	Inglewood, USA	2.9	1917–63	63
	Maracaibo, Venezuela	5.03	1929–90	84
	London, England	0.06–0.08	1865–1931	0.91–1.21
	Savannah, Georgia (USA)	0.1	1918–55	2.7
	Mexico City	7.5	–	250–300
	Houston, Galveston, Texas	1.52	1943–64	60–76
	Central Valley, California	8.53	–	–
	Tokyo, Japan	4	1892–1972	500
	Osaka, Japan	> 2.8	1935–72	76
	Niigata, Japan	> 1.5	–	–
	Pecos, Texas	0.2	1935–66	6.5
	South-central Arizona	2.9	1934–77	96
	Bangkok, Thailand	0.5	–	100
	Shanghai, China	2.62	1921–65	60

seams, each about 30 m in thickness. Moreover, these seams occur at no great depth – the uppermost being at about 70 m below the surface. A further factor to be considered is that the rock salt is highly soluble in water, so the flooding of mines may cause additional collapse. These three conditions – thick seams, shallow depth and high solubility – have produced optimum conditions for subsidence and many subsidence lakes called 'flashes' have developed (Wallwork, 1956). Some of these are illustrated in Figure 6.8.

Some subsidence is created by a process called hydrocompaction, which is explained thus. Moisture-deficient, unconsolidated, low-density sediments tend to have sufficient dry strength to support considerable effective stresses without compacting. However, when such sediments, which may include alluvial fans or loess, are thoroughly wetted for the first time (e.g., by percolating irrigation water) the intergranular strength of the deposits is diminished, rapid compaction takes place, and ground surface subsidence follows. Unequal subsidence can create problems for irrigation schemes.

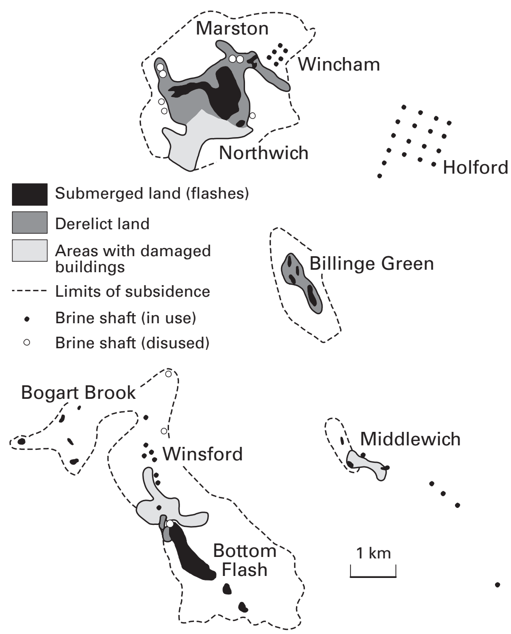

Figure 6.8 Subsidence in the salt area of mid-Cheshire, England, in 1954 (after Wallwork, 1956, figure 3).

Land drainage can promote subsidence of a different type, notably in areas of organic soils. The lowering of the water table makes peat susceptible to oxidation and deflation so that its volume decreases. One of the longest records of this process, and one of the clearest demonstrations of its efficacy, has been provided by the measurements at Holme Fen Post in the English Fenlands. Approximately 3.8 m of subsidence occurred

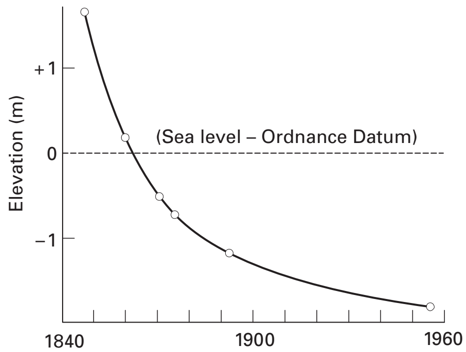

Figure 6.9 The subsidence of the English Fenlands peat at Holme Fen Post from 1842 to 1960 following drainage (from data in Fillenham, 1963).

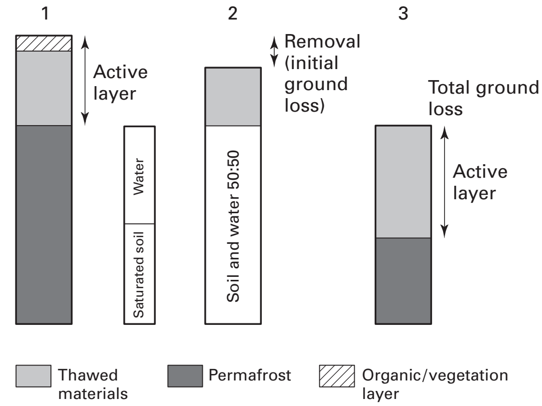

Figure 6.10 Diagram illustrating how the disturbance of high ice-content terrain can lead to permanent ground subsidence. 1–3 indicate stages before, immediately after, and subsequent to disturbance (after Mackay in French, 1976, figure 6.1).

between 1848 and 1957 (Fillenham, 1963), with the fastest rate occurring soon after drainage had been initiated (Figure 6.9). The present rate averages about 1.4 cm per year (Richardson and Smith, 1977). At its maximum natural extent the peat of the English Fenland covered around 1750 km^2. Now only about one-quarter (430 km^2) remains.

A further type of subsidence, sometimes associated with earthquake activity, results from the effects on Earth's crust of large masses of water impounded behind reservoirs. As we shall see later, seismic effects can be generated in areas with susceptible fault systems and this may account for earthquakes recorded at Koyna (India) and elsewhere. This process whereby a mass of water causes coastal depression is called hydro-isostasy.

In tundra regions ground subsidence is associated with thermokarst development, thermokarst being irregular, hummocky terrain produced by the melting of ground ice, permafrost. The development of thermokarst is due primarily to the disruption of the thermal equilibrium of the permafrost and an increase in the depth of the active layer. This is illustrated in Figure 6.10. Following French (1976: 106), consider an undisturbed tundra soil with an active layer of 45 cm. Assume also that the soil beneath 45 cm is supersaturated permafrost and yields on a volume basis upon thawing 50% excess water and 50% saturated soil. If the top 15 cm were removed, the equilibrium thickness of the active layer, under the bare ground conditions, might increase to 60 cm. As only 30 cm of the original active layer remains, 60 cm of the permafrost must thaw before the active layer can thicken to 60 cm, since 30 cm of supernatant water will be released. Thus, the surface subsides 30 cm because of thermal melting associated with the degrading permafrost, to give an overall depression of 45 cm.

Thus the key process involved in thermokarst subsidence is the state of the active layer and its thermal relationships. When, for example, surface vegetation is cleared for agricultural or constructional purposes the depth of thaw will tend to increase. The movement of tracked vehicles has been particularly harmful to surface vegetation and deep channels may soon result from permafrost degradation. Similar effects may be produced by the siting of heated buildings on permafrost, and by the laying of oil, sewer, and water pipes in or on the active layer (Ferrians et al., 1969; Lawson, 1986).

Thus subsidence is a diverse but significant aspect of the part humans play as geomorphologic agents. The damage caused on a worldwide basis can be measured in billions of dollars each year (Coates, 1983), and among the effects are broken dams, cracked buildings (Figure 6.11), offset roads and railways, fractured well casings, deformed canals and ditches, bridges that need releveling, saline encroachment, and increased flood damage.

Figure 6.11 The city of Mexico has subsided by many meters as a result of groundwater abstraction. Many of the ancient buildings in the city center have been severely damaged, and have been cracked and deformed.

Arroyo trenching, gullies, and peat haggs

In the southwestern USA many broad valleys and plains became deeply incised with valley-bottom gullies (*arroyos*) over a short period between 1865 and 1915, with the 1880s being especially important (Cooke and Reeves, 1976). This cutting had a rapid and detrimental effect on the flat, fertile, and easily irrigated valley floors, which are the most desirable sites for settlement and economic activity in a harsh environment. The causes of the phenomenon have been the subject of prolonged debate (Elliott et al., 1999; Gonzalez, 2001).

Many students of this phenomenon have believed that thoughtless human actions caused the entrenchment, and the apparent coincidence of white settlement and arroyo development tended to give credence to this viewpoint. The range of actions that could have been culpable is large: timber-felling, overgrazing, cutting grass for hay in valley bottoms, compaction along well-traveled routes, channeling of runoff from trails and railways, disruption of valley-bottom sods by animals' feet, and the invasion of grasslands by miscellaneous types of scrub.

On the other hand, study of the long-term history of the valley fills shows that there have been repeated phases of aggradation and incision and that some of these took place before the influence of humans could have been a significant factor (Waters and Haynes, 2001). This has prompted debate as to whether the arrival of white communities was in fact responsible for this particularly severe phase of environmental degradation. Huntington (1914), for example, argued that valley filling would be a consequence of a climatic shift to more arid conditions. These, he believed, would cause a reduction in vegetation, which in turn would promote rapid removal of soil from devegetated mountain slopes during storms, and overload streams with sediment. With a return to humid conditions vegetation would be re-established, sediment yields would be reduced, and entrenchment of valley fills would take place. Bryan (1928) put forward a contradictory climatic explanation. He argued that a slight move towards drier conditions, by depleting vegetation cover and reducing soil infiltration capacity, would produce significant increases in storm runoff, which would erode valleys. Another climatic interpretation was advanced by Leopold (1951), involving a change in rainfall intensity rather than quantity. He indicated that a reduced frequency of low-intensity rains would weaken the vegetation cover, while an increased frequency of heavy rains at the same time would increase the incidence of erosion. Support for this contention comes from the work of Balling and Wells (1990) in New Mexico. They attributed early twentieth-century arroyo trenching to a run of years with intense and erosive rainfall characteristics that succeeded a phase of drought conditions in which the productive ability of the vegetation had declined. It is also possible, as Schumm et al. (1984) have pointed out, that arroyo incision could result from neither climatic change nor

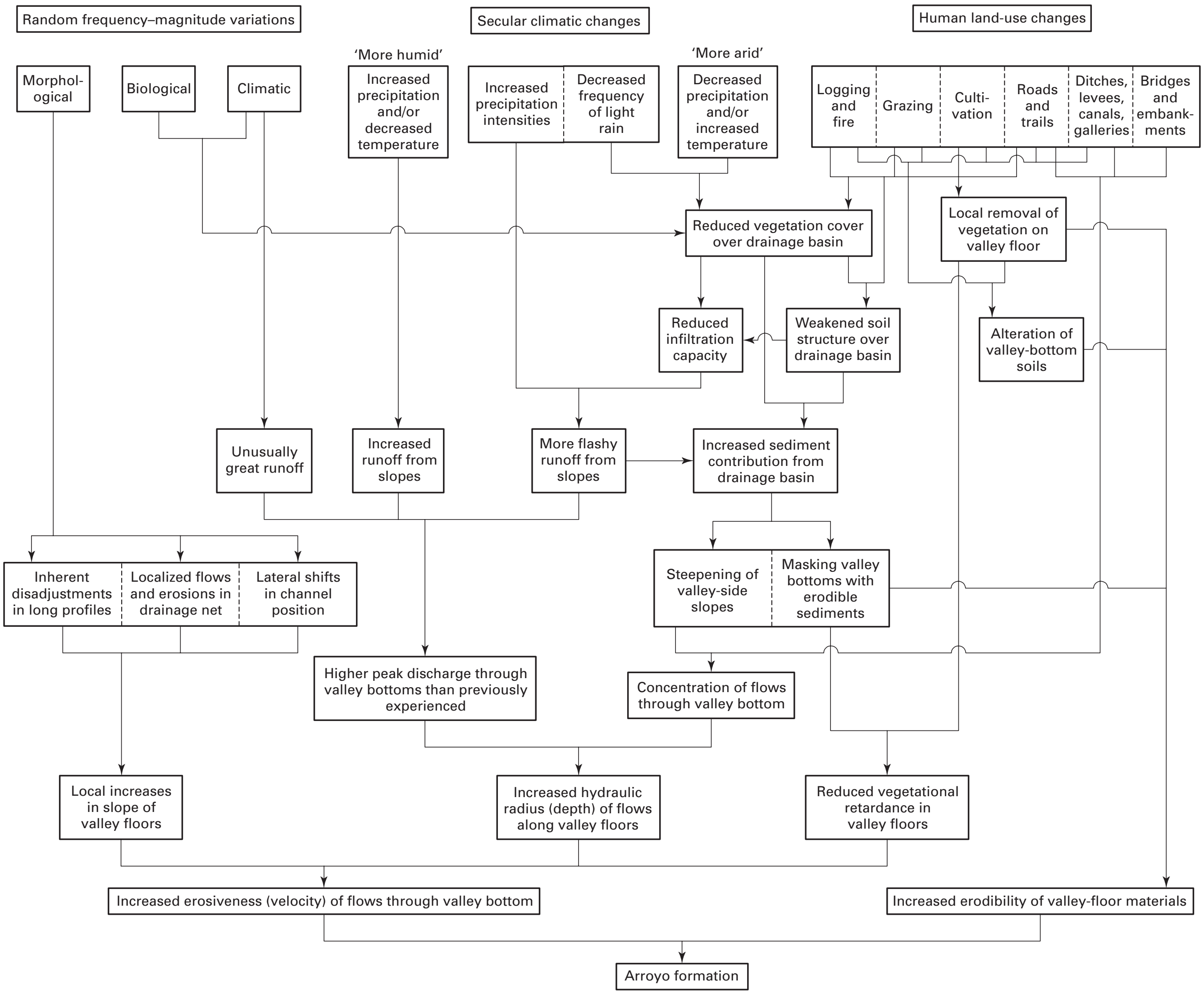

Figure 6.12 A model for the formation of arroyos (gullies) in southwestern USA (after Cooke and Reeves, 1976, figure 1.2).

human influence. It could be the result of some natural geomorphologic threshold being crossed. Under this argument, conditions of valley-floor stability decrease slowly over time until some triggering event initiates incision of the previously 'stable' reach.

It is therefore clear that the possible mechanisms that can lead to alternations of cut-and-fill of valley sediments are extremely complex, and that any attribution of all arroyos in all areas to human activities may be a serious oversimplification of the problem (Figure 6.12). In addition, it is possible that natural environmental changes, such as changes in rainfall characteristics, have operated at the same time and in the same direction as human actions.

In the Mediterranean lands there have also been controversies surrounding the age and causes of alternating phases of aggradation and erosion in valley bottoms. Vita-Finzi (1969) suggested that at some stage during historical times many of the steams in the Mediterranean area, which had hitherto been engaged

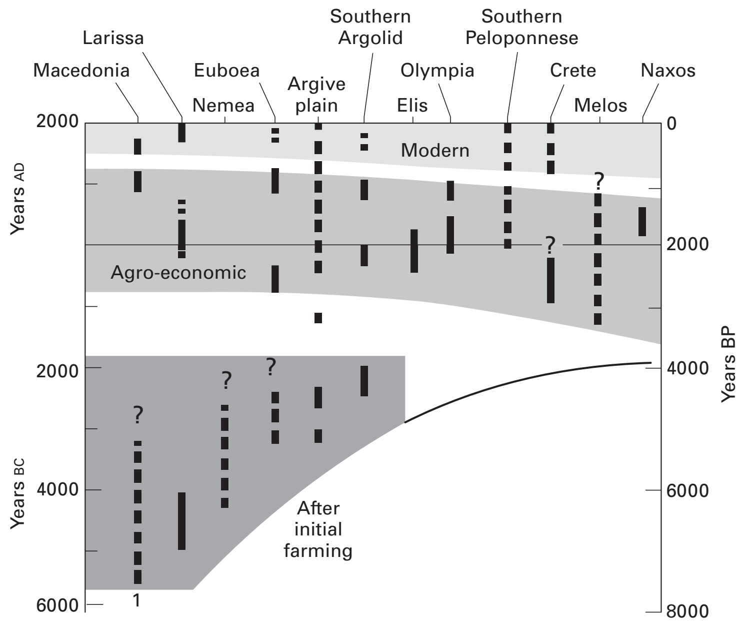

Figure 6.13 Chronology of Holocene alluviation in Greece and the Aegean. Broken bars are dated uncertainly or represent intermittent deposition (from various sources in Van Andel et al., 1990, figure 10).

primarily in downcutting, began to build up their beds. Renewed downcutting, still seemingly in operation today, has since incised the channels into the alluvial fill. He proposed that the reversal of the downcutting trend in the Middle Ages was both ubiquitous and confined in time, and that some universal and time-specific agency was required to explain it. He believed that devegetation by humans was not a medieval innovation and that some other mechanism was required. A solution he gave to account for the phenomenon was precipitation change during the climatic fluctuation known as the **Little Ice Age** (AD 1550–1850). This was not an interpretation that found favor with Butzer (1974). He reported that his investigations showed plenty of post-Classical and pre-1500 alluviation (which could not therefore be ascribed to the Little Ice Age), and he doubted whether Vita-Finzi's dating was precise enough to warrant a 1550–1850 date. Instead, he suggested that humans were responsible for multiple phases of accelerated erosion from slopes, and accelerated sedimentation in valley bottoms, from as early as the middle of the first millennium BC.

Butzer's interpretation has found favor with van Andel et al. (1990) who have detected an intermittent and complex record of cut-and-fill episodes during the late Holocene in various parts of Greece (Figure 6.13). They believe that this evidence is compatible with a model of the control of timing and intensity of landscape destabilization by local economic and political conditions. This is a view shared in the context of the Algarve in Portugal by Chester and James (1991).

A further location with spectacular gullies, locally called *lavaka*, is Madagascar. Here too there have been debates about cultural versus natural causation. Proponents of cultural causes have argued that since humans arrived on the island in the last two thousand years there has been excessive cattle grazing, removal of forest for charcoal and for slash-and-burn cultivation, devastating winter (dry season) burning of grasslands, and erosion along tracks and trails. However, the situation is more complex than that and the *lavaka* are polygenetic. Tectonism and natural climatic acidification may be at least as important, and given the climatic and soil types of the island many *lavaka* are a natural part of the landscape's evolution. Some of them also clearly predate primary (i.e., uncut) rain forest. The many factors, natural and cultural, involved in *lavaka* development are well reviewed by Wells and Andriamihaja (1993).

Another example of drainage incision that demonstrates the problem of disentangling the human from the natural causes of erosion is provided by the eroding peat bogs of highland Britain (Bragg and Tallis, 2001). Over many areas, including the Pennines of northern

England and the Brecon Beacons of Wales, blanket peats are being severely eroded to produce pool and hummock topography, areas of bare peat, and incised gullies (haggs). Many rivers draining such areas are discolored by the presence of eroded peat particles, and sediment yields of organic material are appreciable (Labadz et al., 1991).

Some of the observed peat erosion may be an essentially natural process, for the high water content and low cohesion of undrained peat masses make them inherently unstable. Moreover, the instability must normally become more pronounced as peat continues to accumulate, leading to bog slides and bursts round margins of expanded peat blankets. Conway (1954) suggested that an inevitable end-point of peat build-up on high-altitude, flat or convex surfaces is that a considerable depth of unconsolidated and poorly humidified peat overlies denser and well-humidified peat, so adding to the instability. Once a bog burst or slide occurs, this leads to the formation of drainage gullies which extend back into the peat mass, slumping-off marginal peat downslope, and leading to the drawing off of water from the pools of the hummock and hollow topography of the watershed.

Tallis (1985) believes that there have been two main phases of erosion in the Pennines. The first, initiated 1000–1200 years ago, may have been caused by natural instability of the type outlined above. However, there has been a second stage of erosion, initiated 200–300 years ago, in which miscellaneous human activities appear to have been important. Radley (1962) suggested that among the pressures that had caused erosion were heavy sheep grazing, regular burning, peat cutting, the digging of boundary ditches, the incision of packhorse tracks, and military maneuvers during the First World War. Other causes may include footpath erosion (Wishart and Warburton, 2001) and severe air pollution (Tallis, 1965), the latter causing the loss of a very important peat forming moss, *Sphagnum*. In South Wales, there is some evidence that the blanket peats have degenerated as a result of contamination by particulate pollution (soot, etc.) during the Industrial Revolution (Chambers et al., 1979). On the other hand, in Scotland lake-core studies indicate that severe peat erosion was initiated between AD 1500 and 1700, prior to air pollution associated with industrial growth, and Stevenson et al. (1990) suggest that this erosion initiation may have been caused either by the adverse climatic conditions of the Little Ice Age or by an increasing intensity of burning as land use pressures increased.

Accelerated weathering and the tufa decline

Although fewer data are available and the effects are generally less immediately obvious, there is some evidence that human activities have produced changes in the nature and rate of weathering (Winkler, 1970). The prime cause of this is probably air pollution. It is clear that, as a result of increased emissions of sulfur dioxide through the burning of fossil fuels, there are higher levels of sulfuric acid in rain over many industrial areas. This in itself may react with stones and cause their decay. Chemical reactions involving sulfur dioxide can also generate salts such as calcium sulfate and magnesium sulfate, which may be effective in causing the physical breakdown of rock through the mechanism of salt weathering.

Similarly, atmospheric carbon-dioxide levels have been rising steadily because of the burning of fossil fuels, and deforestation. Carbon dioxide may combine with water, especially at lower temperatures, to produce weak carbonic acid, which can dissolve limestone, marbles, and dolomites. Weathering can also be accelerated by changes in groundwater levels resulting from irrigation. This can be illustrated by considering the Indus Plain in Pakistan (Goudie, 1977), where irrigation has caused the water table to be raised by about 6 m since 1922. This has produced increased evaporation and salinization. The salts that are precipitated by evaporation above the capillary fringe include sodium sulfate, a very effective cause of stone decay. Indeed buildings, such as the great archaeological site of Mohenjo-Daro, are decaying at a catastrophic rate (Figure 6.14).

In other cases accelerated weathering has been achieved by moving stone from one environment to another. Cleopatra's Needle, an Egyptian obelisk in New York City, is an example of rapid weathering of stone in an inhospitable environment. Originally erected on the Nile opposite Cairo about 1500 BC, it was toppled in about 500 BC by Persian invaders, and lay partially buried in Nile sediments until, in 1880, it was moved to New York. It immediately began to

Figure 6.14 The ancient city of Mohenjo-Daro in Pakistan was excavated in the 1920s. Irrigation has been introduced into the area, causing groundwater levels to be raised. This has brought salt into the bricks of the ancient city, producing severe disintegration.

suffer from scaling and the inscriptions were largely obliterated within ten years because of the penetration of moisture, which enabled frost-wedging and hydration of salts to occur.

During the 1970s and 1980s an increasing body of isotopic dates became available for deposits of tufa (secondary freshwater deposits of limestone, also known as travertine). Some of these dates suggest that over large parts of Europe, from Britain to the Mediterranean basin and from Spain to Poland, rates of tufa formation were high in the early and mid-Holocene, but declined markedly thereafter (Weisrock, 1986: 165–7). Vaudour (1986) maintains that since around 3000 years BP 'the impact of man on the environment has liberated their disappearance', but he gives no clear indication of either the basis of this point of view or of the precise mechanism(s) that might be involved. If the late Holocene reduction in tufa deposition is a reality, then it is necessary to consider a whole range of possible mechanisms, both natural and anthropogenic (Nicod, 1986: 71–80; Table 6.7). As yet the case for an anthropogenic role is not proven (Goudie et al., 1993).

Accelerated mass movements

There are many examples of **mass movements** being triggered by human actions (Selby, 1979). For instance, landslides can be created either by undercutting or by overloading (Figure 6.15). When a road is constructed, material derived from undercutting the upper hillside may be cast on to the lower hillslope as a relatively loose fill to widen the road bed. Storm water is then often diverted from the road on to the loose fill.

Because of the hazards presented by both natural and accelerated mass movements, humans have developed a whole series of techniques to attempt to control them. Such methods, many of which are widely used by engineers, are listed in Table 6.8. These techniques are increasingly necessary, as human capacity to change a hillside and to make it more prone to slope failure has been transformed by engineering development. Excavations are going deeper, buildings and other structures are larger, and many sites that are at best marginally suitable for engineering projects are now being used because of increasing pressure on land. This applies especially to some of the expanding urban areas in the humid parts of low latitudes – Hong Kong, Kuala Lumpur, Rio de Janeiro, and many others. It is very seldom that human agency deliberately accelerates mass movements; most are accidentally

Table 6.7 Some possible mechanisms to account for the alleged Holocene tufa decline

Climatic/natural	*Anthropogenic*
Discharge reduction following rainfall decline leading to less turbulence	Discharge reduction due to overpumping, diversions, etc.
Degassing leads to less deposition	Increased flood scour and runoff variability of channels due to deforestation, urbanization, ditching, etc.
Increased rainfall causing more flood scour	Channel shifting due to deforestation of floodplains leads to tufa erosion
Decreasing temperature leads to less evaporation and more CO_2 solubility	Reduced CO_2 flux in system after deforestation
Progressive Holocene peat development and soil podzol development through time leads to more acidic surface waters	Introduction of domestic stock causes breakdown of fragile tufa structures
	Deforestation = less fallen trees to act as foci for tufa barrages
	Increased stream turbidity following deforestation reduces algal productivity

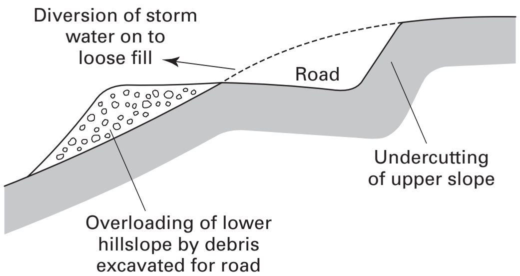

Figure 6.15 Slope instability produced by road construction.

Table 6.8 Methods used to control mass movements on slopes. Source: after R. F. Baker and H. E. Marshall, in Dunne and Leopold (1978, table 15.16)

Type of movement	*Method of control*
Falls	Flattening the slope Benching the slope Drainage Reinforcement of rock walls using anchor bolts and grouting with cement Covering of walls with steel mesh
Slides and flows	Grading or benching to flatten slope Drainage of surface water with ditches Sealing surface cracks to prevent infiltration Subsurface drainage Rock and earth buttresses at foot Retaining walls at foot Pilings through the potential slide mass

caused, the exception possibly being the deliberate triggering of a threatening snow avalanche (Perla, 1978).

The forces producing slope instability and landsliding can be divided usefully into disturbing forces and resisting properties (Cooke and Doornkamp, 1990: 113–14). The factors leading to an increase in shear stress (disturbing forces) can be listed as follows (modified after Cooke and Doornkamp, 1990: 113):

1 removal of lateral or underlying support
  - undercutting by water (e.g., river, waves), or glacier ice
  - weathering of weaker strata at the toe of a slope
  - washing out of granular material by seepage erosion
  - *human cuts and excavations, drainage of lakes or reservoirs*

2 increased disturbing forces
  - natural accumulations of water, snow, talus
  - *pressure caused by human activity* (e.g., stockpiles of ore, tip-heaps, rubbish dumps, or buildings)

3 transitory earth stresses
  - earthquakes
  - *continual passing of heavy traffic*

4 increased internal pressure
  - build-up of pore-water pressures (e.g., in joints and cracks, especially in the tension crack zone at the rear or the slide)

Some of the factors are natural, while others (italicized) are affected by humans. Factors leading to a decrease in the shearing resistance of materials making up a slope can also be summarized (also modified after Cooke and Doornkamp, 1990: 113).

1 Materials:
  - beds which decrease in shear strength if water content increases (clays, shale, mica, schist, talc, serpentine) (e.g., *when local water-table is artificially increased in height by reservoir construction*), or as a result of stress release (vertical and/or horizontal) following slope formation;
  - low internal cohesion (e.g., consolidated clays, sands, porous organic matter);
  - in bedrock – faults, bedding planes, joints, foliation in schists, cleavage, brecciated zones, and pre-existing shears.

2 Weathering changes:
  - weathering reduces effective cohesion, and to a lesser extent the angle of shearing resistance;
  - absorption of water leading to changes in the fabric of clays (e.g., loss of bonds between particles or the formation of fissures).

3 Pore-water pressure increase:
  - high groundwater table as a result of increased precipitation, or *as a result of human interference* (e.g., *dam construction*) (see 1 above).

Once again the italics show that there are a variety of ways in which humans can play a role.

Some mass movements are created by humans piling up waste soil and rock into unstable accumulations that fail spontaneously. At Aberfan, in South Wales, a major disaster occurred when a coal-waste tip 180 m high began to move as an earth flow. The tip had been constructed not only as a steep slope but also upon a spring line. This made an unstable configuration, which eventually destroyed a school and claimed over 150 lives. In Hong Kong, where a large proportion of the population is forced to occupy steep slopes developed on deeply weathered granites and other rocks, mass movements are a severe problem, and So (1971) has shown that many of the landslides and washouts (70% of those in the great storm of June 1966, for example) were associated with road sections and slopes artificially modified through construction and cultivation.

In southeastern France humans have accelerated landslide activity by building excavations for roads and by loading slopes with construction material (Julian and Anthony, 1996). The undercutting and removal of the trees on slopes for the construction of roads and paths has also led to landsliding in the Himalayas (Barnard et al., 2001). The arrival of European settlers in New Zealand, particularly since the 1840s, had a profound effect on landslide activity, as they cleared the forest and converted it to pasture (Glade, 2003).

One of the most serious mass movements partly caused by human activity was that which caused the Vaiont Dam disaster in Italy in 1963, in which 2600 people were killed (Kiersch, 1965). Heavy antecedent rainfall and the presence of young, highly folded sedimentary rocks provided the necessary conditions for a slip to take place, but it was the construction of the Vaiont Dam itself which changed the local groundwater conditions sufficiently to affect the stability of a rock mass on the margins of the reservoir: 240×10^6 m^3 of ground slipped, causing a rise in water level which overtopped the dam and caused flooding and loss of life downstream. Comparable slope instability resulted when the Franklin D. Roosevelt lake was impounded by the Columbia River in the USA (Coates, 1977), but the effects were, happily, less serious.

It is evident from what has been said about the predisposing causes of the slope failure *triggered* by the Vaiont Dam that human agency was only able to have such an impact because the natural conditions were broadly favorable. Exactly the same lesson can be learnt from the accelerated landsliding in southern Italy. Nossin (1972) has demonstrated how, in Calabria, road construction has triggered off (and been hindered by) landsliding, but he has also stressed that the area is fundamentally susceptible to such mass movement activity because of geologic conditions. It is an area where recent rapid uplift has caused downcutting by rivers and the undercutting of slopes by erosion. It is also an area of incoherent metamorphic rocks, with frequent faulting. Further, water is often trapped by Tertiary clay layers, providing further stimulus to movement.

Although the examples of accelerated mass movements that have been given here are essentially associated with the effects of modern construction projects, more long-established activities, including deforestation and agriculture, are also highly important. For example, Innes (1983) has demonstrated, on the basis of lichenometric dating of debris-flow deposits in the Scottish Highlands, that most of the flows have developed in the past 250 years, and he suggests that intensive burning and grazing may be responsible.

Fire, whether natural or man-induced, can be a major cause of slope instability and debris flow generation by removing or reducing protective vegetation, by increasing peak stream flows, and by leading to larger soil moisture contents and soil-water pore pressures (because of reduced interception of rainfall and decreased moisture loss by transpiration) (Wondzell and King, 2003). Examples of fire-related debris flow generation are known from many sites in the USA, including Colorado (Cannon et al., 2001b), New Mexico (Cannon et al., 2001a), the Rocky Mountains and the Pacific North West (Wondzell and King, 2003).

However, as with so many environmental changes of that nature in the past, there are considerable difficulties in being certain about causation. This has been well expressed by Ballantyne (1991: 84):

> Although there is growing evidence for Late Holocene erosion in upland Britain, the causes of this remain elusive. A few studies have presented evidence linking erosion to vegetation degradation and destruction due to human influence, but the validity of climatic deterioration as a cause of erosion remains unsubstantiated. This uncertainty stems from a tendency to link erosion with particular causes only through assumed coincidence in timing, a procedure fraught with difficulty because of imprecision in the dating of both putative causes and erosional effects. Indeed, in many reported instances, it is impossible to refute the possibility that the timing of erosional events or episodes may be linked to high magnitude storms of random occurrence, and bears little relation to either of the casual hypotheses outlined above. . . .

Deliberate modification of channels

Both for purposes of navigation and flood control humans have deliberately straightened many river channels. Indeed, the elimination of meanders contributes to flood control in two ways. First, it eliminates some overbank floods on the outside of curves, against which the swiftest current is thrown and where the water surface rises highest. Second, and more importantly, the resultant shortened course increases both the gradient and the flow velocity, and the floodwaters erode and deepen the channel, thereby increasing its flood capacity.

It was for this reason that a program of channel cutoffs was initiated along the Mississippi in the early 1930s. By 1940 it had lowered flood stages by as much as 4 m at Arkansas City, Arkansas. By 1950 the length of the river between Memphis, Tennessee and Baton Rouge, Louisiana (600 km down the valley) had been reduced by no less than 270 km as a result of 16 cutoffs.

Some landscapes have become dominated by artificial channels, normally once again because of the need for flood alleviation and drainage. This is especially evident in an area such as the English Fenlands where straight constructed channels contrast with the sinuous courses of original rivers such as the Great Ouse.

Table 6.9 Human impacts on Australian stream channel morphology

Channel incision by changes to resistance of valley flow (drains, cattle tracks)
Enlargement due to catchment clearing and grazing
Channel enlargement by sand and gravel extraction
Erosion by boats
Scour downstream from dams
Channelization and river training
Acceleration of meander migration rates by removal of riparian vegetation
Channel avulsion because of clearing of floodplain vegetation
Sedimentation resulting from mining
Channel contraction below dams
Channel invasion and narrowing by exotic vegetation

Table 6.10 Causes of riverbed degradation. Source: after Galay (1983)

Type	*Primary cause*	*Contributory cause*
Downstream progressing	Decrease of bed-material discharge	Dam construction
		Excavation of bed material
		Diversion of bed material
		Change in land use
		Storage of bed material
	Increased water discharge	Diversion of flow
		Rare floods
	Decrease in bed-material size	River emerging from lake
	Other	Thawing of permafrost
Upstream progressing	Lower base level	Drop in lake level
		Drop in level of main river
		Excavation of bed material
	Decrease in river length	Cutoffs
		Channelization
		Stream capture
		Horizontal shift of base level
	Removal of control point	Natural erosion
		Removal of dam

Nondeliberate river-channel changes

There are thus many examples of the intentional modification of river-channel geometry by humans – by the construction of embankments, by channelization, and by other such processes. The complexity and diversity of causes of stream channel change is brought out in the context of Australia (Table 6.9) (Rutherford, 2000), and more generally by Downs and Gregory (2004). Major changes in the configuration of channels can be achieved accidentally (Table 6.10), either because of human-induced changes in stream discharge or in their sediment load: both parameters affect channel capacity (Park, 1977). The causes of observed cases of riverbed degradation are varied and complex and result from a variety of natural and human changes (Table 6.11). A useful distinction can be drawn between degradation that proceeds downstream, and that which proceeds upstream, but in both cases the complexity of causes is evident.

Deliberate channel straightening causes various types of sequential channel adjustment both within and downstream from straightened reaches, and the types of adjustment vary according to such influences as stream gradient and sediment characteristics. Brookes (1987) recognized five types of change *within* the straightened reaches (types W1 to W5) and two

Table 6.11 Accidental channel changes

Phenomenon	*Cause*
Channel incision	Clear-water erosion below dams caused by sediment removal
Channel aggradation	Reduction in peak flows below dams Addition of sediment to streams by mining, agriculture, etc.
Channel enlargement	Increase in discharge level produced by urbanization
Channel diminution	Discharge decrease following water abstraction or flood control Trapping and stabilizing of sediment by artificially introduced plants
Channel planform	Change in nature of sediment load and its composition, together with flow regime

types of change downstream (types D1 and D2). They are illustrated in Figure 6.16.

Type W1 is degradation of the channel bed, which results from the fact that straightening increases the slope by providing a shorter channel path. This in turn increases its sediment transport capability.

Type W2 is the development of an armored layer on the channel bed by the more efficient removal of fine materials as a result of the increased sediment transport capability referred to above.

Type W3 is the development of a sinuous thalweg in streams that are not only straightened but which are also widened beyond the width of the natural channel.

Type W4 is the recovery of sinuosity as a result of bank erosion in channels with high slope gradients.

Type W5 is the development of a sinuous course by deposition in streams with a high sediment load and a relatively low valley gradient.

Types D1 and D2 result from deposition downstream as the stream tries to even out its gradient, the deposition occurring as a general raising of the bed level, or as a series of accentuated point bar deposits.

It is now widely recognized that the urbanization of a river basin results in an increase in the peak flood flows in a river. It is also recognized that the morphology of stream channels is related to their discharge characteristics, and especially to the discharge at which bank full flow occurs. As a result of urbanization, the frequency of discharges which fill the channel will increase, with the effect that the beds and banks of channels in erodible materials will be eroded so as to enlarge the channel (Trimble, 1997b). This in turn will lead to bank caving, possible undermining of structures, and increases in turbidity (Hollis and Luckett, 1976). Trimble (2003) provides a good historical analysis of how the San Diego Creek in Orange County, California, has responded to flow and sediment yield changes related to the spread of both agriculture and urbanization.

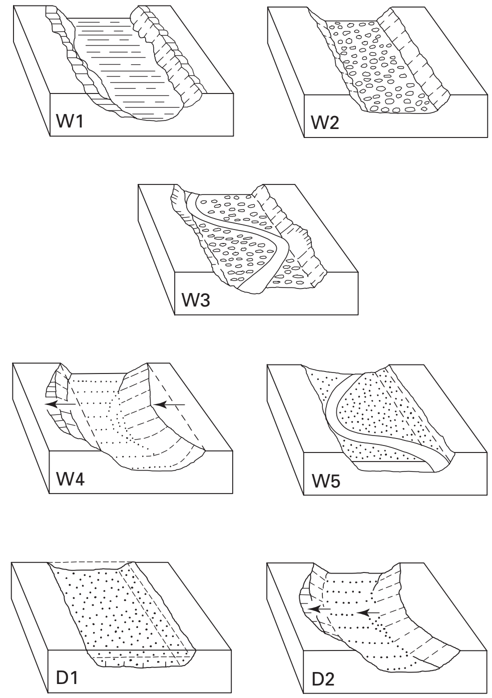

Figure 6.16 Principal types of adjustment in straightened river changes (after Brookes, 1987, figure 4). For an explanation of the different types see text.

Changes in channel morphology also result from discharge diminution and sediment load changes produced by flood-control works and diversions for irrigation (Brandt, 2000). This can be shown for the North Platte and the South Platte in America, where both peak discharge and mean annual discharge have declined to 10–30% of their pre-dam values. The North Platte, 762–1219 m wide in 1890 near the Wyoming Nebraska border, has narrowed to about 60 m at present, while the South Platte River was about 792 m wide, 89 km above its junction with the North Platte

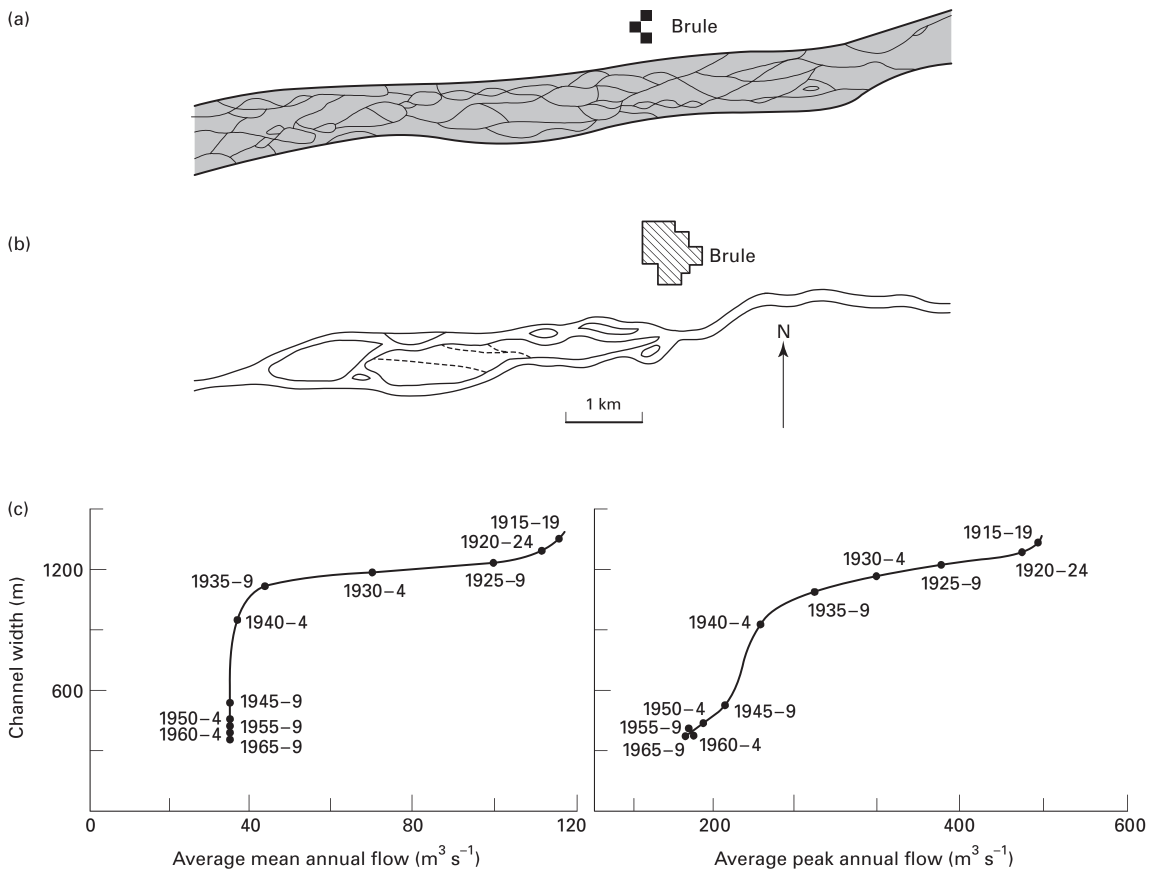

Figure 6.17 The configuration of the channel of the South Platte River at Brule, Nebraska, USA: (a) in 1897 and (b) in 1959. Such changes in channel form result from discharge diminution (c) caused by flood-control works and diversions for irrigation (after Schumm, 1977, figure 5.32 and Williams, 1978).

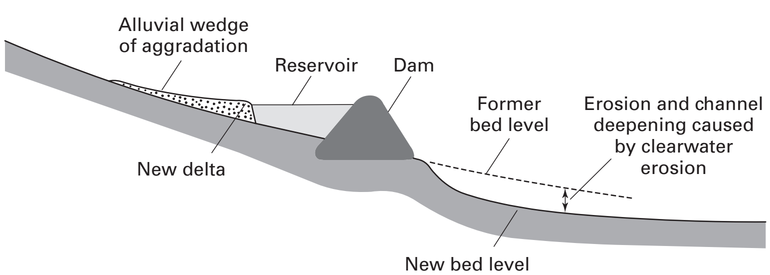

Figure 6.18 Diagrammatic long profile of a river showing the upstream aggradation and the downstream erosion caused by dam and reservoir construction.

in 1897, but had narrowed to about 60 m by 1959 (Schumm, 1977: 161). The tendency of both rivers has been to form one narrow, well-defined channel in place of the previously wide, braided channels, and, in addition, the new channel is generally somewhat more sinuous than the old (Figure 6.17).

Similarly, the building of dams can lead to channel aggradation upstream from the reservoir and channel deepening downstream because of the changes brought about in sediment loads (Figure 6.18). Some data on observed rates of degradation below dams are presented in Table 6.12. They show that the average rate of degradation has been of the order of a few meters over a few decades following closure of the dams. However, over time the rate of degradation seems to become less or to cease altogether, and Leopold et al.

Table 6.12 Riverbed degradation below dams. Source: From data in Galay (1983)

River	*Dam*	*Amount (m)*	*Length (km)*	*Time (years)*
South Canadian (USA)	Conchos	3.1	30	10
Middle Loup (USA)	Milburn	2.3	8	11
Colorado (USA)	Hoover	7.1	111	14
Colorado (USA)	Davis	6.1	52	30
Red (USA)	Denison	2.0	2.8	3
Cheyenne (USA)	Angostura	1.5	8	16
Saalach (Austria)	Reichenhall	3.1	9	21
South Saskatchewan (Canada)	Diefenbaker	2.4	8	12
Yellow (China)	Samenxia	4.0	68	4

Table 6.13 Channel capacity reduction below reservoirs. Source: modified after Petts (1979, table 1)

River	*Dam*	*Channel capacity loss (%)*
Republican, USA	Harlan County	66
Arkansas, USA	John Martin	50
Rio Grande, USA	Elephant Buttre	50
Tone, UK	Clatworthy	54
Meavy, UK	Burrator	73
Nidd, UK	Angram	60
Burn, UK	Burn	34
Derwent, UK	Ladybower	40

(1964: 455) suggest that this can be brought about in several ways. First, because degradation results in a flattening of the channel slope in the vicinity of the dam, the slope may become so flat that the necessary force to transport the available materials is no longer provided by the flow. Second, the reduction of flood peaks by the dam reduces the competence of the transporting stream to carry some of the material on its bed. Thus if the bed contains a mixture of particle size the river may be able to transport the finer sizes but not the larger, and the gradual winnowing of the fine particles will leave an armor of coarser material that prevents further degradation.

The overall effect of the creation of reservoirs by the construction of a dam is to lead to a reduction in downstream channel capacity (see Petts, 1979, for a review). This seems to amount to between about 30 m and 70% (see Table 6.13).

Equally far-reaching changes in channel form are produced by land-use changes and the introduction of soil conservation measures. Figure 6.19 is an idealized representation of how the river basins of Georgia in the USA have been modified through human agency between 1700 (the time of European settlement) and the present. Clearing of the land for cultivation (Figure 6.19b) caused massive slope erosion, which resulted in the transfer of large quantities of sediment into channels and floodplains. The phase of intense erosive land use persisted and was particularly strong during the nineteenth century and the first decades of the twentieth century, but thereafter (Figure 6.19c) conservation measures, reservoir construction, and a reduction in the intensity of agricultural land use led to further channel changes (Trimble, 1974). Streams ceased to carry such a heavy sediment load, they became much less turbid, and incision took place into the floodplain sediments. By means of this active streambed erosion, streams incised themselves into the modern alluvium, lowering their beds by as much as 3–4 m.

In the Platte catchment of southwest Wisconsin a broadly comparable picture of channel change has been documented by Knox (1977). There, as in the Upper Mississippi Valley (Knox, 1987), it is possible to identify stages of channel modification associated with various stages of land use, culminating in decreased overbank sedimentation as a result of better land management in the past half century.

Other significant changes produced in channels include those prompted by accelerated sedimentation associated with changes in the vegetation communities growing along channels. The introduction of salt cedar in the southern USA has caused significant floodplain aggradation. In the case of the Brazos River in Texas, for example, the plants encourage sedimentation by their damming and ponding effect. They clogged channels by invading sand banks and sand bars, and so increased the area subject to flooding. Between 1941 and 1979 the channel width declined from 157 to 67 m, and the amount of aggradation was as much as 5.5 m (Blackburn et al., 1983). Equally, the establishment or re-establishment of riparian forest has been implicated with channel narrowing in southeastern France during the twentieth century (Liébault and Piégay, 2002).

There is, however, a major question about the ways in which different vegetation types affect channel form (Trimble, 2004). Are tree-lined banks more stable than

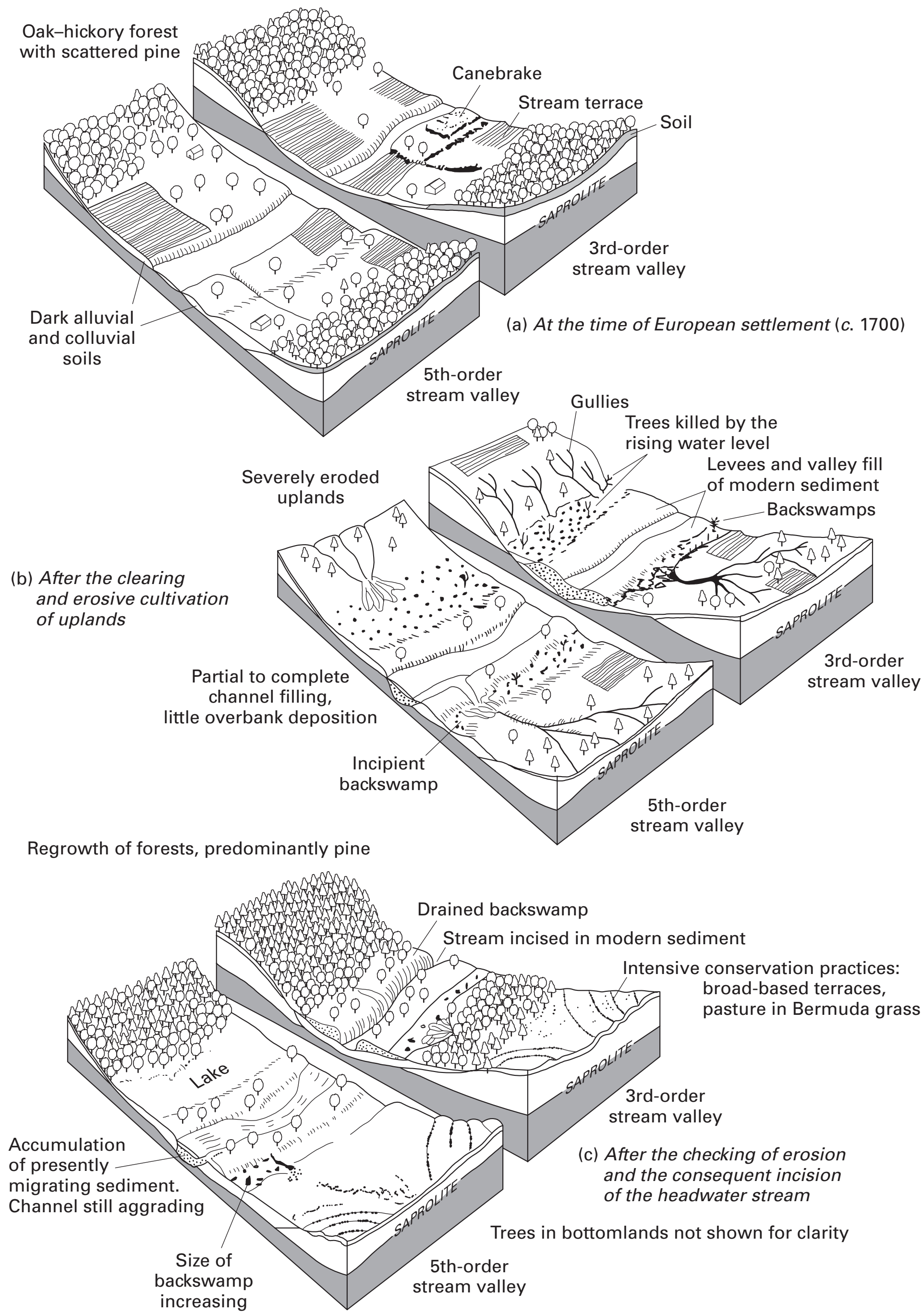

Figure 6.19 Changes in the evolution of fluvial landscapes in the Piedmont of Georgia, USA, in response to land-use change between 1700 and 1970 (after Trimble, 1974, p. 117, in S. W. Trimble, *Man-induced soil erosion on the southern Piedmont*, Soil Conservation Society of America. © Soil Conservation Society of America).

those flowing through grassland? On the one hand tree roots stabilize banks and their removal might be expected to cause channel widening and shallowing (Brooks and Brierly, 1997). On the other hand, forests produce log-jams that can cause aggradation or concentrate flow on to channel banks, thereby leading to their erosion. These issues are discussed in Trimble (1997b) and Montgomery (1997).

Another organic factor that can modify channel form is the activity of grazing animals. These can break the banks down directly by trampling and can reduce bank resistance by removing protective vegetation and loosening soil (Trimble and Mendel, 1995).

Finally, the addition of sediments to stream channels by mining activity can cause channel aggradation. Mine wastes can clog channel systems (Gilbert, 1917; Lewin et al., 1983). Equally, the mining of aggregates from river beds themselves can lead to channel deepening (Bravard and Petts, 1996: 246–7).

Reactivation and stabilization of sand dunes

To George Perkins Marsh the reactivation and stabilization of sand dunes, especially coastal dunes, was a theme of great importance in his analysis of human transformation of nature. He devoted 54 pages to it:

> The preliminary steps, whereby wastes of loose, drifting, barren sands are transformed into wooded knolls and plains, and finally through the accumulation of vegetable mold, into arable ground, constitute a conquest over nature which proceeds agriculture – a geographical revolution – and therefore, an account of the means by which the change has been effected belongs properly to the history of man's influence on the great features of physical geography (1965: 393).

He was fascinated by 'the warfare man wages with the sand hills' and asked (1965: 410) 'in what degree the naked condition of most dunes is to be ascribed to the improvidence and indiscretion of man'.

His analysis showed quite clearly that most of the coastal dunes of Europe and North America had been rendered mobile, and hence a threat to agriculture and settlement, through human action, especially because of grazing and clearing. In Britain the cropping of dune warrens by rabbits was a severe problem, and a most significant event in their long history was the myxomatosis outbreak of the 1950s, which severely reduced the rabbit population and led to dramatic changes in stability and vegetative cover.

Appreciation of the problem of dune reactivation on mid-latitude shorelines, and attempts to overcome it, go back a long way (Kittredge, 1948). For example, the menace of shifting sand following denudation is recognized in a decree of 1539 in Denmark, which imposed a fine on those who destroyed certain species of sand plants on the coast of Jutland. The fixation of coastal sand dunes by planting vegetation was initiated in Japan in the seventeenth century, while attempts at the reafforestation of the spectacular Landes dunes in southwest France began as early at 1717, and came to fruition in the nineteenth century through the plans of the great Bremontier: 81,000 hectares of moving sand had been fixed in the Landes by 1865. In Britain possibly the most impressive example of sand control is provided by the reafforestation of the Culbin Sands in northeast Scotland with conifer plantations (Edlin, 1976).

Human-induced dune instability is not, however, a problem that is restricted to mid-latitude coasts. In inland areas of Europe, clearing, fire, and grazing have affected some of the late Pleistocene dune fields that were created on the arid steppe margins of the great ice sheets, and in eastern England the dunes of the Breckland presented problems on many occasions. There are records of carriages being halted by sand-blocked roads and of one village, Downham, being overwhelmed altogether.

However, it is possibly on the margins of the great subtropical and tropical deserts that some of the strongest fears are being expressed about sand-dune reactivation. This is one of the facets of the process of desertification. The increasing population levels of both humans and their domestic animals, brought about by improvement in health and by the provision of boreholes, has led to an excessive pressure on the limited vegetation resources. As ground cover has been reduced, so dune instability has increased. The problem is not so much that dunes in the desert cores are relentlessly marching on to moister areas, but that the fossil dunes, laid down during the more arid phase peaking around 18,000 years ago, have been reactivated *in situ*.

A wide range of methods (Figure 6.20) is available to attempt to control drifting sand and moving dunes as follows:

1 drifting sand
   - enhancement of deposition of sand by the creation of large ditches, vegetation belts, and barriers and fences

Figure 6.20 Techniques to control dune movement: (a) a sand fence on a dune that threatens part of the town of Walvis Bay in Namibia; (b) a patchwork of palm frond fences being used at Erfoud on the edge of the Sahara in Morocco; (c) vegetation growth on coastal sand dunes at Hout Bay in South Africa being encouraged by irrigation.

- enhancement of transport of sand by aerodynamic streamlining of the surface, change of surface materials, or paneling to direct flow
- reduction of sand supply, by surface treatment, improved vegetation cover, or erection of fences
- deflection of moving sand, by fences, barriers, tree belts, etc.

2 moving dunes
- removal by mechanical excavation
- destruction by reshaping, trenching through dune axis, or surface stabilization of barchan arms
- immobilization by trimming, surface treatment, and fences

In practice most solutions to the problem of dune instability and sand blowing have involved the establishment of a vegetation cover. This is not always easy. Species used to control sand dunes must be able to endure undermining of their roots, burning, abrasion, and often severe deficiencies of soil moisture. Thus the species selected need to have the ability to recover after partial growth in the seedling stages, to promote rapid litter development, and to add nitrogen to the soil through root nodules. During the early stages of growth they may need to be protected by fences, sand traps, and surface mulches. Growth can also be stimulated by the addition of synthetic fertilizers.

In hearts of deserts sand dunes are naturally mobile because of the sparse vegetation cover. Even here, however, humans sometimes attempt to stabilize sand surfaces to protect settlements, pipelines, industrial plant and agricultural land. The use of relatively porous barriers to prevent or divert sand movement has proved comparatively successful, and palm fronds or chicken wire have made adequate stabilizers. Elsewhere surfaces have been strengthened by the application of high-gravity oil or by salt-saturated water (which promotes the development of wind-resistant surface crusts).

In temperate areas coastal dunes have been effectively stabilized by the use of various trees and other plants (Ranwell and Boar, 1986). In Japan *Pinus thumbergii* has been successful, while in the great Culbin Sands plantations of Scotland *P. nigra* and *P. laricio* have been used initially, followed by *P. sylvestris*. Of the smaller shrubs, *Hippophae* has proved highly efficient, sometimes too efficient, at spreading. Its clearance from areas where it is not welcome is difficult precisely

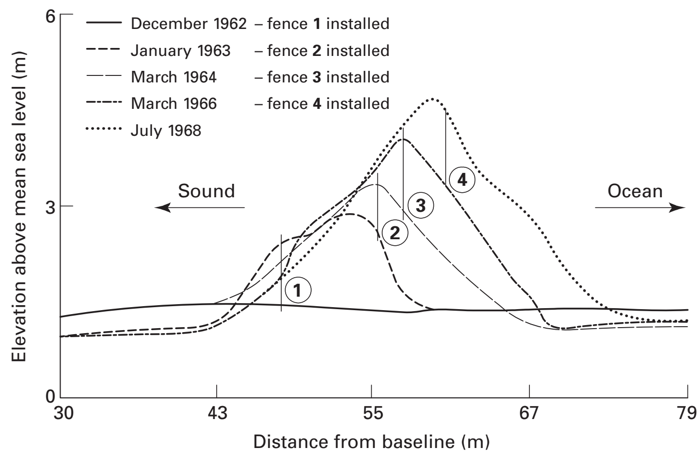

Figure 6.21 Sand accumulation using the method of multiple fences in North Carolina, USA. This raised the dune height approximately 4 m over a period of 6 years (after Savage and Woodhouse, in Goldsmith, 1978, figure 36).

because of some of the properties that make is such an efficient sand stabilizer: vigorous suckering growth and the rapid regrowth of cut stems (Boorman, 1977). Different types of grass have also been employed, especially in the early stages of stabilization. These include two grasses that are moderately tolerant of salt: *Elymus farctus* (sand twitch) and *Leymus arenarius* (lime grass). Another grass that is much used, not least because of its rapid and favorable response to burial by drifting sand, is *Ammophila arenaria* (marram).

Further stabilization of coastal dunes has been achieved by setting up sand fences. These generally consist of slats about 1.0–1.5 m high, and have a porosity of 25–50%. They have proved to be effective in building incipient dunes in most coastal areas. By installing new fences regularly, large dunes can be created with some rapidity (see Figure 6.21). Alternative methods, such as using junk cars on the beaches at Galveston, Texas, have been attempted with little success.

Accelerated coastal erosion

Because of the high concentration of settlements, industries, transport facilities, and recreational developments on coastlines, the pressures placed on coastal landforms are often acute (Nordstrom, 1994) and the consequences of excessive erosion serious. While most areas are subject to some degree of natural erosion and accretion, the balance can be upset by human activity in a whole range of different ways (Table 6.14). However, humans seldom attempt to accelerate coastal erosion deliberately. More usually, it is an unexpected or unwelcome result of various economic projects. Frequently coast erosion has been accelerated as a result of human efforts to reduce it.

One of the best forms of coastal protection is a good beach. If material is removed from a beach, accelerated cliff retreat may take place. Removal of beach materials may be necessary to secure valuable minerals, including heavy minerals, or to provide aggregates for construction. The classic example of the latter was the mining of 660,000 tonnes of shingle from the beach at Hallsands in Devon, England, in 1887 to provide material for the construction of dockyards at Plymouth. The shingle proved to be undergoing little or no natural replenishment and in consequence the shore level was reduced by about 4 m. The loss of the protective shingle soon resulted in cliff erosion to the extent of 6 m between 1907 and 1957. The village of Hallsands was cruelly attacked by waves and is now in ruins.

Another common cause of beach and cliff erosion at one point is coast protection at another (Figure 6.22). As already stated, a broad beach serves to protect the cliffs behind, and beach formation is often encouraged by the construction of **groynes** and a range of 'hard engineering' structures is available (Figure 6.23). However, these structures sometimes merely displace the erosion (possibly in an even more marked form) further along the coast. This is illustrated in Figure 6.24.

Piers or breakwaters can have similar effects to groynes. This has occurred at various places along the British coast: erosion at Seaford resulted from the Newhaven breakwater, while erosion at Lowestoft resulted

Table 6.14 Mechanisms of human-induced erosion in coastal zones. Source: Hails (1977: 348, table 9.11)

Human-induced erosion zones	Effects
Beach mining for placer deposits (heavy minerals) such as zircon, rutile, ilmenite and monazite	Loss of sand from frontal dunes and beach ridges
Construction of groynes, breakwaters, jetties and other structures	Downdrift erosion
Construction of offshore breakwaters	Reduction in littoral drift
Construction of retaining walls to maintain river entrances	Interruption of littoral drift resulting in downdrift erosion
Construction of sea-walls, revetments, etc.	Wave reflection and accelerated sediment movement
Deforestation	Removal of sand by wind
Fires	Migrating dunes and sand drift after destruction of vegetation
Grazing of sheep and cattle	Initiation of blow-outs and transgressive dunes: sand drift
Off-road recreational vehicles (dune buggies, trail bikes, etc.)	Triggering mechanism for sand drift attendant upon removal of vegetative cover
Reclamation schemes	Changes in coastal configuration and interruption of natural processes, often causing new patterns in sediment transport
Increased recreational needs	Accelerated deterioration, and destruction, of vegetation on dunal areas, promoting erosion by wind and wave action

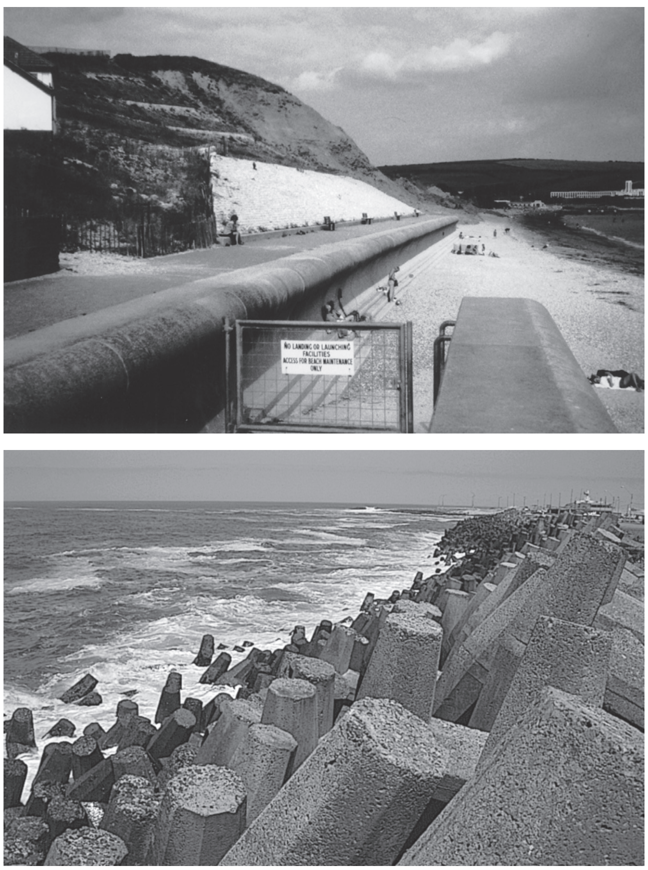

Figure 6.22 Coastal defense: (a) at Weymouth, southern England; (b) at Arica, northern Chile. The piecemeal emplacement of expensive sea walls and cliff protection structures is often only of short-term effectiveness and can cause accelerated erosion downdrift.

from the pier at Gorleston. Figure 6.25 illustrates the changes in location of beach erosion achieved by the building of jetties or breakwaters at various points. At Madras in southeast India, for example, a 1000-m-long breakwater was constructed in 1875 to create a sheltered harbor on a notoriously inhospitable coast, dominated by sand transport from north to south. On the south side of the breakwater over 1×10^6 m^2 of new land formed by 1912, but erosion occurred for 5 km north of the breakwater. At Ceara in Brazil, also in 1875, a detached breakwater was erected over a length of 430 m more or less parallel to the shore. It was believed that by using a detached structure littoral drift would be able to move along the coast uninterrupted by the presence of a conventional structure built across the surf zone. This, however, proved to be a fallacy (Komar, 1976), since the removal of the wave action which provided the energy for transporting the littoral sands resulted in their deposition within the protected area.

Figure 6.26 shows the evolution of the coast at West Bay in Dorset, southern England, following the construction of a jetty. As time goes on the beach in the foreground appears to build outwards, while the cliff behind the jetty retreats and so needs to be protected with a sea-wall and with large imported rock armor. Likewise, the construction of some sea-walls, erected to reduce coastal erosion and flooding, has had the opposite effect to the one intended (see Figure 6.27). Given the extent to which artificial structures have

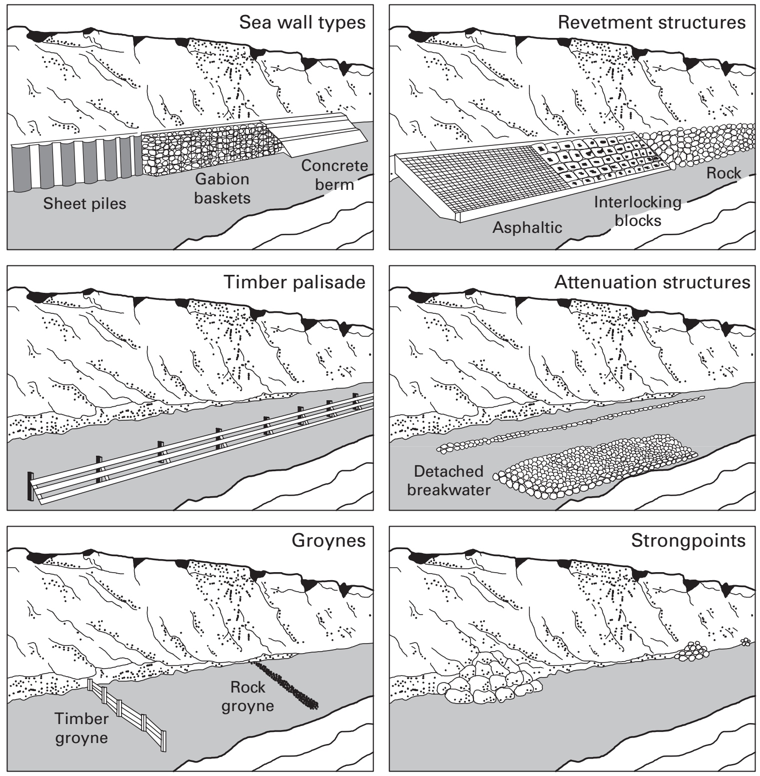

Figure 6.23 A selection of 'hard engineering' structures designed to afford coastal protection (modified from A. H. Brampton, 'Cliff conservation and protection: methods and practices to resolve conflicts', in J. Hooke (ed.), *Coastal and earth science conservation* (Geological Society Publishing House, 1998), figures 3.1, 3.2, 3.4, 3.5, 3.6, and 3.7).

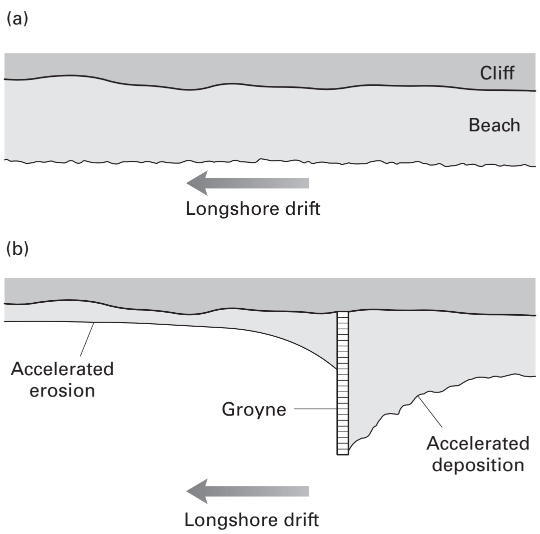

Figure 6.24 Diagrammatic illustration of the effects of groyne construction on sedimentation on a beach.

spread along the coastlines of the world, this is a serious matter (Walker, 1988).

Problems of this type are exacerbated because there is now abundant evidence to suggest that much of the reservoir of sand and shingle that creates beaches is in some respects a relict feature. Much of it was deposited on continental shelves during the maximum of the last glaciation (around 18,000 years BP), when sea level was about 120 m below its present level. It was transported shoreward and incorporated in present-day beaches during the phase of rapidly rising post-glacial sea levels that characterized the Flandrian transgression until about 6000 years BP. Since that time, with the exception of minor oscillations of the order of a few meters, world sea levels have been stable and much less material is, as a consequence, being added to beaches and shingle complexes. Therefore, according to Hails (1977: 322), 'in many areas, there is virtually no offshore supply to be moved onshore, except for small quantities resulting from seasonal changes.' It is because of these problems that many erosion prevention schemes now involve beach nourishment (by the artificial addition of appropriate sediments to build up the beach), or employ miscellaneous sand bypassing techniques (including pumping and dredging) whereby sediments are transferred from the accumulation side of an artificial barrier to the erosional side (King, 1974). Such methods of beach nourishment are reviewed by Bird (1996).

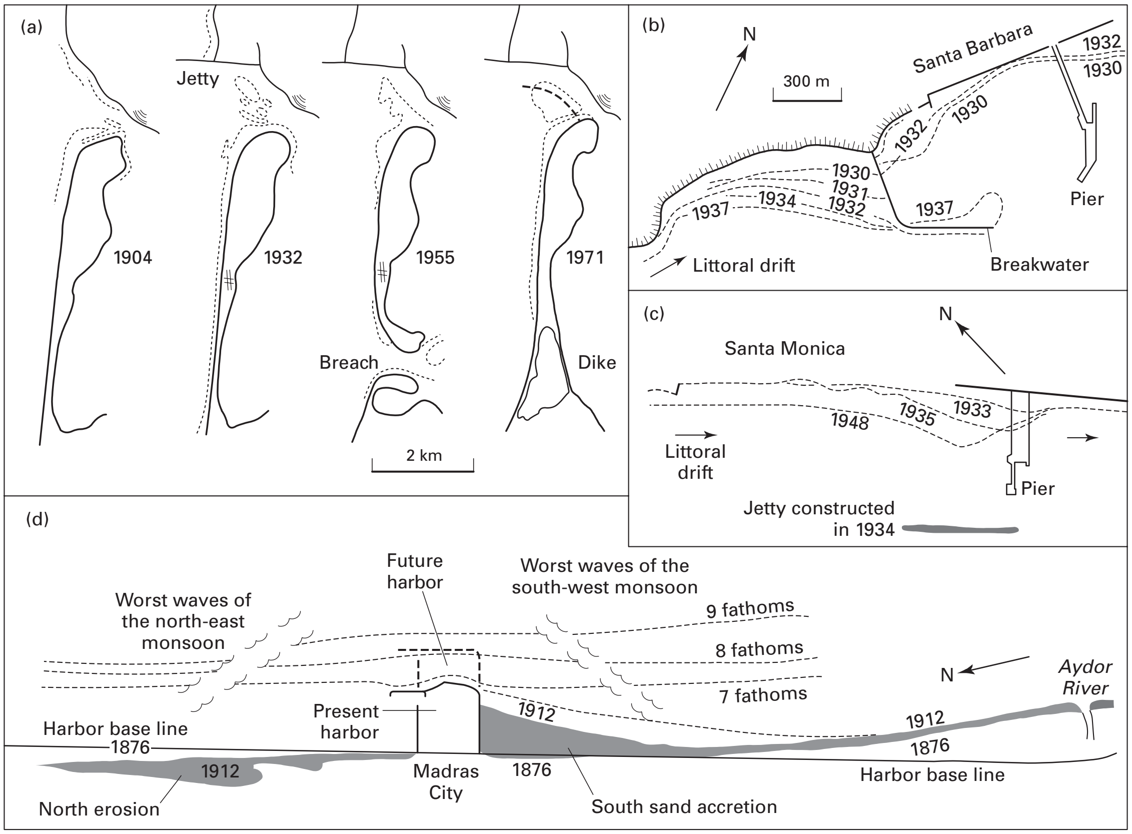

Figure 6.25 Examples of the effects of shoreline installations on beach and shoreline morphology. (a) Erosion of Bayocean Spit, Tillamook Bay, Oregon, after construction of a north jetty in 1914–17. The heavy dashed line shows the position of the new south jetty under construction. (b) The deposition–erosion pattern around the Santa Barbara breakwater in California. (c) Sand deposition in the protected lee of Santa Monica breakwater in California. (d) Madras Harbor, India, showing accretion on updrift side of the harbor and erosion on the downdrift side (after Komar, *Beach processes and sedimentation*, p. 334, © 1976. Reprinted by permission of Prentice-Hall Inc.).

In some areas, however, sediment-laden rivers bring material into the coastal zone, which becomes incorporated into beaches through the mechanism of longshore drift. Thus any change in the sediment load of such rivers may result in a change in the sediment budget of neighboring beaches. When accelerated soil erosion occurs in a river basin the increased sediment load may cause coastal accretion and siltation. But where the sediment load is reduced through action such as the construction of large reservoirs, behind which sediments accumulate, coastal erosion may result. This is believed to be one of the less desirable consequences of the construction of the Aswan Dam on the Nile: parts of its delta have shown recently accelerated recession.

The Nile sediments, on reaching the sea, used to move eastward with the general anticlockwise direction of water movements in that part of the eastern Mediterranean, generating sand bars and dunes that contributed to delta accretion. About a century ago an inverse process was initiated and the delta began to retreat. For example, the Rosetta mouth of the Nile lost about 1.6 km of its length from 1898 to 1954. The imbalance between sedimentation and erosion appears to have started with the Delta Barrages (1861) and culminated with the High Dam itself a century later. In addition, large amounts of sediment are retained in an extremely dense network of irrigation channels and drains that has been developed in the Nile Delta itself (Stanley, 1996). Much of the Egyptian coast is now

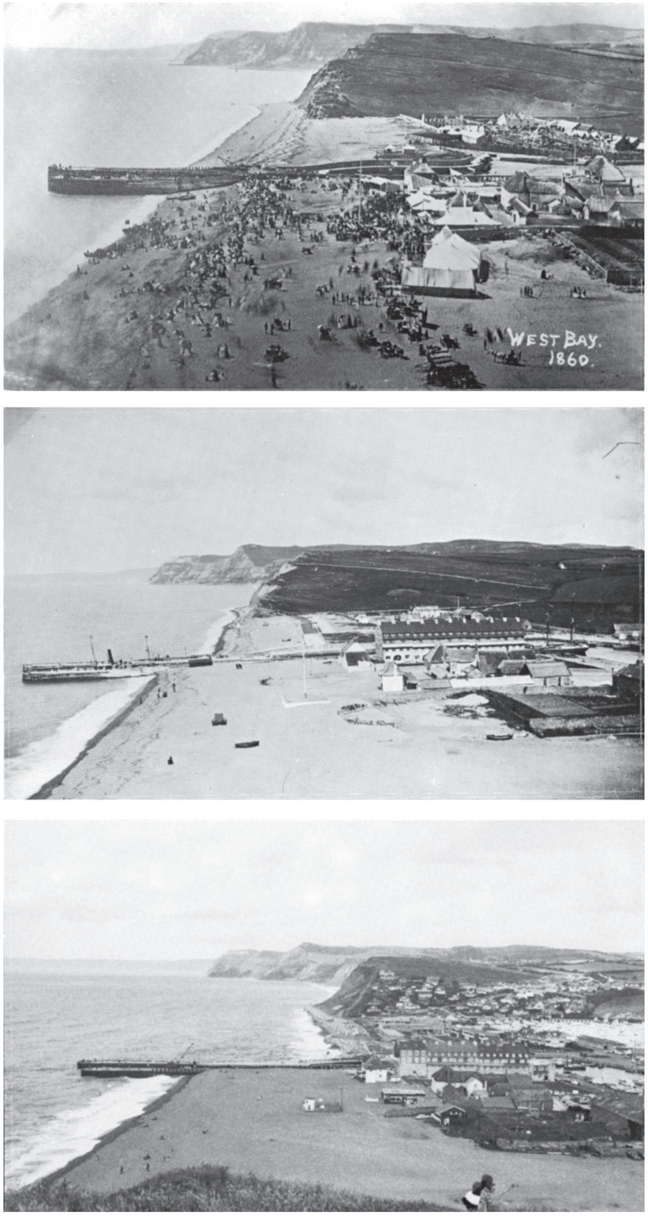

Figure 6.26 A jetty was built at West Bay, Dorset, to facilitate entry to the harbor. Top: in 1860 it had had little effect on the coastline. Center: by 1900 sediment accumulation had taken place in the foreground but there was less sediment in front of the cliff behind the town. Bottom: by 1976 the process had gone even further and the cliff had to be protected by a sea-wall. Even this has since been severely damaged by winter storms.

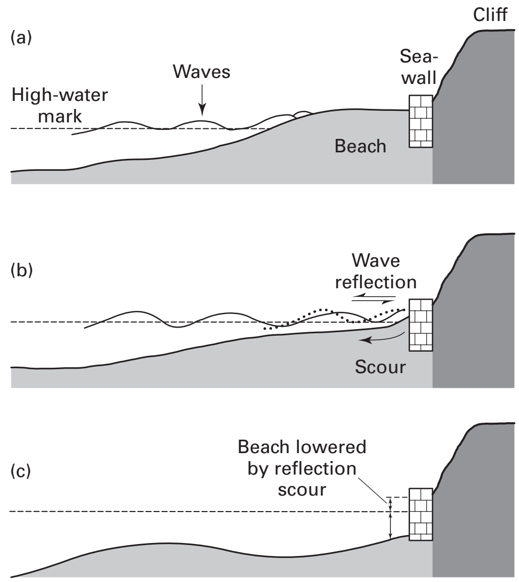

Figure 6.27 Sea-walls and erosion: (a) a broad, high beach prevents storm waves breaking against a sea-wall and will persist, or erode only slowly; but where the waves are reflected by the wall (b) scour is accelerated, and the beach is quickly removed and lowered (c) (modified after Bird, 1979, figure 6.3).

'undernourished' with sediment and, as a result of this overall erosion of the shoreline, the sand bars bordering Lake Manzala and Lake Burullus on the seaward side are eroded and likely to collapse. If this were to happen, the lakes would be converted into marine bays, so that saline water would come into direct contact with low-lying cultivated land and fresh-water aquifers.

Likewise in Texas, where over the past century four times as much coastal land has been lost as has been gained, one of the main reasons for this change is believed to be the reduction in the suspended loads of some of the rivers discharging into the Gulf of Mexico (Table 6.15). The four rivers listed carried, in 1961–70, on average only about one-fifth of what they carried in 1931–40. Comparably marked falls in sediment loadings occurred elsewhere in the eastern USA (Figure 6.28). Likewise, in France the once mighty Rhône only carries about 5% of the load it did in the nineteenth century; and in Asia, the Indus discharges less than 20% of the load it did before construction of large barrages over the past half century (Milliman, 1990). On a global basis, large dams may retain 25–30% of the global flux of river sediment (Vörösmarty et al., 2003).

Table 6.15 Suspended loads of Texas rivers discharging into the Gulf of Mexico. Source: modified from Hails (1977, table 9.1) after data from Stout et al. and Curtis et al.

River	*Suspended load (million tonnes)*		*Percent**
	1931–40	*1961–70*	
Brazos	350	120	30
San Bernard	1	1	100
Colorado	100	11	10
Rio Grande	180	6	3
Total	631	138	20

*1961–70 loads as a percentage of 1931–40 loads.

A good case study of the potential effects of dams on coastal sediment budgets is provided in California by Willis and Griggs (2003). Given that rivers provide the great bulk of beach material (75 to 90%) in the state, the reduction in sediment discharge by dammed rivers can have highly adverse effects. Almost a quarter of the beaches in California are down coast from rivers that have had sediment supplies diminished by one-third or more. Most of those threatened beaches are in southern California where much of the state's tourism and recreation activities are concentrated.

Construction of great levees on the lower Mississippi River since 1717 has also affected the Gulf of Mexico coast. The channelization of the river has increased its velocity, reduced overbank deposition of silt on to swamps, marshes, and estuaries, and changed the salinity conditions of marshland plants (Cronin, 1967). As a result, the coastal marshes and islands have suffered from increased erosion or a reduced rate of development. This has been vividly described by Biglane and Lafleur (1967: 691):

> Like a bullet through a rifle barrel, waters of the mighty Mississippi are thrust toward the Gulf between the confines of the flood control levees. Before the day of these man-made structures, these waters poured out over tremendous reaches of the coast . . . Freshwater marshes (salinities averaging 4–6%) were formed by deposited silts and vegetative covers of wire grass . . . As man erected his flood protection devices, these marshes ceased to form as extensively as before.

The changes between 1956 and 1990 are shown in Figure 6.29. However, as with so many examples of environmental change, it is unlikely that just one factor, in this case channelization, is the sole cause of the observed trend. In their study of erosion loss in the Mississippi Delta and neighboring parts of the Louisiana Coast, Walker et al. (1987) suggest that this loss is the result of a variety of complex interactions among a number of physical, chemical, biological, and cultural processes. These processes include, in addition to channelization, worldwide sea-level changes, subsidence resulting from sediment loading by the delta of the underlying crust, changes in the sites of deltaic sedimentation as the delta evolves, catastrophic storm

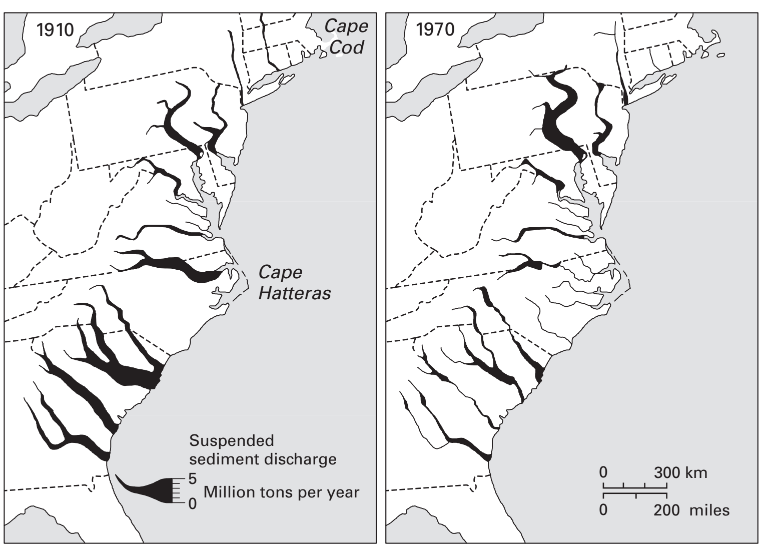

Figure 6.28 The decline in suspended sediment discharge to the eastern seaboard of the USA between 1910 and 1970 as a result of soil conservation measures, dam construction and land-use changes (after Meade and Trimble, 1974).

Figure 6.29 Comparison of the outlines of the Mississippi birdsfoot delta from the 1950s to 1990 gives a clear indication of the transformation from marsh to open water. Artificial controls upriver have decreased the amount of sediment carried by the river; artificial levees along much of the lower course have kept flood-borne sediment from replenishing the wetlands; and in the active delta itself rock barriers installed across breaks similarly confine the river. The Gulf of Mexico is intruding as the marshland sinks or is washed away.

surges, and subsidence resulting from subsurface fluid withdrawal.

In some areas anthropogenic vegetation modification creates increased erosion potential. This has been illustrated by Stoddart (1971) for the hurricane-afflicted coast of Belize, Central America. He showed that natural, dense vegetation thickets on low, sand islands (*cays*) acted as a baffle against waves and served as a massive sediment trap for coral blocks, shingle, and sand transported during extreme storms. However, on many islands the natural vegetation had been replaced by coconut plantations. These had an open structure easily penetrated by seawater, they tended to have little or no ground vegetation (thus exposing the cay surface to stripping and channeling), and they had a dense but shallow root net easily undermined by marginal sapping. Thus Stoddart found (p. 191) that 'where the natural vegetation had been replaced by coconuts before the storm (Hurricane Hattie), erosion and beach retreat led to net vertical decreases in height of 3–7 ft; whereas where natural vegetation remained, banking of storm sediment against the vegetation hedge led to a net vertical increase in height of 1–5 ft.'

Other examples of markedly accelerated coastal erosion and flooding result from anthropogenic degradation of dune ridges. Frontal dunes are a natural defense against erosion, and coastal changes may be long-lasting once they are breached. Many of those areas in eastern England which most effectively resisted the great storm and surge of 1952 were those where humans had not intervened to weaken the coastal dune belt.

Not all dune stabilization and creation schemes have proved desirable (Dolan et al., 1973). In North Carolina (see Figure 6.30) the natural barrier-island system along the coastline met the challenge of periodic extreme storms, such as hurricanes, by placing no permanent obstruction in the path of the powerful waves. Under these natural conditions, most of the initial stress of such storms is sustained by relatively broad beaches (Figure 6.30a). Since there is no resistance from impenetrable landforms, water can flow between the dunes (which do not form a continuous line) and across the islands, with the result that wave energy is rapidly exhausted. However, between 1936 and 1940, 1000 km of sand fencing was erected to create an artificial barrier dune along part of the Outer Banks, and 2.5 million trees and various grasses (especially *Ammophila*

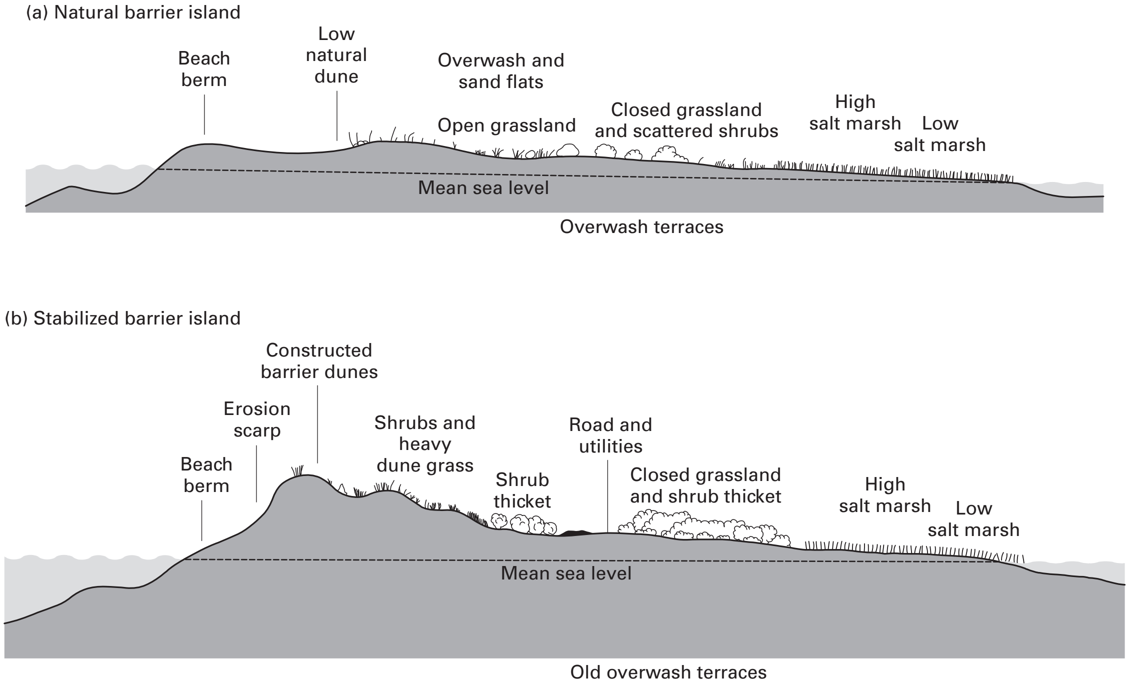

Figure 6.30 Cross-sections of two barrier islands in North Carolina, USA. The upper diagram (a) is typical of the natural systems and the lower (b) illustrates the stabilized systems (after Dolan et al., 1973, figure 4).

breviligulata) were planted to create large artificial dunes. The altered barrier islands (see Figure 6.30b) not only have the artificial barrier-dune system, they also have beaches that are often only 30 m wide, compared with 140 m for the unaltered islands. This beach-narrowing process, combined with the presence of a permanent dune structure, has created a situation in which high wave energy is concentrated in an increasingly restricted run up area, resulting in a steeper beach profile, increased turbulence, and greater erosion. Another problem associated with artificial dune stabilization is the flooding that occurs when northeast storms pile the water of the lagoon, Pamlico Sound, up against the barrier island. In the past, these surge waters simply flowed out between the low, discontinuous dunes and over the beach to the sea, but with the altered dune chain the water cannot drain off readily and vast areas of land are at times submerged.

General treatments of coastal problems and their management are provided by French (1997, 2001) and by Viles and Spencer (1995). What has become apparent in recent years is that there has been an increasing trend towards so-called soft means of coastal protection, rather than using hard engineering structures such as sea walls or groynes. Beach nourishment, the encouragement of dune formation, and promotion of salt marsh accretion are becoming recognized as being aesthetically pleasing, effective, and economically advantageous.

Changing rates of salt marsh accretion

In Britain in recent decades, the nature of some salt marshes and the rate at which they accrete have been transformed by a major vegetational change, namely the introduction of a salt-marsh plant, *Spartina alterniflora*. This cord-grass appears to have been introduced to Southampton Water in southern England by accident from the east coast of North America, possibly in shipping ballast. The crossing of this species with the native *Spartina maritima* produced an invasive cord-grass of which there were two forms, *Spartina townsendii* and *Spartina anglica*, the latter of which is now the main species. It appeared first at Hythe on Southampton Water in 1870 and then spread rapidly to other salt marshes in Britain: partly because of natural spread and partly because of deliberate planning. *Spartina* now reaches as far north as the Island of Harris in the west of Scotland, and to the Cromarty Firth in the east (Doody, 1984).

The plant has often been effective at excluding other species and also at trapping sediment. Rates of accretion can therefore become very high. Ranwell (1964) gives rates as high as 8–10 cm per year. There is evidence that this has caused progressive silting of estuaries such as those of the Dee (Marker, 1967) and the Severn (Page, 1982).

However, for reasons that are not fully understood, *Spartina* marshes have frequently suffered dieback, which has sometimes led to marsh recession. In the case of Poole Harbour and Beaulieu Estuary, this may date back to the 1920s, but elsewhere on the south coast it has generally been rapid and extensive since about 1960 (Tubbs, 1984). Among the hypotheses that have been put forward to explain dieback are the role of rising sea level, pathogenic fungi, increased wave attack, and the onset of waterlogging and anaerobic conditions on mature marsh. Some support for the latter view comes from the fact that in areas where the introduction has been more recent, for example in Wales and northwest England, the area of *Spartina* still appears to be increasing (Deadman, 1984).

The human impact on seismicity and volcanoes

The seismic and tectonic forces that mold the relief of Earth and cause such hazards to human civilization are two of the fields in which efforts to control natural events have had least success and where least has been attempted. Nonetheless, the fact that humans have been able, inadvertently, to trigger off small earthquakes by nuclear blasts, as in Nevada (Pakiser et al., 1969), by injecting water into deep wells, as in Colorado, by mining, by building reservoirs, and by fluid extraction suggests that in due course it may be possible to 'defuse' earthquakes by relieving tectonic strains gradually in a series of nondestructive, low-intensity earthquakes. One problem, however, is that there is no assurance that an earthquake purposefully triggered by human action will be a small one, or that it will be restricted to a small area. The legal implications are immense.

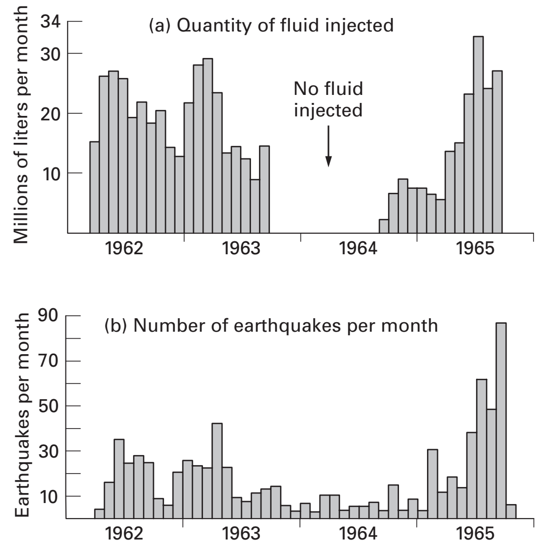

Figure 6.31 Correlation between quantity of waste water pumped into a deep well and the number of earthquakes near Denver, Colorado (after Birkeland and Larson, 1978p. 573).

The demonstration that increasing water pressures could initiate small-scale faulting and seismic activity was unintentionally demonstrated near Denver (Evans, 1966), where nerve-gas waste was being disposed of at a great depth in a well in the hope of avoiding contamination of useful groundwater supplies. The waste was pumped in at high pressures and triggered off a series of earthquakes (see Figure 6.31), the timing of which corresponded very closely to the timing of waste disposal in the well. It is also now thought that the pumping of fluids into the Inglewood Oil Field, Los Angeles, to raise the hydrostatic pressure and increase oil recovery, may have been responsible for triggering the 1963 earthquake which fractured a wall of the Baldwin Hills Reservoir. It appears that increased fluid pressure reduces the frictional force across the contact surface of a fault and allows slippage to occur, thereby causing an earthquake.

In general earthquake triggering has been related to fluid injection, but for reasons that are still obscure there may be some cases where increased seismicity has resulted from fluid abstraction (Segall, 1989).

The significance of these 'accidents' was verified experimentally at an oilfield in Colorado, where variations in seismicity have been produced by deliberately controlled variations in the fluid pressure in a zone that is seismically active (Raleigh et al., 1976).

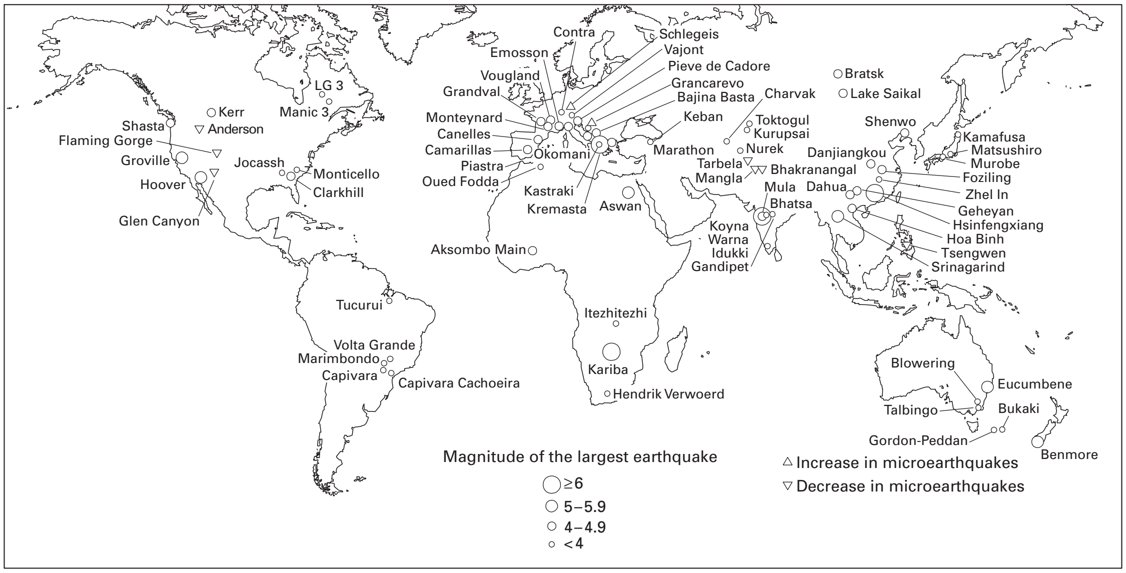

Figure 6.32 Worldwide distribution of reservoir-triggered changes in seismicity (after Gupta, 2002, figure 1).

Perhaps the most important anthropogenically induced seismicity results from the creation of large reservoirs (Talwani, 1997; Guha, 2000; Gupta, 2002). Reservoirs impose stresses of significant magnitude on crustal rocks at depths rarely equaled by any other human construction. With the ever increasing number and size of reservoirs the threat rises. There are at least six cases (Koyna, Jremasta, Hsinfengkiang, Kariba, Hoover, and Marathon) where earthquakes of a magnitude greater than 5, accompanied by a long series of foreshocks and aftershocks, have been related to reservoir impounding. However, as Figure 6.32 shows, there are many more locations where the filling of reservoirs behind dams has led to appreciable levels of seismic activity. Detailed monitoring has shown that earthquake clusters occur in the vicinity of some dams after their reservoirs have been filled, whereas before construction activity was less clustered and less frequent. Similarly, there is evidence from Vaiont (Italy), Lake Mead (USA), Kariba (Central Africa), Koyna (India), and Kremasta (Greece) that there is a linear correlation between the storage level in the reservoir and the logarithm of the frequency of shocks. This is illustrated for Vaiont (Figure 6.33a), Koyna (Figure 6.33b), and Nurek (Figure 6.33c). It is also apparent from Nurek that as the great reservoir has filled, so the depth of the more shallow-seated earthquakes appears to have increased.

One reason why dams induce earthquakes involves the hydro-isostatic pressure exerted by the mass of the water impounded in the reservoir, together with changing water pressures across the contact surfaces of faults. Given that the deepest reservoirs provide surface loads of only 20 bars or so, direct activation by the mass of the impounded water seems an unlikely cause (Bell and Nur, 1978) and the role of changing pore pressure assumes greater importance. Paradoxically, there are some possible examples of reduced seismic activity induced by reservoirs (Milne, 1976). One possible explanation of this is the increased incidence of stable sliding (fault creep) brought about by higher pore-water pressure in the vicinity of the reservoir.

However, the ability to prove an absolutely concrete cause-and-effect relationship between reservoir activity and earthquakes is severely limited by our inability to measure stress below depths of several kilometers, and some examples of induced seismicity may have been built on the false assumption that because an earthquake occurs in proximity to a reservoir it has to be induced by that reservoir (Meade, 1991).

Miscellaneous other human activities appear to affect seismic levels. In Johannesburg, South Africa, for example, gold mining and associated blasting activity have produced tens of thousands of small tremors, and there is a notable reduction in the number that occurs on Sundays, a day of rest. In Staffordshire, England,

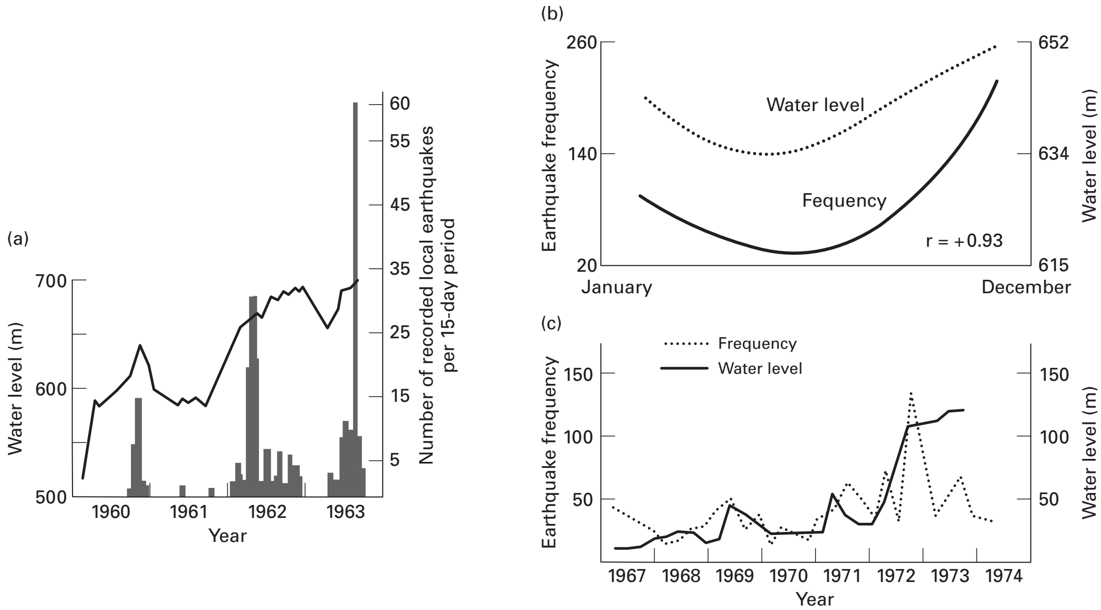

Figure 6.33 Relationships between reservoir levels and earthquake frequencies for: (a) Vaiont Dam, Italy; (b) Koyna, India (these curves show the 3-monthly average of water level and the total number of earthquakes for the same months from 1964 to 1968); (c) The Nurek Dam, Tajikistan (after Judd, 1974 and Tajikistan Academy of Sciences, 1975).

coal mining has caused increased seismic activity and up to 25% of all earthquakes recorded by the British Geological Survey may be related to coal mining. There are also cases where seismicity and faulting can be attributed to fluid extraction, for example, in the oilfields of Texas and California and the gas fields of the Po Valley in Italy and of Uzbekistan (Cypser and Davis, 1998).

When looking at the human impact on volcanic activity human impotence becomes apparent, although some success has been achieved in the control of lava flows. Thus in 1937 and 1947 the US Army attempted to divert lava from the city of Hilo, Hawaii, by bombing threatening flows, while elsewhere, where lava rises in the crater, breaching of the crater wall to direct lava towards uninhabited ground may be possible. In 1973 an attempt was made to halt advance of lava with cold water during the Icelandic eruption of Krikjufell. Using up to 4×10^6 L of pumped waste per hour, the lava was cooled sufficiently to decrease its velocity at the flow front so that the chilled front acted as a dam to divert the still fluid lava behind (Williams and Moore, 1973).

Points for review

What are the causes and consequences of accelerated sedimentation?
How do humans cause land subsidence?
In what ways may humans accelerate mass movements?
Why are many of the world's coastlines eroding?

Guide to reading

Brookes, A., 1988, *Channelised rivers*. Chichester: Wiley. An advanced research monograph with broad scope.

Downs, P. W. and Gregory, K. J., 2004, *River channel management*. Arnold: London. A comprehensive review of river channels and their management.

Goudie, A. S., 1993, Human influence in geomorphology. *Geomorphology*, 7, 37–59. A general review, with a concern for the future, in a major journal.

Nir, D., 1983, *Man, a geomorphological agent: an introduction to anthropic geomorphology*. Jerusalem: Keter. A general survey that was ahead of its time.