5 THE HUMAN IMPACT ON THE WATERS

Introduction

Because water is so important to human affairs, humans have sought to control water resources in a whole variety of ways. Also because water is such an important part of so many natural and human systems, its quantity and quality have undergone major changes as a consequence of human activities. We can quote Gleick (1993: 3):

> . . . we must now acknowledge that many of our efforts to harness water have been inadequate or misdirected . . . Rivers, lakes, and groundwater aquifers are increasingly contaminated with biological and chemical wastes. Vast numbers of people lack clean drinking water and rudimentary sanitation services. Millions of people die every year from water-related diseases such as malaria, typhoid, and cholera. Massive water developments have destroyed many of the world's most productive wetlands and other aquatic habitats.

In recent decades human demand for freshwater has increased rapidly. Global water use has more than tripled since 1950, and annual irretrievable water losses increased about sevenfold in the twentieth century (Table 5.1a).

Deliberate modification of rivers

Although there are many ways in which humans influence water quantity and quality in rivers and streams – for example, by direct channel manipulation, modification of basin characteristics, urbanization and pollution – the first of these is of particularly great importance (Mrowka, 1974). Indeed, there are a great variety of methods of direct channel manipulation and many of them have a long history. Perhaps the most widespread of these is the construction of dams and reservoirs (Figure 5.1). The first recorded dam was constructed in Egypt some 5000 years ago, but since that time the adoption of this technique has spread variously to improve agriculture, to prevent floods, to generate power, or to provide a reliable source of water.

There are some 75,000 dams in the USA. Most are small, but the bulk of the storage of water is associated

Table 5.1 Major changes in the hydrological environment
(a) Irretrievable water losses (km^3 $year^{-1}$)

Users	*1900*	*1940*	*1950*	*1960*	*1970*	*1980*	*1990*	*2000*
Agriculture	409	679	859	1180	1400	1730	2050	2500
Industry	3.5	9.7	14.5	24.9	38.0	61.9	88.5	117
Municipal supply	4.0	9.0	14	20.3	29.2	41.1	52.4	64.5
Reservoirs	0.3	3.7	6.5	23.0	66.0	120	170	220
Total	417	701	894	1250	1540	1950	2360	2900

(b) Number of large dams (> 15 m high) constructed or under construction, 1950–86. Source: data provided by United Nations Environment Program (UNEP) and World Commission on Dams

Continent	*1950*	*1982*	*1986*	*Under construction (31 December 1986)*
Africa	133	665	763	58
Asia	1562	22,789	22,389	613
Australasia/Oceania	151	448	492	25
Europe	1323	3961	4114	222
North and Central America	2099	7303	6595	39
South America			884	69
Total	5268	35,166	36,327*	1036

*The figure by the end of the twentieth century was *c*. 45,000.

Figure 5.1 The Kariba Dam on the Zambezi River between Zambia and Zimbabwe. Such large dams can provide protection against floods and water shortages, and generate a great deal of electricity. However, they can have a whole suite of environmental consequences.

with a relatively limited number of structures. Those dams creating reservoirs of more than 1.2×10^9 m^3 (1×10^6 acre-feet) account for only 3% of the total number of structures, but they account for 63% of the total storage. In all the dams are capable of storing a volume of water almost equaling one year's runoff and they store around 5000 m^3 (4 acre-feet) of water per person. The decade of the 1960s saw the greatest spate of dam construction in American history (18,833 dams were built then). Since the 1980s, however, there have been only relatively minor increases in storage. The dam building era is over, but the environmental effects remain and the physical integrity of many rivers has been damaged (Graf, 2001).

The construction of large dams increased markedly, especially between 1945 and the early 1970s (Beaumont, 1978). Engineers have now built more than 45,000 large dams around the world and, as Table 5.1b shows, such large dams (i.e., more than 15 m high) are still being constructed at an appreciable rate, especially in Asia. In the late 1980s some 45 very large dams (more than 150 m high) were under construction. Indeed, one of the most striking features of dams and reservoirs is that they have become increasingly large (Beckinsale, 1969). Thus in the 1930s the Hoover or Boulder Dam in the USA (221 m high) was by far the tallest in the world and it impounded the largest reservoir, Lake Mead, which contained 38×10^9 m^3 of water. By the 1980s it was exceeded in height by at least 18 others,

Table 5.2 Peak flow reduction downstream from selected British reservoirs. Source: after Petts and Lewin (1979: 82, table 1)

Reservoir	*Catchment inundated (%)*	*Peak flow reduction (%)*
Avon, Dartmoor	1.38	16
Fernworth, Dartmoor	2.80	28
Meldon, Dartmoor	1.30	9
Vyrnwy, mid-Wales	6.13	69
Sutton Bingham, Somerset	1.90	35
Blagdon, Mendip	6.84	51
Stocks, Forest of Bowland	3.70	70
Daer, Southern Uplands	4.33	56
Camps, Southern Uplands	3.13	41
Catcleugh, Cheviots	2.72	71
Ladybower, Peak District	1.60	42
Chew Magna, Mendips	8.33	73

Table 5.3 The ratios of post- to pre-dam discharges for flood magnitudes of selected frequency. Source: after Petts and Lewin (1979: 84, table 2)

Reservoir	*Recurrence interval (years)*			
	1.5	*2.3*	*5.0*	*10.0*
Avon, River Avon	0.90	0.89	0.93	1.02
Stocks, River Hodder	0.83	0.86	0.84	0.95
Sutton Bingham, River Yeo	0.52	0.61	0.69	0.79

and some of these impounded reservoirs with four times the volume of Lake Mead. The massive new Three Gorges Dam in China is a major cause of current environmental concern, as is the damming of the Narmada River in India.

Large dams are capable of causing almost total regulation of the streams they impound but, in general, the degree to which peak flows are reduced depends on the size of the dam and the impounded lake in relation to catchment characteristics. In Britain, as Table 5.2 shows, peak flow reduction downstream from selected reservoirs varies considerably, with some tendency for the greatest degree of reduction to occur in those catchments where the reservoirs cover the largest percentage of the area. When considering the magnitude of floods of different recurrence intervals before and after dam construction, it is clear that dams have much less effect on rare events of high magnitude (Petts and Lewin, 1979), and this is brought out in Table 5.3. Nonetheless, most dams achieve their aim: to regulate river discharge. They are also highly successful in fulfilling the needs of surrounding communities: millions of people depend upon them for survival, welfare, and employment.

However, dams may have a whole series of environmental consequences that may or may not have been anticipated (Figure 5.2) (World Commission on Dams, 2000). Some of these are dealt with in greater detail elsewhere, such as subsidence (p. 167), earthquake triggering (p. 193), the transmission and expansion in the range of organisms, inhibition of fish migration (p. 55), the build-up of soil salinity (p. 96), changes in groundwater levels creating slope instability (p. 176) and water-logging (p. 97). Several of these processes may in turn affect the viability of the scheme for which the dam was created.

A particularly important consequence of impounding a reservoir behind a dam is the reduction in the sediment load of the river downstream. A clear demonstration of this effect has been given for the South Saskatchewan River in Canada (Table 5.4) by Rasid (1979). During the pre-dam period, typified by 1962, the total annual suspended loads at Saskatoon and Lemsford Ferry were remarkably similar. As soon as the reservoir began to fill late in 1963, however, some of the suspended sediment began to be trapped, and the transitional period was marked by a progressive reduction in the proportion of sediment which reached Saskatoon. In the four years after the dam was fully operational the mean annual sediment load at Saskatoon was only 9% that at Lemsford Ferry.

Even more dramatic are the data for the Colorado River in the USA (Figure 5.3). Prior to 1930 it carried around 125–150 million tonnes of suspended sediment per year to its delta at the head of the Gulf of California. Following a series of dams the Colorado now discharges neither sediment nor water to the sea (Schwarz et al., 1991). There have also been marked changes in the amount of sediment passing along the Missouri and Mississippi rivers over the period 1938 to 1982. Downstream sediment loads have been reduced by about half over that period (Figure 5.4a). Meade (1996) has attempted to compare the situation in the 1980s with that which existed before humans started to interfere will those rivers (*c*. AD 1700) (Figure 5.4b).

Sediment retention is also well illustrated by the Nile (Table 5.5), both before and after the construction

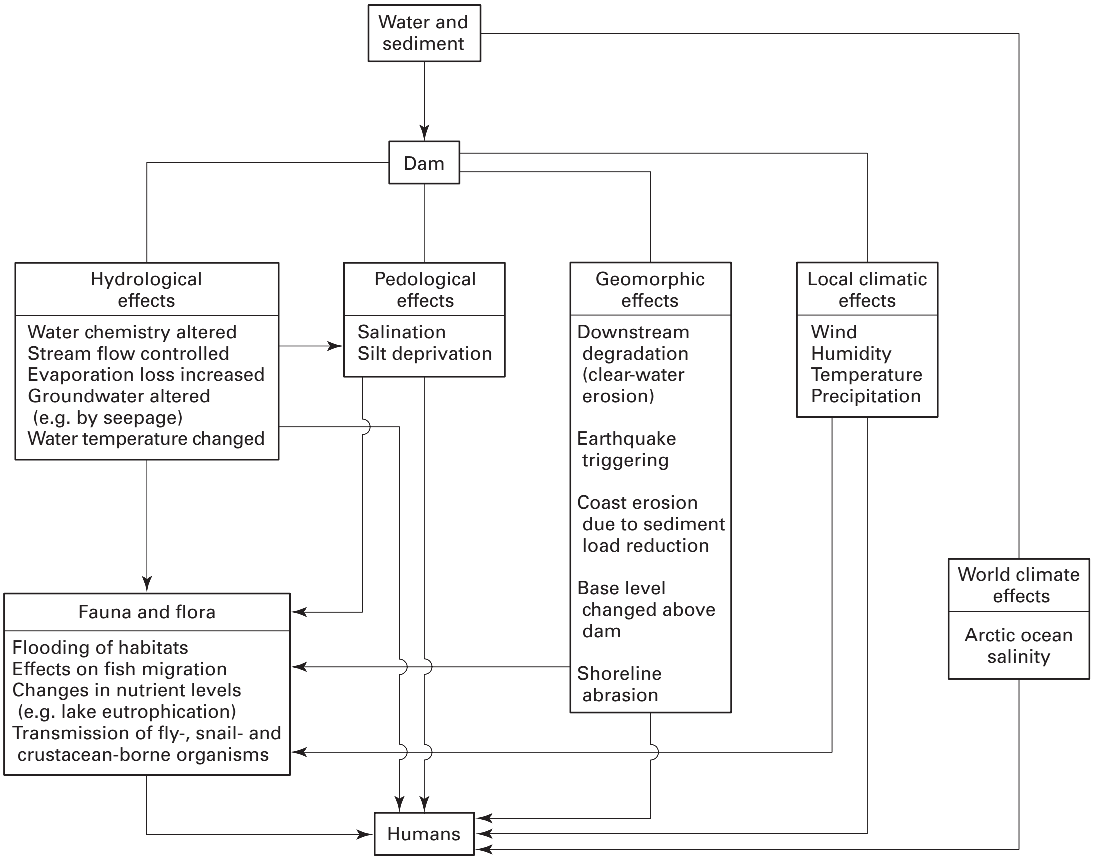

Figure 5.2 Generalized representation of the possible effects of dam construction on human life and various components of the environment.

Table 5.4 Total yearly suspended load (thousand imperial tons) of the South Saskatchewan River at Lemsford Ferry and Saskatoon, 1962–70. Source: Rasid (1979, table 1)

Period of record	*Year*	*Lemsford Ferry*	*Saskatoon*	*Difference at Saskatoon (%)*
Pre-dam	1962	1813	1873	+3
Transitional	1963	4892	4478	–8
	1964	7711	4146	–46
	1965	9732	2721	–72
	1966	5228	1675	–68
	Mean	6891	3255	–53
Post-dam	1967	12,619	446	–96
	1968	2661	101	–96
	1969	10,562	2146	–80
	1970	5643	118	–98
	Mean	7871	703	–91

of the great Aswan High Dam. Until its construction the late summer and autumn period of high flow was characterized by high silt concentrations, but since it has been finished the silt load is rendered lower throughout the year and the seasonal peak is removed. Petts (1985, table XVIII) indicates that the Nile now only transports 8% of its natural load below the Aswan High Dam, although this figure seems to be exceptionally low. Other rivers for which data are available carry between 8 and 50% of their natural suspended loads below dams.

Sediment removal in turn has various possible consequences, including a reduction in flood-deposited nutrients on fields, less nutrients for fish in the southeast Mediterranean Sea, accelerated erosion of the Nile Delta, and accelerated riverbed erosion since less sediment is available to cause bed aggradation. The

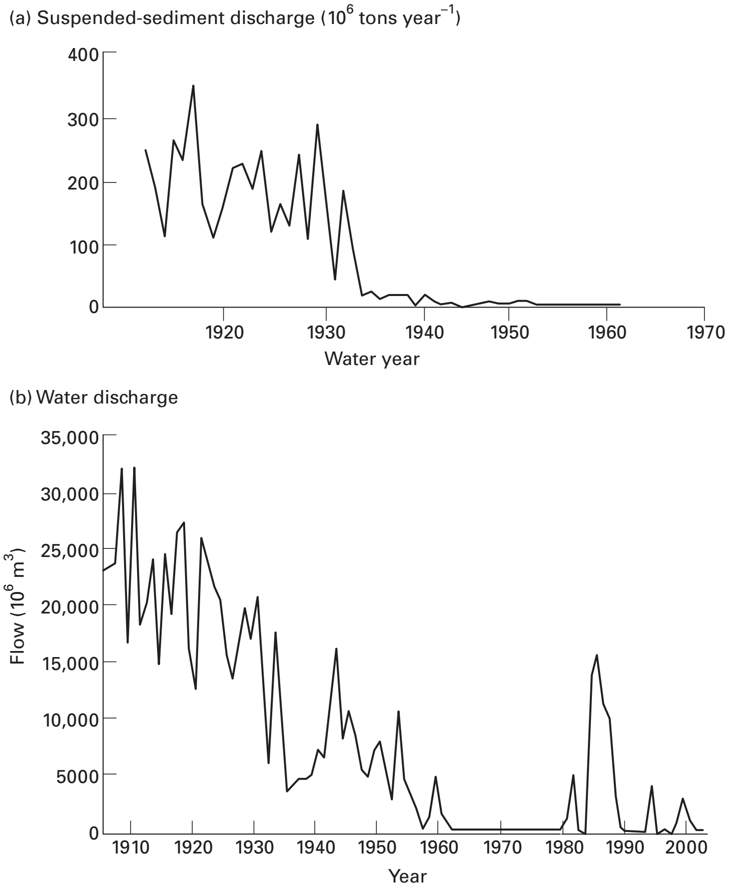

Figure 5.3 Historical (a) sediment and (b) water discharge trends for the Colorado River, USA (after the US Geological Survey, in Schwarz et al., 1991).

last process is often called 'clear-water erosion' (see Beckinsale, 1972), and in the case of the Hoover Dam it affected the river channel of the Colorado for 150 km downstream by causing incision. In turn, such channel incision may initiate headward erosion in tributaries and may cause the lowering of groundwater tables and the undermining of bridge piers and other structures downstream of the dam. On the other hand, in regions such as northern China, where modern dams trap silt, the incision of the river channel downstream may alleviate the strain on **levees** and lessen the expense of levee strengthening or heightening.

However, clear-water erosion does not always follow from silt retention in reservoirs. There are examples of rivers where, before impoundment, floods carried away the sediment brought into the main stream by steep tributaries. Reduction of the peak discharge after the completion of the dam leaves some rivers unable to scour away the sediment that accumulates as large fans of sand or gravel below each tributary mouth (Dunne and Leopold, 1978). The bed of the main stream is raised and if water-intakes, or other structures, lie alongside the river they can be threatened again by flooding or channel shifting across the accumulating wedge of sediment. Rates of **aggradation** of a meter a year have been observed, and tens of kilometers of channel have been affected by sedimentation. One of the best-documented cases of aggradation concerns the Colorado River below Glen Canyon Dam in the USA. Since dam closure the extremes of river flow have been largely eliminated so that the 10 years' recurrence interval flow has been reduced to less than one-third. The main channel flow is no longer capable of removing sediment provided by flash-flooding tributaries, and deposits up to 2.6 m thick have accumulated within the upper Grand Canyon (Petts, 1985: 133).

Some landscapes in the world are dominated by dams, canals, and reservoirs. Probably the most striking example of this (Figure 5.5) is the 'tank' landscape of southeast India where myriads of little streams

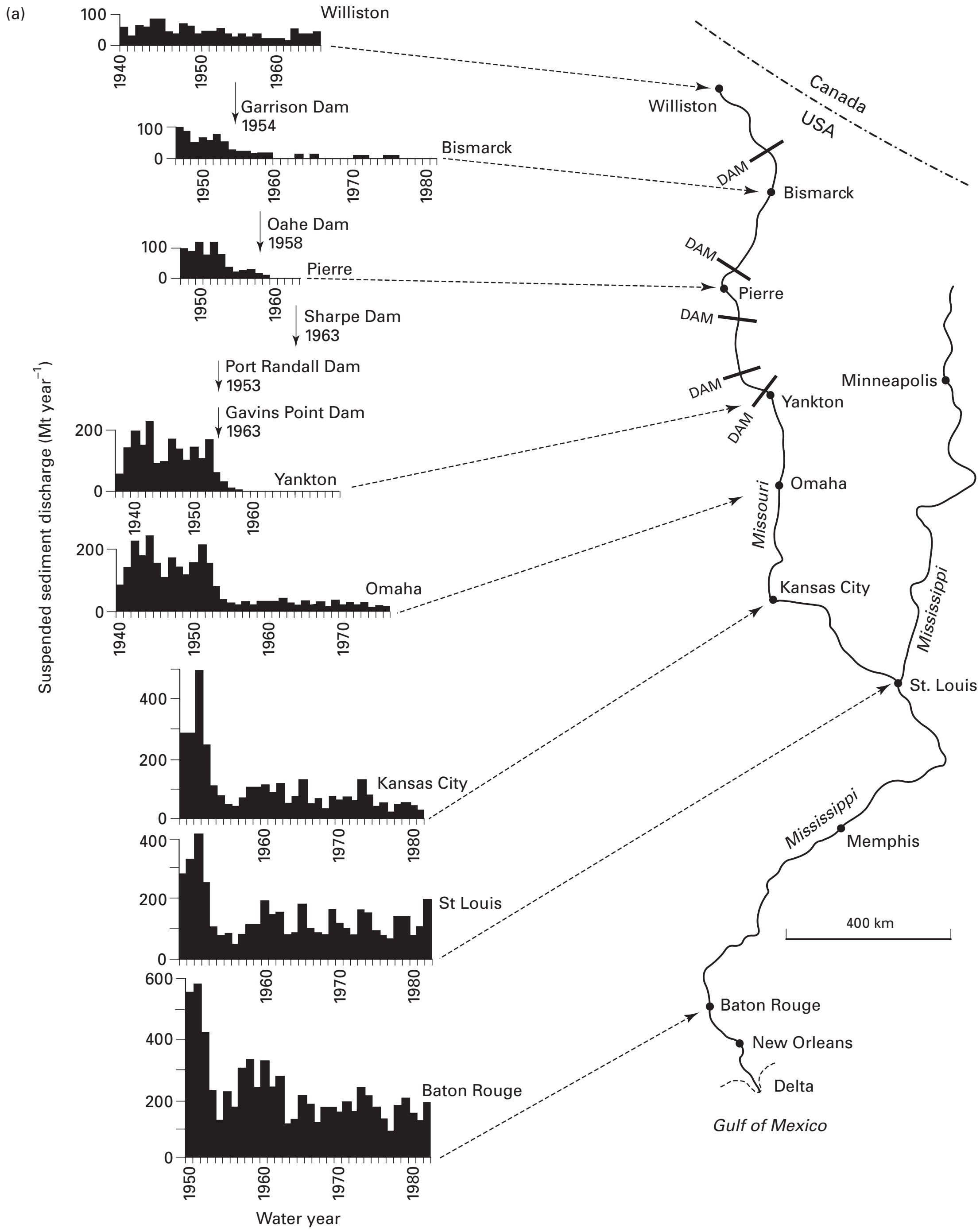

Figure 5.4 (a) Suspended sediment discharge on the Mississippi and Missouri rivers between 1939 and 1982 (after Meade and Parker, 1985, with modifications). (b) Long-term average discharges of suspended sediment in the lower Mississippi River *c*. 1700 and *c*. 1980.

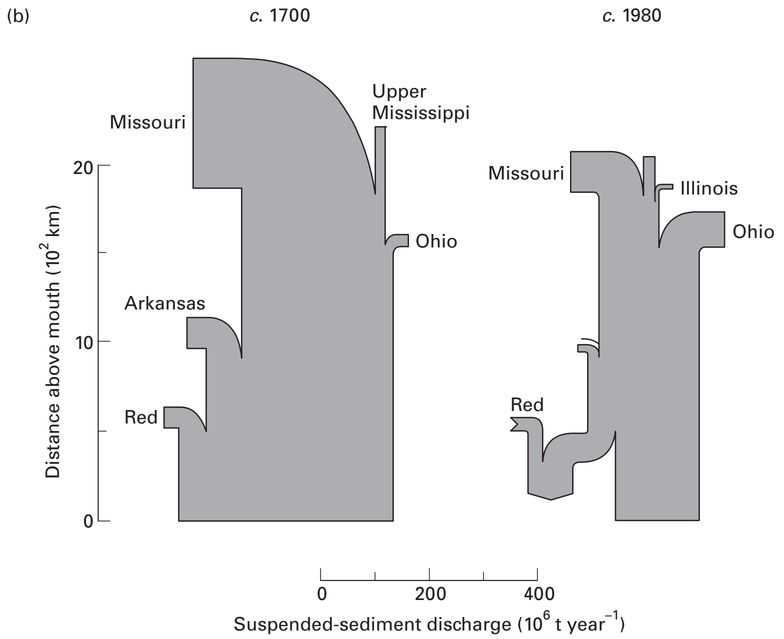

Figure 5.4 (*cont'd*)

Table 5.5 Silt concentrations (in parts per million) in the Nile at Gaafra before and after the construction of the Aswan High Dam. Source: Abul-Atta (1978: 199)

Month	*Before (averages for the period 1958–63)*	*After*	*Ratio*
January	64	44	1.5
February	50	47	1.1
March	45	45	1
April	42	50	0.8
May	43	51	0.8
June	85	49	1.7
July	674	48	14.0
August	2702	45	60
September	2422	41	59.1
October	925	43	21.5
November	124	48	2.58
December	71	47	1.63

and areas of overland flow have been dammed by small earth structures to give what Spate (Spate and Learmonth, 1967: 778) has likened to ‘a surface of vast overlapping fish-scales’. In the northern part of the subcontinent, in Sind, the landscape changes wrought by hydrology are no less striking, with the mighty snow-fed Indus being controlled by large embankments (*bunds*) and interrupted by great barrages. Its waters are distributed over thousands of square kilometers by a canal network (Figure 5.6) that has evolved over the past 4000 years (Figure 5.7). Another landscape where equally far-reaching changes have been wrought is The Netherlands. Coates (1976) has calculated that, before 1860, reclamation of that country from the sea, in the extension of drainage lines, involved the movement of 1000×10^6 m^3 of material. The area is dominated by human constructions: canals, rivers, drains, and lakes.

Another direct means of river manipulation is channelization. This involves the construction of embankments, dikes, levees, and floodwalls to confine floodwaters; and improving the ability of channels to transmit floods by enlarging their capacity through straightening, widening, deepening, or smoothing (Table 5.6).

Some of the great rivers of the world are now lined by extensive embankment systems such as those that run for more than 1000 km alongside the Nile, 700 km along the Hwang Ho, 1400 km by the Red River in Vietnam, and over 4500 km in the Mississippi Valley (Ward, 1978). Like dams, embankments and related structures often fulfil their purpose but they may also create some environmental problems and have some disadvantages. For example, they reduce natural storage for floodwaters, both by preventing water from spilling on to much of the floodplain, and by stopping bank storage in cases where impermeable floodwalls

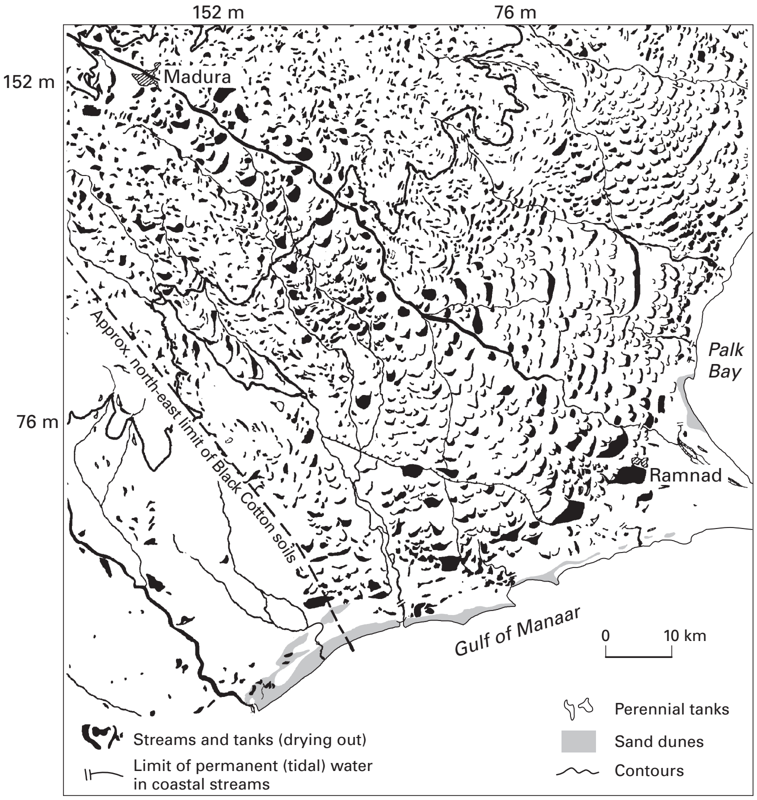

Figure 5.5 The Madurai–Ramanathapuram tank country in south India (after Spate and Learmonth, 1967, figure 25.12).

Figure 5.6 A large irrigation canal taking water across the Indus Plain from the Sukkur Barrage in Sind, Pakistan.

are used. Likewise the flow of water in tributaries may be constrained. In addition, embankments may occasionally exacerbate the flood problem they were designed to reduce by preventing floodwaters downstream of a breach from draining back into the channel once the peak has passed.

Channel improvement, designed to improve water flow, may also have unforeseen or undesirable effects. For example, the more rapid movement of water along improved channel sections can aggravate flood peaks further downstream and cause excessive erosion. The lowering of water tables in the 'improved' reach may cause overdrainage of adjacent agricultural land so that sluices must be constructed in the channel to maintain levels. On the other hand, lined channels may obstruct soil water movement (interflow) and shallow groundwater and so cause surface saturation. Brookes (1985) and Gregory (1985) provide useful reviews on the impact of channelization.

Channelization may also have miscellaneous effects on fauna through the increased velocities of water flow, reductions in the extent of shelter in the channel bed, and by reduced nutrient inputs due to the destruction of overhanging bank vegetation (see Keller, 1976). In the case of large swamps, such as those of the Sudd in Sudan or the Okavango in Botswana, the channelization of rivers could completely transform the whole character of the swamp environment. Figure 5.8 illus-

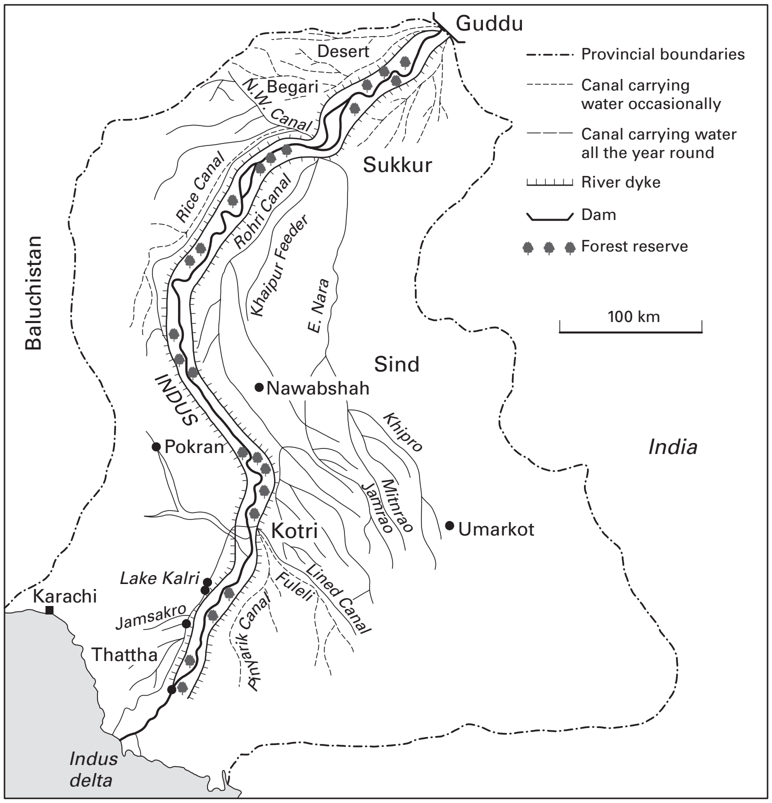

Figure 5.7 The irrigated areas in Sind (Pakistan) along the Indus Valley (after Manshard, 1974, figure 5.7).

Table 5.6 Selected terminologies for the methods of river channelization in the USA and UK. Source: Brookes (1985, table 1)

American term	*British equivalent*	*Method involved*
Widening Deepening	Resectioning Resectioning	Increase of channel capacity by manipulating width and/or depth variable
Straightening	Realigning	Increasing velocity of flow by steepening the gradient
Diking	Embanking	Raising of channel banks to confine floodwaters
Bank stabilization	Bank protection	Methods to control bank erosion, e.g., gabions and concrete structures
Clearing and snagging	Pioneer tree clearance Control of aquatic plants Dredging of sediments Urban clearing	Removal of obstructions from a watercourse, thereby decreasing the resistance and increasing the velocity of flow

trates some of the differences between natural and artificial channels.

Another type of channel modification is produced by the construction of bypass and diversion channels to carry excess floodwater or to enable irrigation to take place. Such channels may be as old as irrigation itself. They may contribute to the salinity problems encountered in many irrigated areas.

Deliberate modification of a river regime can also be achieved by long-distance interbasin water transfers (Shiklomanov, 1985), transfers necessitated by the unequal spatial distribution of water resources, and by the increasing rates of water consumption. The total volume of water in the various transfer systems in operation and under construction on a global scale is about 300 km^3 per year, with the largest countries in terms of volume of transfers being Canada, the Commonwealth of Independent States, the USA, and India.

In future decades it is likely that many even greater schemes will be constructed (see Figure 5.9); route lengths of some hundreds of kilometers will be common, and the water balances of many rivers and lakes

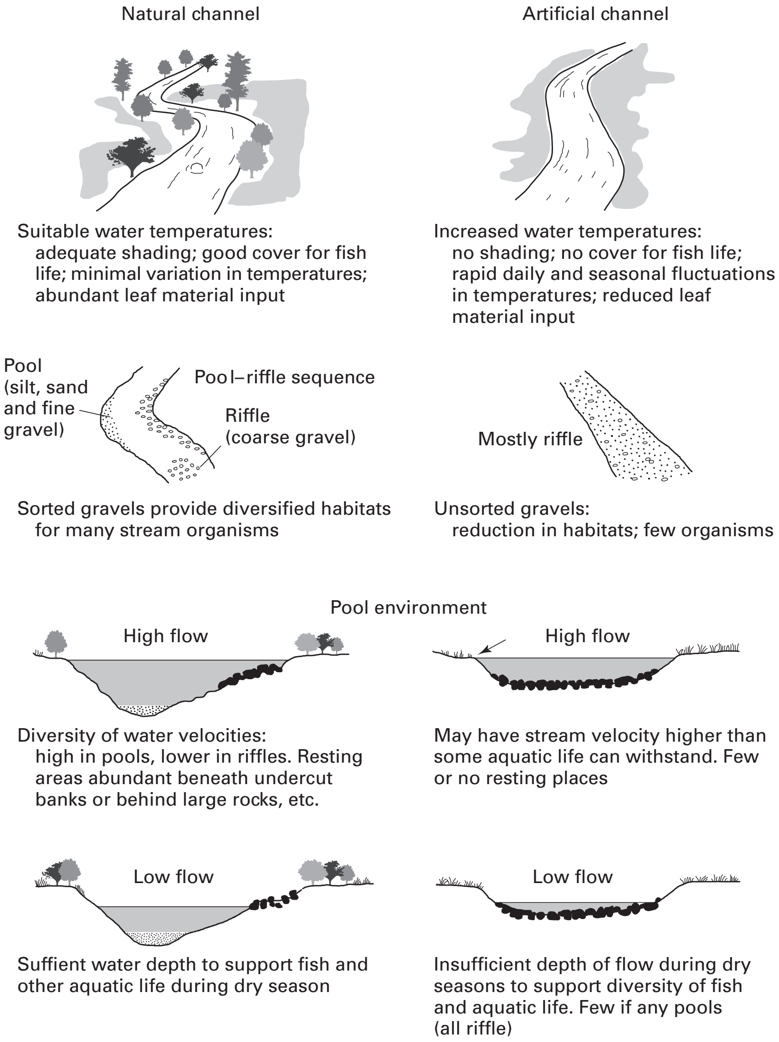

Figure 5.8 Comparison of the natural channel morphology and hydrology with that of a channelized stream, suggesting some possible ecological consequences (after Keller, 1976, figure 4).

will be transformed. This is already happening in the CIS (Figure 5.10), where the operation of various anthropogenic activities of this type have caused runoff in the most intensely cultivated central and southern areas to decrease by 30–50% compared with normal natural runoff. At the same time, inflows into the Caspian and Aral Seas have declined sharply. The level of the Aral has fallen and its area decreased.

When one turns to the coastal portions of rivers, to estuaries, the possible effects of another human impact, dredging, can be as complex as the effects of dams and reservoirs upstream (La Roe, 1977). Dredging and filling are certainly widespread and often desirable. Dredging may be performed to create and maintain canals, navigation channels, turning basins, harbors, and marinas; to lay pipelines; and to obtain a source of material for fill or construction. Filling is the deposition of dredged materials to create new land. There are miscellaneous ecological effects of such actions. In the first place, filling directly disrupts habitats. Second, the generation of large quantities of suspended silt tends physically to smother bottom-dwelling plants and animals; tends to smother fish by clogging their gills; reduces photosynthesis through the effects of turbidity; and tends to lead to eutrophication by an increased nutrient release. Likewise, the destruction of marshes, mangroves, and sea grasses by dredge and fill can result in the loss of these natural purifying systems. The removal of vegetation may also cause erosion. Moreover, as silt deposits stirred up by dredging accumulate elsewhere in the estuary they tend to create a 'false bottom'. Characterized by shifting, unstable sediments, the dredged bottom, fill deposits, or spoil areas are slowly – if at all – recolonized by fauna and flora. Furthermore, dredging tends to change the configuration of currents, the rate of freshwater drainage and may provide avenues for saltwater intrusion.

Urbanization and its effects on river flow

The process of urbanization has a considerable hydrological impact, in terms of controlling rates of erosion and the delivery of pollutants to rivers, and in terms of influencing the nature of runoff and other hydrological characteristics (Hollis, 1988). An attempt to generalize some of these impacts using a historical model of urbanization is summarized usefully by Savini and Kammerer (1961) and reproduced here in Table 5.7.

One of the most important effects is the way in which urbanization affects flood runoff. Research both in the USA and in Britain has shown that, because urbanization produces extended impermeable surfaces of bitumen, tarmac, tiles, and concrete, there is a tendency for flood runoff to increase in comparison with rural sites. City drainage densities may be greater than those in natural conditions (Graf, 1977) and the installation of sewers and storm drains accelerates runoff, as illustrated in Figure 5.11a. The greater the area that is sewered, the greater is the discharge for a particular recurrence level (Figure 5.11b). Peak discharges are higher and occur sooner after runoff starts in basins that have been affected by urbanization and the installation of sewers. Some runoff may be generated in

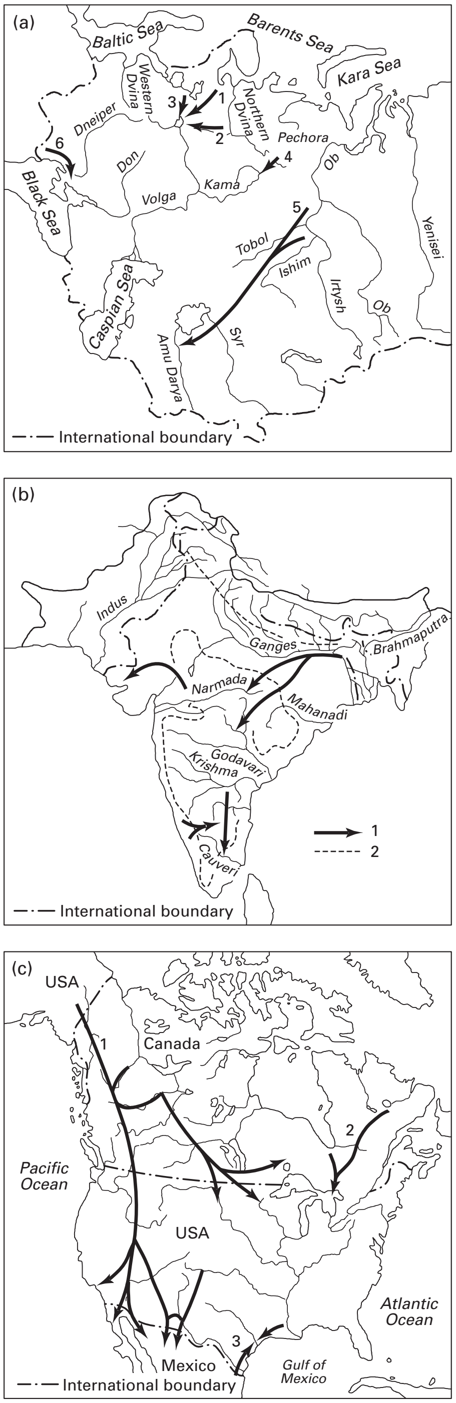

Figure 5.9 (*left*) Some major schemes proposed for large-scale interbasin water transfers: (a) projected water transfer systems in the Commonwealth of Independent States: 1, from the Onega River and in future from Onega Bay; 2, from the Sukhona and Northern Dvina rivers; 3, from the Svir River and Lake Onega; 4, from the Pechora River; 5, from the Ob River; 6, from the Danube delta. (b) Projected systems for water transfers in India: 1, scheme of the national water network; 2, scheme of the Grand Water Garland. (c) Some major projects for water transfers in North America: 1, North American Water and Power Alliance (NAWAPA); 2, Grand Canal; 3, Texas River basins (after Shiklomanov, 1985, figs 12.6, 12.9 and 12.11, in *Facets of hydrology II*, ed. J. C. Rodda, by permission of John Wiley and Sons Ltd).

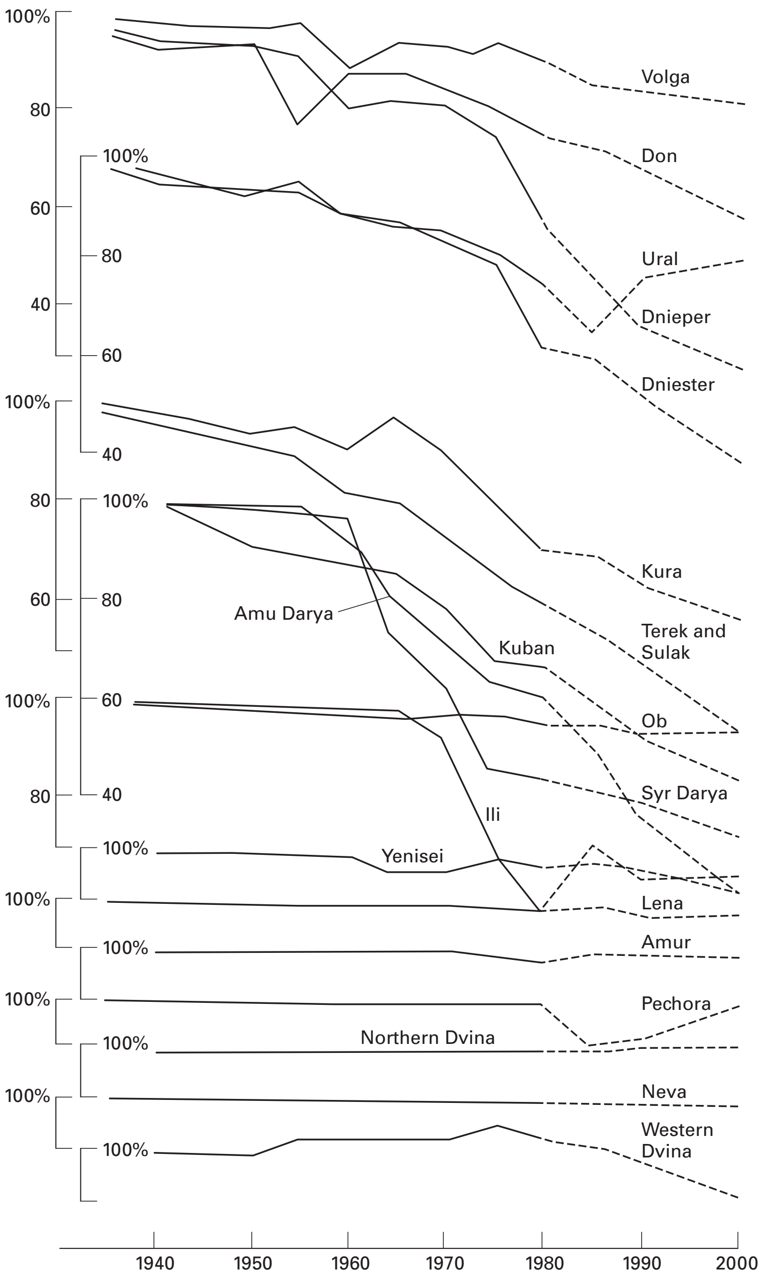

Figure 5.10 Changes in annual runoff in the Commonwealth of Independent States due to human activity during 1936–2000 (from Shiklomanov, 1985, figure 12.7, in *Facets of hydrology II*, ed. J. C. Rodda, by permission of John Wiley and Sons Ltd).

urban areas because low vegetation densities mean that evapotranspiration is limited.

However, in many cases the effect of urbanization is greater on small floods; as the size of the flood and its recurrence interval increase, so the effect of urbanization diminishes (Martens, 1968; Hollis, 1975). A probable explanation for this is that, during a severe and prolonged storm event, a nonurbanized catchment may become so saturated and its channel network so extended that it begins to behave hydrologically as if it were an impervious catchment with a dense surface-water drain network. Under these conditions, a rural catchment produces floods of a type and size similar to those of its urban counterpart. Moreover, a further mechanism probably operates in the same direction, for in an urban catchment it seems probable that some throttling of flow occurs in surface-water drains during intense storms, tending to attenuate the

Table 5.7 Stages of urban growth and their miscellaneous hydrological impacts. Source: modified after Savini and Kammerer (1961)

Stage	*Activity*	*Impact*
Transition from pre-urban stage	Removal of trees or vegetation	Decrease in transpiration and increase in storm flow
	Construction of scattered houses with limited sewerage and water facilities	
	Drilling of wells	Some lowering of water table
	Construction of septic tanks, etc.	Some increase in soil moisture and perhaps some contamination
Transition from early-urban to middle-urban stage	Bulldozing of land	Accelerated land erosion
	Mass construction of houses, etc.	Decreased infiltration
	Discontinued use and abandonment of some shallower wells	Rise in water table
	Diversion of nearby streams for public supply	Decrease in runoff between points of diversion of disposal
	Untreated or inadequately treated sewerage into streams and wells	Pollution of streams and wells
Transition from middle-urban to late-urban stage	Urbanization of area completed by addition of more buildings	Reduced infiltration and lowered water table, higher flood peaks and lower low flows
	Larger quantities of untreated waste into local streams	Increased pollution
	Abandonment of remaining shallow wells because of pollution	Rise in water table
	Increase in population requiring establishment of new water supply and distribution systems	Increase in local stream flow if supply is from outside basin
	Channels of streams restricted at least in part to artificial channels and tunnels	Higher stage for a given flow (therefore increased flood damage), changes in channel geometry and sediment load
	Construction of sanitary drainage system and treatment plant for sewerage	Removal of additional water from area
	Improvement of storm drainage system	
	Drilling of deeper, large-capacity industrial wells	Lowered water pressure, some subsidence, saltwater encroachment
	Increased use of water for air-conditioning	Overloading of sewers and other drainage facilities
	Drilling of recharge wells	
	Waste-water reclamation and utilization	Raising of water pressure surface
		Recharge of groundwater aquifers: more efficient use of water resources

very highest discharges. Thus, Hollis believes, while the size of small frequent floods is increased many times by urbanization, large, rare floods (the ones likely to cause extreme damage) are not significantly affected by the construction of suburban areas within a catchment area (Figure 5.11c). Hollis's findings may not be universally applicable. For example, K. V. Wilson (1967) working in Jackson, Mississippi, found that the 50-year flood for an urbanized catchment was three times higher than that of a rural one.

Nonetheless, a whole series of techniques has been developed in an attempt to reduce and delay urban storm runoff (Table 5.8). Of particular current interest are sustainable urban drainage systems (SUDS). These tackle urban surface runoff problems at source using features such as soakaways, permeable pavements, grassed swales or vegetated filter strips, infiltration trenches, ponds (detention and retention basins), and wetlands to attenuate flood peak flows.

Vegetation modification and its effect on river flow

As we have already noted in Chapter 1, one of the first major indications that humans could inadvertently adversely affect the environment was the observation that deforestation could create torrents and floods. The deforestation that gives rise to such flows can be produced both by felling and by fire (Scott, 1997).

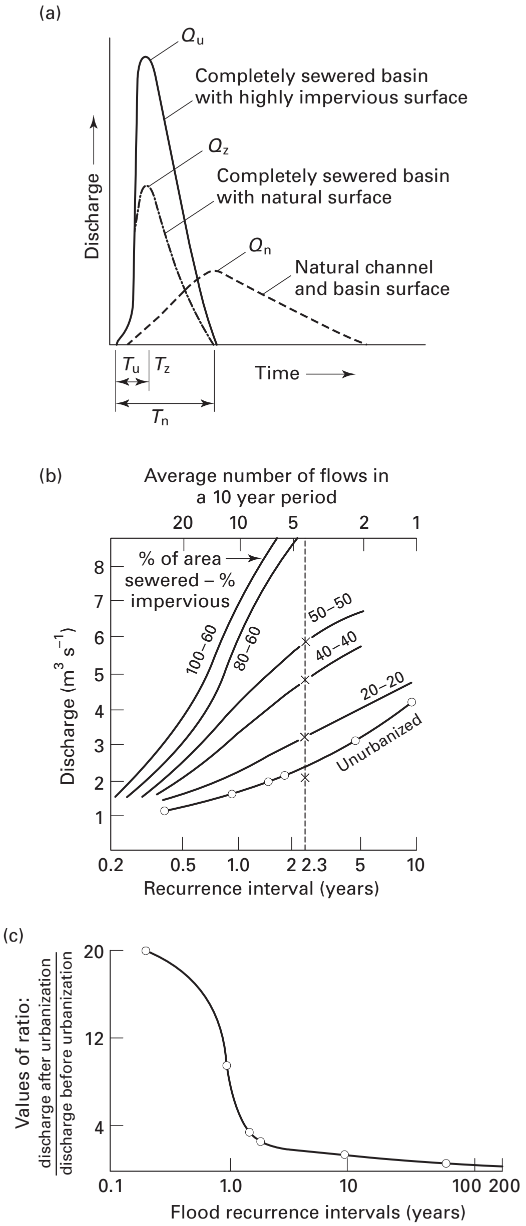

Figure 5.11 Some hydrological consequences of urbanization. (a) Effect of urban development on flood hydrographs. Peak discharges (*Q*) are higher and occur sooner after runoff starts (*T*) in basins that have been developed or sewered (after Fox, 1976, figure 3). (b) Flood frequency curves for a 1 mile^2 basin in various states of urbanization (after US Geological Survey, in Viessman et al., 1977, figure 11.33). (c) Effects of flood magnitude with paving 20% of a basin (after Hollis, 1975).

The first experimental study, in which a planned land-use change was executed to enable observation of the effects of stream flow, began at Wagon Wheel Gap, Colorado, in 1910. Here stream flow from two similar watersheds of about 80 hectares each were compared for eight years. One valley was then clear-felled and the records were continued. After the clear-felling the annual water yield was 17% above that predicted from the flows of the unchanged control valley. Peak flows are also increased. Studies on two small basins in the Australian Alps (Wallace's Creek, 41 km^2; Yarrango Billy River, 224 km^2), which were burned over, showed that rainstorms, which from previous records would have been expected to give rise to flows of 6080 m^3 per second, produced a peak of 370 m^3 per second (a five or sixfold increase). Likewise catchment experiments in Arizona have shown that when chaparral scrub is burned there is a tenfold increase in water yield.

Experiments with tropical catchments have shown typical maximum and mean annual stream-flow increases of 400–450 mm per year on clearance with increases in water yield of up to 6 mm per year for each percentage reduction in forest area above a 15% change in cover characteristics (Anderson and Spencer, 1991: 49). Additional data for the effects of land-use change on annual runoff levels are presented for tropical areas in Table 5.9.

As vegetation regenerates after a forest has been cut or burned, so stream flow tends to revert to normal, although the process may take some decades. This is illustrated in Figure 5.12 which shows the dramatic effects produced on the Coweeta catchments in North Carolina by two spasms of clear-felling, together with the gradual return to normality in between.

The substitution of one forest type for another may also affect stream flow. This can again be exemplified from the Coweeta catchments, where two experimental catchments were converted from a mature deciduous hardwood forest cover to a cover of pine (*Pinus strobus*). Fifteen years after the conversion, annual stream flow was found to be reduced by about 20% (Swank and Douglass, 1974). The reason for this notable change is that the interception and subsequent evaporation of rainfall is greater for pine than it is for hardwoods during the dormant season.

Fears have also been expressed that the replacement of tall natural forests by eucalyptus will produce a

Table 5.8 Measures for reducing and delaying urban storm runoff, including various types of sustainable urban drainage systems (SUDS). Source: after US Department of Agriculture, Soil Conservation Service (1972) in Viessman et al. (1977: 569)

Area	*Reducing runoff*	*Delaying runoff*
Large flat roof	Cistern storage Rooftop gardens Pool storage or fountain storage Sod roof cover	Ponding on roof by constricted drainpipes Increasing roof roughness: rippled roof graveled roof
Car parks	Porous pavement: gravel car parks porous or punctured asphalt Concrete vaults and cisterns beneath car parks in high value areas Vegetated ponding areas around car parks Gravel trenches	Grassy strips on car parks Grassed waterways draining car parks Ponding and detention measures for impervious areas: rippled pavement depressions basins
Residential	Cisterns for individual homes or groups of homes Gravel drives (porous) Contoured landscape Groundwater recharge: perforated pipe gravel (sand) trench porous pipe dry wells Vegetated depressions	Reservoir or detention basin Planting a high-delaying grass (high roughness) Grassy gutters or channels Increased length of travel of runoff by means of gutters, diversions and so on
General	Gravel alleys Porous pavements	Gravel alleys

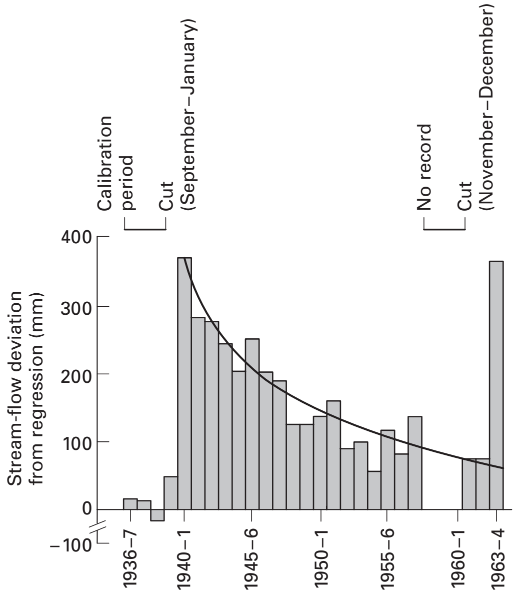

Figure 5.12 The increase of water yield after clear-felling a forest: a unique confirmation from the Coweeta catchment in North Carolina, USA.

decline in stream flow. However, most current research does not support this contention, for transpiration rates from eucalyptus are similar to those from other tree species (except in situations with a shallow groundwater table) while their interception losses are, if anything, generally rather less than those from other tree species of similar height and planting density (Bruijnzeel, 1990).

The reasons why the removal of a forest cover and its replacement with pasture, crops or bare ground have such important effects on stream flow are many. A mature forest probably has a higher rainfall interception rate, a tendency to reduce rates of overland flow, and probably generates soils with a higher infiltration capacity and better general structure. All these factors will tend to produce both a reduction in overall runoff levels and less extreme flood peaks. However, with careful management the replacement of forest by other land-use types need not be detrimental in terms of either sediment loss or flood generation. In Kenya, for example, the tea plantations with shade

Table 5.9 Impact of water use by invading alien plants on the mean annual runoff (MAR) in primary catchment areas of South Africa and Lesotho. Source: Le Maitre et al. (2000)

River system	*MAR (10^6 m^3)*	*Condensed invaded area (ha)*	*Incremental water use (10^6 m^3)*	*Water use (% of MAR)*	*Reduction in rainfall equivalents (mm)*
Limpopo	2381.82	122,457	190.38	7.99	155
Olifants	2904.10	217,855	290.44	10.00	133
Vaal	4567.37	64,632	190.53	4.17	295
Orange	7147.76	141,012	141.40	1.98	100
Olifants, Sout and Doring	1008.35	37,623	35.52	3.52	94
Namaqualand coast	25.01	46,618	22.76	91.00	49
W Cape and Agulhas coast	2056.75	384,636	646.50	31.43	168
Breede and Riversdale coast	2088.35	84,398	181.63	8.70	215
Gouritz	670.63	59,399	74.79	11.15	126
South Cape coast	1297.30	52,993	134.46	10.36	254
Gamtoos	494.71	34,289	96.53	19.51	282
Port Elizabeth Coast, Swartkops and Coega	150.04	11,358	40.18	26.78	354
Sundays	279.89	3964	8.34	2.98	210
Bushmans and Alexandria coast	172.92	22,894	73.08	42.26	319
Gt Fish	520.72	6980	21.12	4.06	303
Border Coast	578.91	12,483	55.58	9.60	445
Great Kei	1042.35	30,694	138.22	13.26	450
Former Transkei	7383.76	68,493	217.38	2.94	317
S KwaZulu-Natal	3121.20	46,442	126.37	4.05	272
Tugela	3990.88	62,151	104.67	2.62	168
North KwaZulu-Natal	4741.74	100,574	229.86	4.85	229
Komati to Nwanedzi	2871.4	124,494	283.26	9.86	228
RSA	49,495.96	1,736,438	3303.00	6.67	190

trees, protective grass covers, and carefully designed culverts were found to be 'a hydrologically effective substitute for natural forest' (Pereira, 1973: 127).

In many studies the runoff from clean-tilled land tends to be greater than that from areas under a dense crop cover, but tilling the soil surface does not always increase runoff (Gregory and Walling, 1973: 345). There are reports from the CIS suggesting that the reverse may be the case, and that autumn plowing can decrease surface runoff, presumably because of its effect on surface retention and on soil structure.

Grazing practices also influence runoff, for heavy grazing can both compact the soil and cause vegetation removal (Trimble and Mendel, 1995). In general it tends to lead to an increase in runoff.

In some parts of the world, such as southern Africa, the spread of invasive exotic plants (see p. 53) may cause greater loss of water then the native vegetation and so cause reduction in stream flow. Some calculations of this are presented in Table 5.9. The incremental water use of alien plants is estimated to be 3300 × 10^6 m^3 per year, equivalent to a 190 mm reduction in rainfall, and equivalent to almost three-quarters of the virgin mean annual runoff of the huge Vaal River (Le Maitre et al., 2000).

Changes in riverbank vegetation may have a particularly strong influence on river flow. In the southwest USA, for instance, many streams are lined by the salt cedar (*Tamarix pentandra*). With roots either in the water table or freely supplied by the capillary fringe, these shrubs have full potential transpiration opportunity. The removal of such vegetation can cause large increases in stream flow. It is interesting to note that the salt cedar itself is an alien, native to Eurasia, which was introduced by humans. It has spread explosively in the southwest USA, increasing from about 4000 hectares in 1920 to almost 400,000 hectares in the early 1960s (Harris, 1966). In the Upper Rio Grande valley in New Mexico, the salt cedar was introduced to try and combat anthropogenic soil erosion, but it spread so explosively that it came to consume approximately 45% of the area's total available water (Hay, 1973).

Reforestation of abandoned farmlands reverses the effects of deforestation: increased interception and evapotranspiration can cause a decline in water yield. In parts of the eastern USA, farm abandonment and recolonization of the land by pines, spruce, and cedar has been occurring throughout the twentieth century, and this has reduced stream flow by important amounts at a time when water supplies for some eastern cities were becoming critically short (Dunne and Leopold, 1978).

A process that is often associated with afforestation is peat drainage. The hydrological effects of this are the subject of controversy, since there are cases of both increased and decreased flood peaks after drainage (Holden et al., 2004). It has been suggested that differences in peat type alone might account for the different effects. Thus it is conceivable that the drainage of a *Sphagnum* catchment would lead to increased flooding since *Sphagnum* compacts with drainage, reducing its storage volume and its permeability. On the other hand, in the case of non-*Sphagnum* peat there would be relatively less change in structure, but there would be a reduction in moisture content and an increase in storage capacity, thereby tending to reduce flood flows. The nature of the peat is, however, but one feature to consider (Robinson, 1979). The intensity of the drainage works (depth, spacing, etc.) may also be important. In any case, there may be two (sometimes conflicting) processes operating as a result of peat drainage: the increased drainage network will facilitate rapid runoff, and the drier soil conditions will provide greater storage for rainfall. Which of these two tendencies is dominant will depend on local catchment conditions.

However, the impact of land drainage upon downstream flood incidence has long been a source of controversy. Much depends on the scale of study, the nature of land management, and the character of the soil that has been drained. After a detailed review of experience in the UK, Robinson (1990) found that the drainage of heavy clay soils that are prone to prolonged surface saturation in their undrained state generally led to a reduction of large and medium flow peaks. He attributed this to the fact that their natural response is ‘flashy’ (with limited soil water storage available), whereas their change to more permeable soils, which are less prone to such surface saturation, improves the speed of subsurface flow, thereby tending to increase peak flow levels.

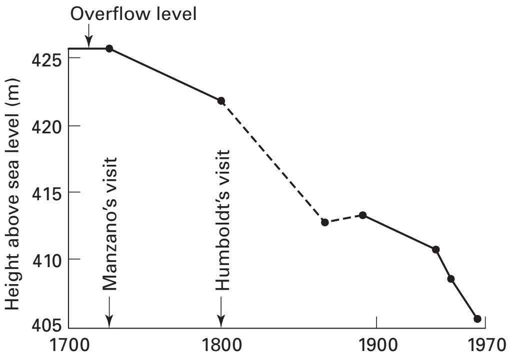

Figure 5.13 Variations in the level of Lake Valencia, Venezuela, to 1968 (after Böckh, 1973, figure 18.2).

The human impact on lake levels

One of the results of human modification of river regimes is that lake levels have suffered some change, although it is not always possible to distinguish between the part played by humans and that played by natural climatic changes.

A lake basin for which there are particularly long records of change is the Valencia Basin in Venezuela (Böckh, 1973). It was the declining level of the waters in this lake that so struck the great German geographer von Humboldt in 1800. He recorded its level as being about 422 m above sea level, and some previous observations on its level were made by Manzano in 1727, which established it as being at 426 m. The 1968 level was about 405 m, representing a fall of no less than 21 m in about 240 years (Figure 5.13). Humboldt believed that the cause of the declining level was the deforestation brought about by humans, and this has been supported by Böckh (1973), who points also to the abstraction of water for irrigation. This remarkable fall in level meant that the lake ceased to have an overflow into the River Orinoco. It has as a consequence become subject to a build-up in salinity, and is now eight times more saline than it was 250 years ago.

Even the world’s largest lake, the Caspian, has been modified by human activities. The most important change was the fall of 3 m in its level between 1929 and the late 1970s (see Figure 5.14). This decline was undoubtedly partly the product of climatic change (Micklin, 1972), for winter precipitation in the northern Volga Basin, the chief flow-generating area of the Caspian, was generally below normal for that period

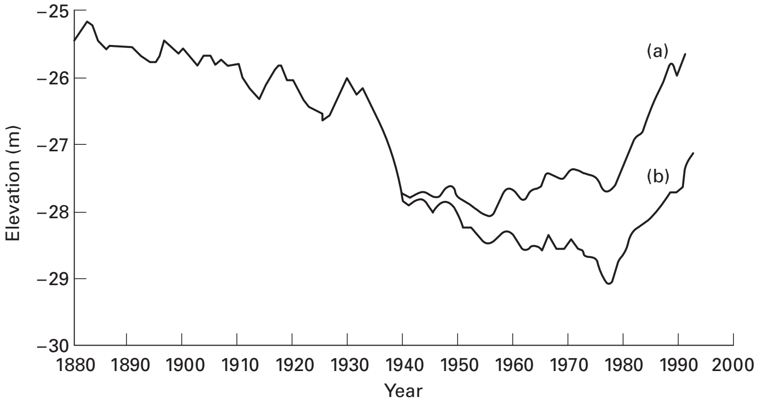

Figure 5.14 Annual fluctuations in the level of the Caspian Sea, for the period 1880–1993. Curve (a) shows the changes in level which would have occurred but for anthropogenic influences, while curve (b) shows the actual observed levels (modified from World Meteorological Organization, 1995, figure 15.3).

because of a reduction in the number of moist cyclones penetrating into the Volga Basin from the Atlantic. Nonetheless, human actions have contributed to this fall, particularly since the 1950s because of reservoir formation, irrigation, municipal and industrial withdrawals, and agricultural practices. In addition to the fall in level, salinity in the northern Caspian has increased by 30% since the early 1930s. A secondary effect of the changes in level has been a decline in fish numbers due to the disappearance of the shallows. These are biologically the most productive zones of the lake, providing a food base for the more valuable types of fish and also serving as spawning grounds for some species. There are plans to divert some water from northward-flowing rivers in Siberia towards the Volga to correct the decline in Caspian levels, but the possible climatic impacts of such action have caused some concern. In any event, an amelioration of climate since the late 1970s has caused some recovery in the level of the lake.

Perhaps the most severe change to a major inland sea is that taking place in the Aral Sea of the CIS (Figure 5.15) (Saiko and Zonn, 2000). Between 1960 and 1990, largely because of diversions of river flow, the Aral Sea lost more than 40% of its area and about 60% of its volume, and its level fell by more than 14 m (Kotlyakov, 1991). By 2002 its level had fallen another 6 m. This has lowered the artesian water table over a band 80–170 km in width, has exposed 24,000 km^2 of former lake bed to desiccation, and has created salty surfaces from which salts are deflated to be transported in dust storms, to the detriment of soil quality. The mineral content of what remains has increased almost threefold over the same period. It is probably the most dire ecological tragedy to have afflicted the CIS, and as with the Caspian's decline much of the blame rests with excessive use of water which would otherwise replenish the sea.

Water abstraction from the Jordan River has caused a decline in the level of the Dead Sea. During the past four decades increasing amounts of water have been diverted from surface and groundwater sources in its catchment. Under current conditions, on average, the annual inflow from all sources to the Dead Sea has been one-half to one-quarter that of the inflow prior to development. The water level has fallen about 20 m over that period (Figure 5.16). Under natural conditions freshwater from the Jordan constantly fed the less salty layer of the sea, which occupied roughly the top 40 m of the 320-m-deep body of water. Because the amount of water entering the lake via the Jordan was more or less equal to the quantity lost by evaporation, the lake maintained its stable, stratified state, with less salty water resting on the waters of high salinity. However, with the recent human-induced diminution in Jordan discharge, the sea's upper layer has receded because of the intense levels of evaporation. Its salinity has approached that of the older and deeper waters. It has now been established that as a consequence the layered structure has collapsed, creating a situation where there is increased precipitation of salts. Moreover, now that circulating waters carry oxygen to the bottom, the characteristic hydrogen-sulfide smell has largely disappeared (Maugh, 1979).

From time to time there have been proposals for major augmentation of lake volumes, either by means of river diversions or by allowing the ingress of seawater through tunnels or canals. Among such plans have

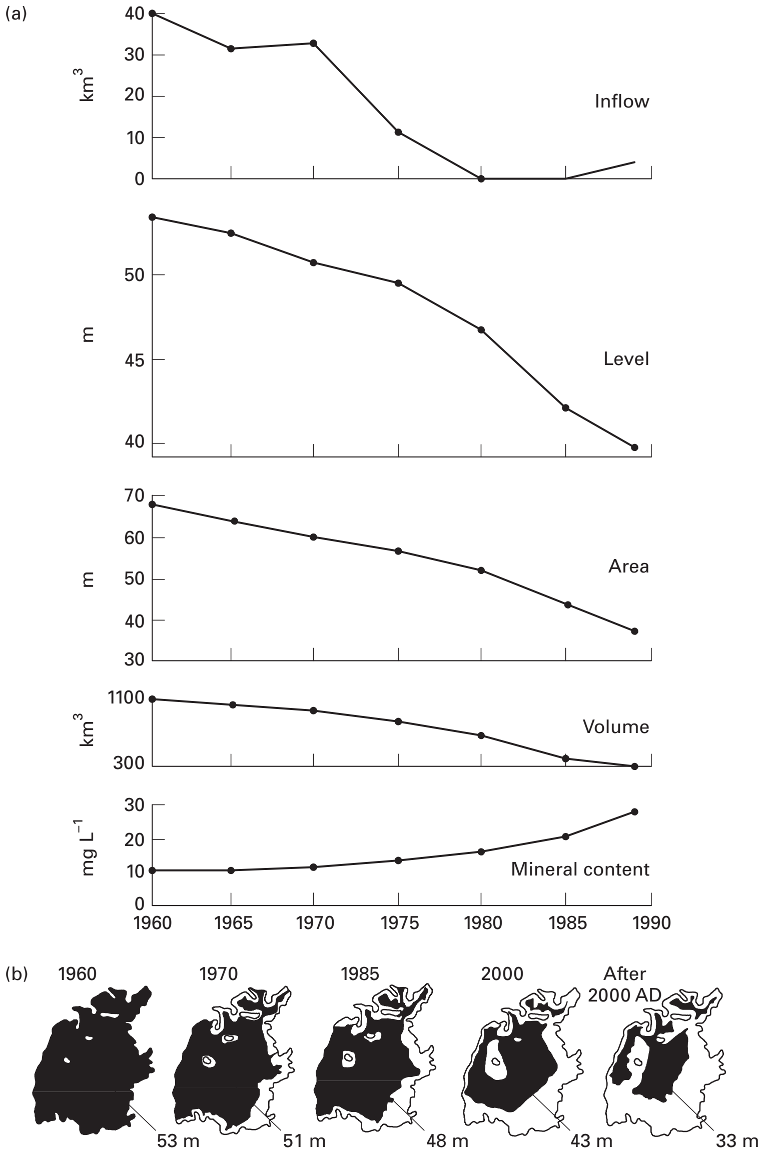

Figure 5.15 Changes in the Aral Sea: (a) 1960–1989 (from data in Kotlyakov, 1991) and (b) 1960 to after 2000 (after Hollis, 1978, p. 63).

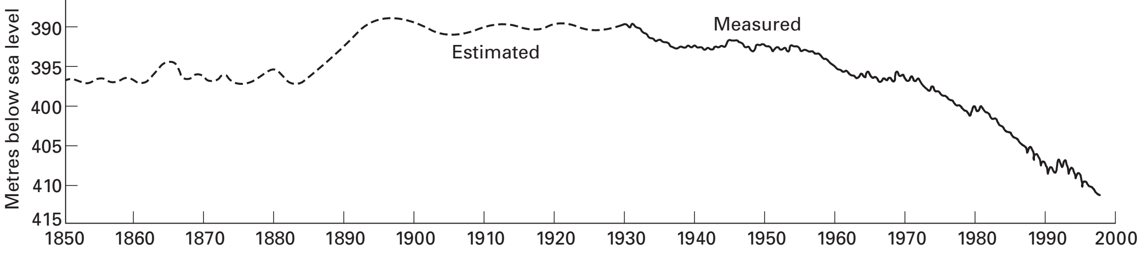

Figure 5.16 The level of the Dead Sea since 1850. Notice the 20-m fall since the 1960s.

been those to flood the salt lakes of the Kalahari by transferring water from the rivers of central Africa such as the Zambezi; the scheme to transfer Mediterranean water to the Dead Sea and to the Quattara Depression; and the Zaire–Chad scheme. Perhaps the most ambitious idea has been the so-called 'Atlantropa' project, whereby the Mediterranean would be empoldered, a dam built at the Straits of Gibraltar, and water fed into the new lake from the Zaire River (Cathcart, 1983).

Changes in groundwater conditions

In many parts of the world humans obtain water supplies by pumping from groundwater (see, e.g., Drennan, 1979). This has two main effects: the reduction in the levels of water tables and the replacement, in coastal areas, of freshwater by saltwater. Environmental consequences of these two phenomena include ground subsidence and soil salinization. Increasing population levels and the adoption of new exploitation techniques (e.g., the replacement of irrigation methods involving animal or human power by electric and diesel pumps) have increased these problems.

Some of the reductions in groundwater levels that have been caused by abstraction are considerable. Figure 5.17 shows the rapid increase in the number of wells tapping groundwater in the London area from 1850 until after the Second World War, while Figure 5.18 illustrates the widespread and substantial changes in groundwater conditions that resulted. The **piezometric** surface in the confined chalk **aquifer** has fallen by more than 60 m over hundreds of square kilometers. Likewise, beneath Chicago, Illinois, pumping since the late nineteenth century has lowered the piezometric head by some 200 m. The drawdown that has taken place in the Great Artesian Basin of Australia locally exceeds 80–100 m (Lloyd, 1986).

The reductions in water levels that are taking place in Nebraska and the High Plains of Texas are some of the most serious, and threaten the long-term viability of irrigated agriculture in that area. Before irrigation development started in the 1930s, the High Plains groundwater system was in a state of dynamic equilibrium, with long-term recharge equal to long-term discharge. However, the groundwater is now being mined at a rapid rate to supply center-pivot (Figure 5.19) and other schemes. In a matter of only 50 years or less, the water level declined by 30 to 50 m in a large area to the north of Lubbock. Since the 1980s the rate of decline has slowed from an average of *c.* 10 cm per year to just over 5 cm per year. This is the result of a combination of higher rainfall over the period together with reduced groundwater withdrawals for irrigation.

Another example of excessive 'mining' of a finite resource is the exploitation of groundwater resources in the oil-rich kingdom of Saudi Arabia. Most of Saudi Arabia is desert, so climatic conditions are not favorable for rapid large-scale recharge of aquifers. Also, much of the groundwater that lies beneath the desert is a fossil resource, created during more humid conditions

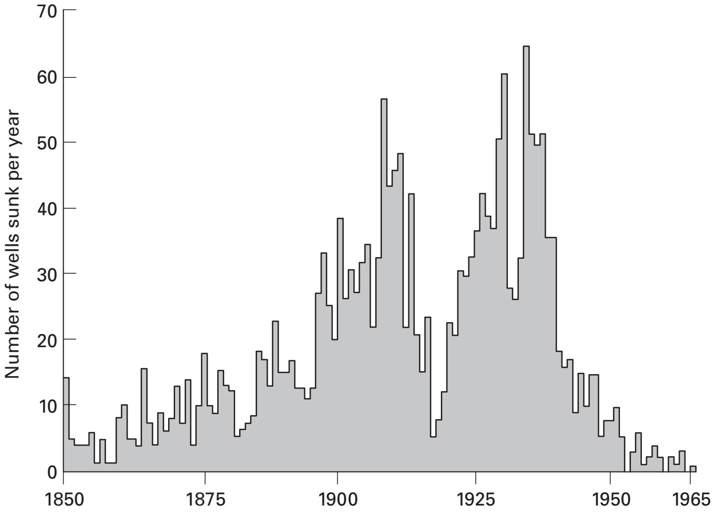

Figure 5.17 Construction of wells tapping the confined aquifer below London, 1850–1965.

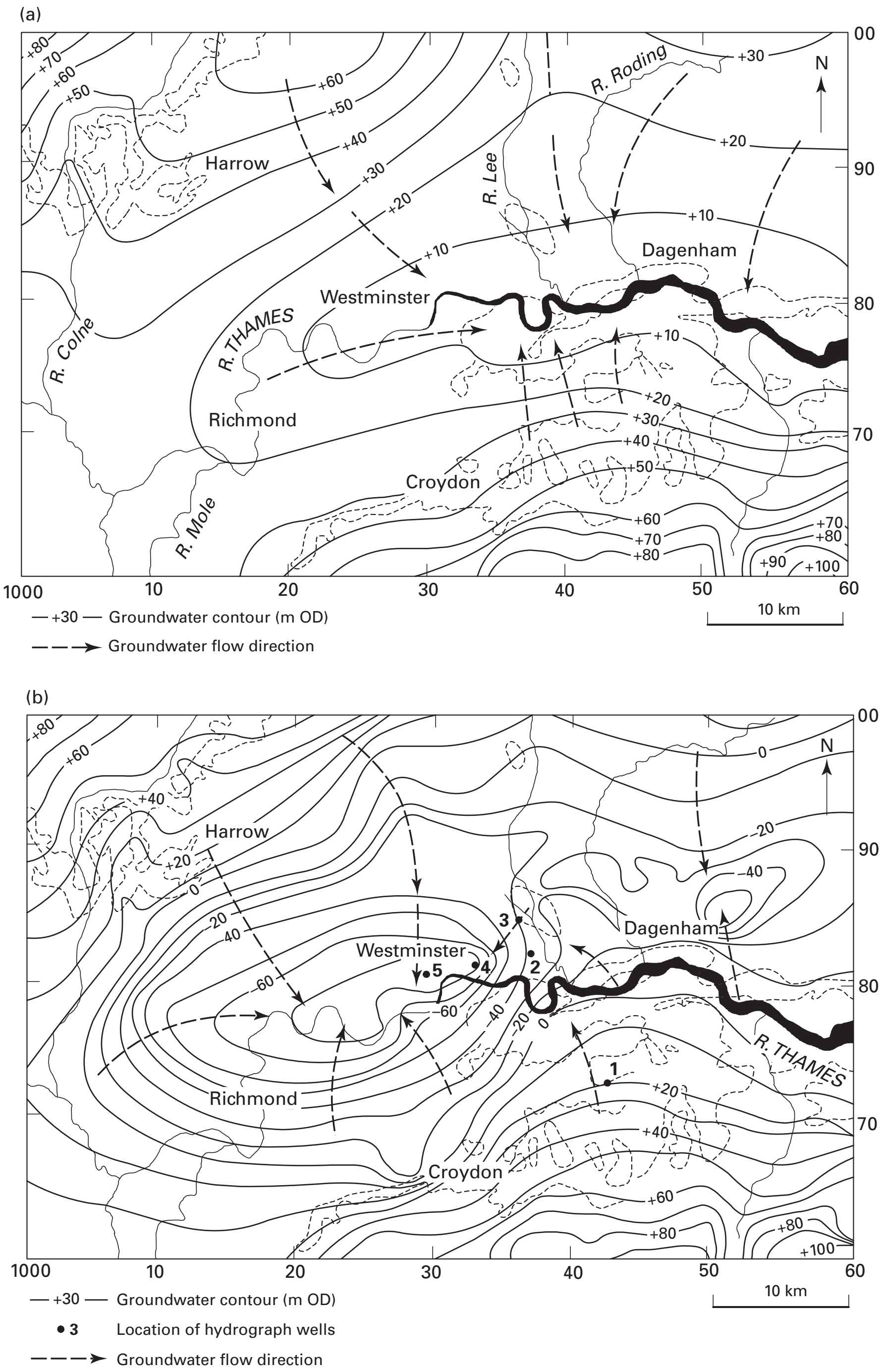

Figure 5.18 Groundwater levels in the London area (a) prior to major development and (b) in 1985 (from Wilkinson and Brassington, 1991, figures 4.5, 4.6, 4.7).

– pluvials – that existed in the Late Pleistocene, between 15,000 and 30,000 years ago. In spite of these inherently unfavorable circumstances, Saudi Arabia's demand for water is growing inexorably as its economy develops. In 1980 the annual demand was 2.4×10^9 m^3. By 1990 it had reached 12×10^9 m^3 (a fivefold increase in just a decade), and it is expected to reach 20×10^9 m^3 by 2010. Only a very small part of the demand can

Figure 5.19 In the High Plains of the USA, fields are irrigated by center-pivot irrigation schemes which use groundwater. Groundwater levels have fallen rapidly in many areas because of the adoption of this type of irrigation technology.

be met by runoff; over three-quarters of the supply is obtained from predominantly nonrenewable groundwater resources. The drawdown on its aquifers is thus enormous. It has been calculated that by 2010 the deep aquifers will contain 42% less water than in 1985. Much of the water is used ineffectively and inefficiently in the agricultural sector (Al-Ibrahim, 1991), to irrigate crops that could easily be grown in more humid regions and then imported.

However, there are situations where humans deliberately endeavor to increase the natural supply of groundwater by attempting artificial recharge of groundwater basins (Peters, 1998). Where the materials containing the aquifer are permeable (as in some alluvial fans, coastal sand dunes, or glacial deposits) the technique of water spreading is much used. In relatively flat areas river water may be diverted to spread evenly over the ground so that infiltration takes place. Alternative water-spreading methods may involve releasing water into basins which are formed either by natural processes (such as the playas of the High Plains in the USA), or by excavation, or by the construction of dikes or small dams. On alluvial plains water can also be encouraged to percolate down to the water table by distributing it to a series of ditches or furrows. In some situations natural channel infiltration can be promoted by building small check dams down a stream course. In irrigated areas surplus water can be spread by irrigating with excess water during the dormant season. When artificial groundwater recharge is required in sediments with impermeable layers such water-spreading techniques are not effective and the appropriate method may then be to pump water into deep pits or into wells. This last technique is used on the coastal plain of Israel, both to replenish the groundwater reservoirs when surplus irrigation water is available, and to attempt to diminish the problems associated with saltwater intrusion.

In some industrial areas, reductions in industrial activity have caused a recent reduction in groundwater abstraction, and as a consequence groundwater levels have begun to rise, a trend that is exacerbated by considerable leakage losses from ancient, deteriorating pipe and sewer systems. In cities such as London, Liverpool, and Birmingham an upward trend has already been identified (Brassington and Rushton, 1987; Price and Reed, 1989). In London, because of a 46% reduction in groundwater abstraction, the water table in the Cretaceous Chalk and Tertiary beds has risen by as much as 20 m. Such a rise has numerous implications, which are listed in Table 5.10. The trend in groundwater levels beneath Trafalgar Square is shown in Figure 5.20.

Table 5.10 Possible effects of a rising groundwater level. Source: modified after Wilkinson and Brassington (1991, table 4.3: 42)

Increase in spring and river flows
Re-emergence of 'dry springs'
Surface water flooding
Pollution of surface waters and spread of underground pollution
Flooding of basements
Increased leakage into tunnels
Reduction of slope and retaining wall stability
Reduction in bearing capacity of foundations and piles
Increased hydrostatic uplift and swelling pressures on foundations and structures
Swelling of clays
Chemical attack on foundations

There is, finally, a series of ways in which unintentionally changes in groundwater conditions can occur in urban areas. As we have clearly seen, in cities surface runoff is increased by the presence of impermeable surfaces. One consequence of this would be that less water went to recharge groundwater. However, there is an alternative point of view, namely that groundwater recharge can be accelerated in urban

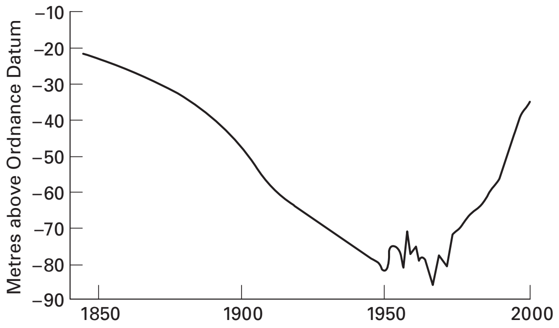

Figure 5.20 Changing groundwater levels beneath Trafalgar Square, central London, showing the sharp decline until the 1950s and the 1960s, and the substantial rise since then (from Environment Agency (UK) data).

areas because of leaking water mains, sewers, septic tanks, and soakaways (Figure 5.21). In cities in arid areas there is often no adequate provision for storm runoff, and the (rare) increased runoff from impermeable surfaces will infiltrate into the permeable surroundings. In some cities recharge may result from over-irrigation of parks and gardens. Indeed, where the climate is dry, or where large supplies of water are imported, or where pipes and drains are poorly maintained, groundwater recharge in urban areas is likely to exceed that in rural areas.

Water pollution

Water pollution is not new, but is frequently undesirable: it causes disease transmission through infection; it may poison humans and animals; it may create objectionable odors and unsightliness; it may be the cause of the unsatisfactory quality even of treated water; it may cause the eutrophication of water bodies; and it may affect economic activities such as shellfish culture.

The causes and forms of water pollution created by humans are many and can be classified into groups as follows (after Strandberg, 1971):

1 sewage and other oxygen-demanding wastes;
2 infectious agents;
3 organic chemicals;
4 other chemical and mineral substances;
5 sediments (turbidity);
6 radioactive substances;
7 heat (thermal pollution).

Moreover, many human activities can contribute to changes in water quality, including agriculture, fire, urbanization, industry, mining, irrigation, and many others. Of these, agriculture is probably the most important. Some pollutants merely have local effects,

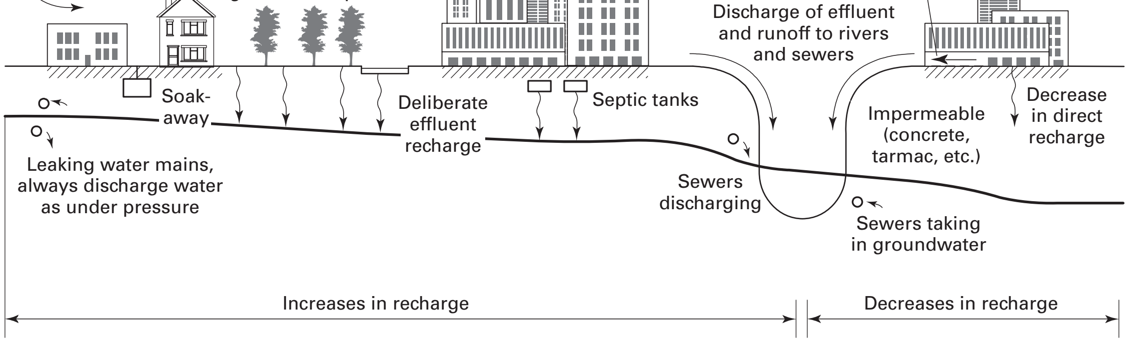

Figure 5.21 Urban effects on groundwater recharge (after Lerner, 1990, figure 2).

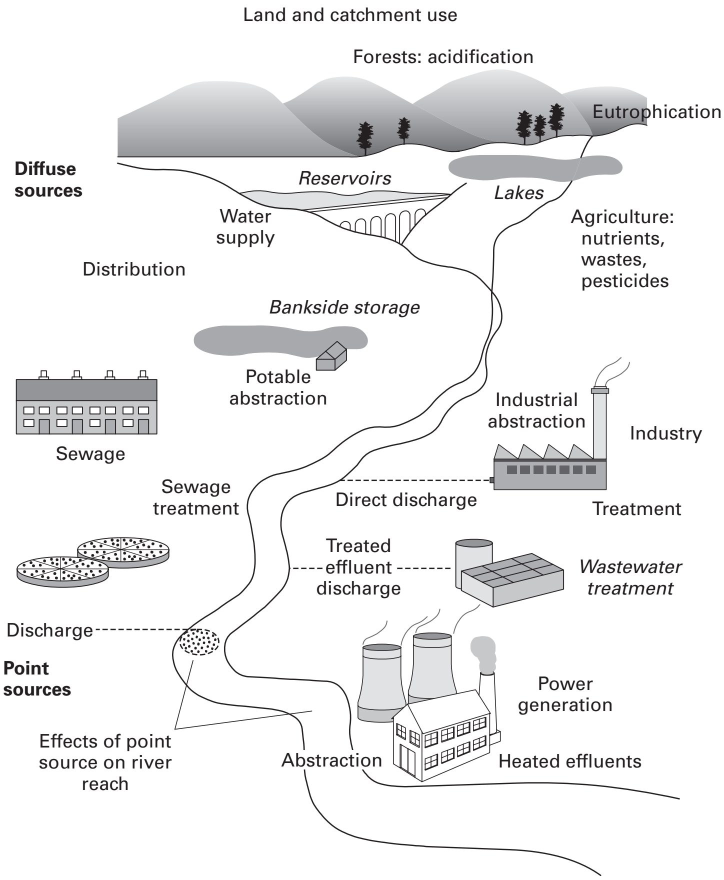

Figure 5.22 Diffuse and point sources of pollution into river systems (after Newson, 1992, figure 7.7).

while others, such as acid rain or DDT (dichlorodiphenyltrichloroethane), may have continental or even planetary implications.

It is also possible to categorize water pollutants according to whether or not they are derived from 'point' or 'nonpoint' (also called 'diffuse') sources (Figure 5.22). Municipal and industrial wastes tend to fall into the former category because they are emitted from one specific and identifiable place (e.g., a sewage pipe or industrial outfall). Pollutants from nonpoint sources include agricultural wastes, many of which enter rivers in a diffuse manner as chemicals percolate into groundwater or are washed off into fields, as well as some mining pollutants, uncollected sewage, and some urban storm-water runoff.

It is plainly not a simple matter to try to estimate the global figure for the extent of water pollution caused by humans. For one thing we know too little about the natural long-term levels of dissolved materials in the world's rivers. Nonetheless, Meybeck (1979) calculated that about 500 million tonnes of dissolved salts reach the oceans each year as a result of human activity. These inputs have increased by more than 30% the natural values for sodium, chloride, and sulfate, and have created an overall global augmentation of river mineralization by about 12%. Likewise, Peierls et al. (1991) have demonstrated that the quantity of nitrates in world rivers now appears to be closely correlated to human population density. Using published data for 42 major world rivers they found a highly significant correlation between annual nitrate concentration and human population density that explained 76% of the variation in nitrate concentration for the 42 rivers. They maintain that 'human activity clearly dominates nitrate export from land.' Meybeck (2001a) argued that on a global scale nutrient inputs to the oceans by rivers have already increased 2.2 times for nitrate and four times for ammonia.

Nitrate trends in most rivers in Europe and North America reveal a marked increase since the 1950s. This

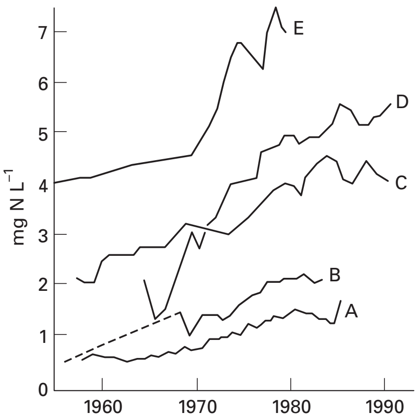

Figure 5.23 Recent trends of nitrate concentrations in some rivers: A, Mississippi at mouth; B, Danube at Budapest; C, Rhine at the Dutch–German border; D, Seine at mouth; E, Thames at mouth (from Meybeck, 2001b, figure 17.6).

can be attributed to the growth in use of nitrate fertilizers (Meybeck, 2001b). Trends for the Mississippi, Danube, Rhine, Seine, and Thames are shown in Figure 5.23.

There are three main classes of chemical pollutant that deserve particular attention: nitrates and phosphates; metals; and synthetic and industrial organic pollutants.

Nitrates and phosphates, trends in the concentration of which are reviewed by Heathwaite et al. (1996), are an important cause of a process called eutrophication. Nitrates normally occur in drainage waters and are derived from soil nitrogen, from nitrogen-rich glacial deposits, and from atmospheric deposition. Anthropogenic sources include synthetic fertilizers, sewage, and animal wastes from feedlots. Land-use changes (e.g., logging) can also increase nitrate inputs to streams. Phosphate levels are also rising in some parts of the world. Major sources include detergents, fertilizers and human wastes.

Metals, such as nitrates and phosphates, occur naturally in soil and water. However, as the human use of metals has burgeoned, so has the amount of water pollution they cause. In addition, some metal ions reach river waters because they become more quickly mobilized as a result of acid rain. Aluminum is a notable example of this. From a human point of view, the metals of greatest concern are probably lead, mercury, arsenic, and cadmium, all of which have adverse health effects. Other metals can be toxic to aquatic life, and these include copper, silver, selenium, zinc, and chromium.

The anthropogenic sources of metal pollution include the industrial processing of ores and minerals, the use of metals, the leaching of metals from garbage and solid waste dumps, and animal and human excretions. Nriagu and Pacyna (1988) estimated the global anthropogenic inputs of trace metals into aquatic systems (including the oceans), and concluded that the sources producing the greatest quantities were, in descending order, the following (the metals produced by each source are listed in parentheses):

- domestic wastewater effluents (arsenic, chromium, copper, manganese, nickel);
- coal-burning power stations (arsenic, mercury, selenium);
- nonferrous metal smelters (cadmium, nickel, lead, selenium);
- iron and steel plants (chromium, molybdenum, antimony, zinc);
- the dumping of sewage sludge (arsenic, manganese, lead).

However, in some parts of the world metal pollution may be derived from other sources. There is increasing evidence, for example, that in the western USA water derived from the drainage of irrigated lands may contain high concentrations of toxic or potentially toxic trace elements such as arsenic, boron, chromium, molybdenum, and selenium. These can cause human health problems and poison fish and wildlife in desert wetlands (Lently, 1994).

Synthetic and industrial organic pollutants have been manufactured and released in very large quantities since the 1960s. The dispersal of these substances into watercourses has resulted in widespread environmental contamination. There are many tens of thousands of synthetic organic compounds currently in use, and many are thought to be hazardous to life, even at quite low concentrations – concentrations possibly lower than those that can be measured routinely by commonly available analytical methods. Among these pollutants are synthetic organic pesticides, including chlorinated hydrocarbon insecticides (e.g., DDT). Some of these can reach harmful concentrations as a result of biological magnification in the food chain. Other important

Table 5.11 Characteristics of lakes experiencing 'cultural eutrophication'. Source: modified after Mannion (1992, table 11.4)

Biological factors	*Physical factors*
Primary productivity: usually much higher than in unpolluted water and is manifest as extensive algal blooms *Diversity of primary producers*: initially green algae increase, but blue-green algae rapidly become dominant and produce toxins. Similarly, macrophytes (e.g., reed maces) respond well initially but due to increased turbidity and anoxia (see below) they decline in diversity as eutrophication proceeds *Higher trophic level productivity*: overall decrease in response to factors given in this table *Higher trophic level diversity*: decreases due to factors given in this table. The species of macro- and microinvertebrates that tolerate more extreme conditions increase in numbers. Fish are also adversely affected and populations are dominated by surface-dwelling coarse fish such as pike and perch	*Mean depth of water body*: as infill occurs the depth decreases *Volume of hypolimnion*: varies *Turbidity*: this increases, as sediment input increases, and restricts the depth of light penetration that can become a limiting factor for photosynthesis. It is also increased if boating is a significant activity

organic pollutants include PCBs (polychlorinated biphenyls), which have been used extensively in the electrical industry as dielectrics in large transformers and capacitors; PAHs (polycyclic aromatic hydrocarbons), which result from the incomplete burning of fossil fuels; various organic solvents used in industrial and domestic processes; phthalates, which are plasticizers used, for example, in the production of polyvinyl chloride resins; and DBPs (1,4-diphenyl-1,3-butadienes), which are a range of disinfection by-products. The long-term health effects of cumulative exposure to such substances are difficult to quantify. However, some work suggests that they may be implicated in the development of birth defects and certain types of cancer.

Chemical pollution by agriculture and other activities

Agriculture may be one, if not the most, important cause of pollution, either by the production of sediments or by the generation of chemical wastes. With regard to the latter, it has been suggested that denitrification processes in the environment are incapable of keeping pace with the rate at which atmospheric nitrogen is being mobilized through industrial fixation processes and being introduced into the biosphere in the form of commercial fertilizers (Manners, 1978). Nitrogen, with phosphorus, tends to regulate the growth of aquatic plants and therefore the eutrophication of inland waters. Excess nitrates can also cause health hazards to humans and animals.

Eutrophication is the enrichment of waters by nutrients (Ryding and Rast, 1989). The process occurs naturally during, for example, the slow aging of lakes, but it can be accelerated both by runoff from fertilized agricultural land and by the discharge of domestic sewage and industrial effluents (Lund, 1972). This process, often called 'cultural eutrophication', commonly leads to excessive growths of algae, followed in some cases by a serious depletion of dissolved oxygen as the algae decay after death. Oxygen levels may become too low to support fish life, resulting in fish kills. Changes in diatom assemblages can also occur (see especially Battarbee, 1977). The nature of these changes is summarized in Table 5.11.

As agriculture has, in the developed world, become of an increasingly specialized and intensive nature, so the pollution impact has increased. The traditional mixed farm tended to be a more or less closed system that generated relatively few external impacts. This was because crop residues were fed to livestock or incorporated in the soil; and manure was returned to the land in amounts that could be absorbed and utilized. Many farms have become more specialized, with the separation of crop and livestock activities; large numbers of stock may be kept on feedlots, silage may be produced in large silos, and synthetic fertilizers may be applied to fields in large quantities (Conway and Pretty, 1991).

Although there are considerable fluctuations from year to year, the trend in nitrate levels in English rivers is clearly apparent (Figure 5.24b) (Royal Society Study Group, 1983). By 1980 they were 50 to 400%

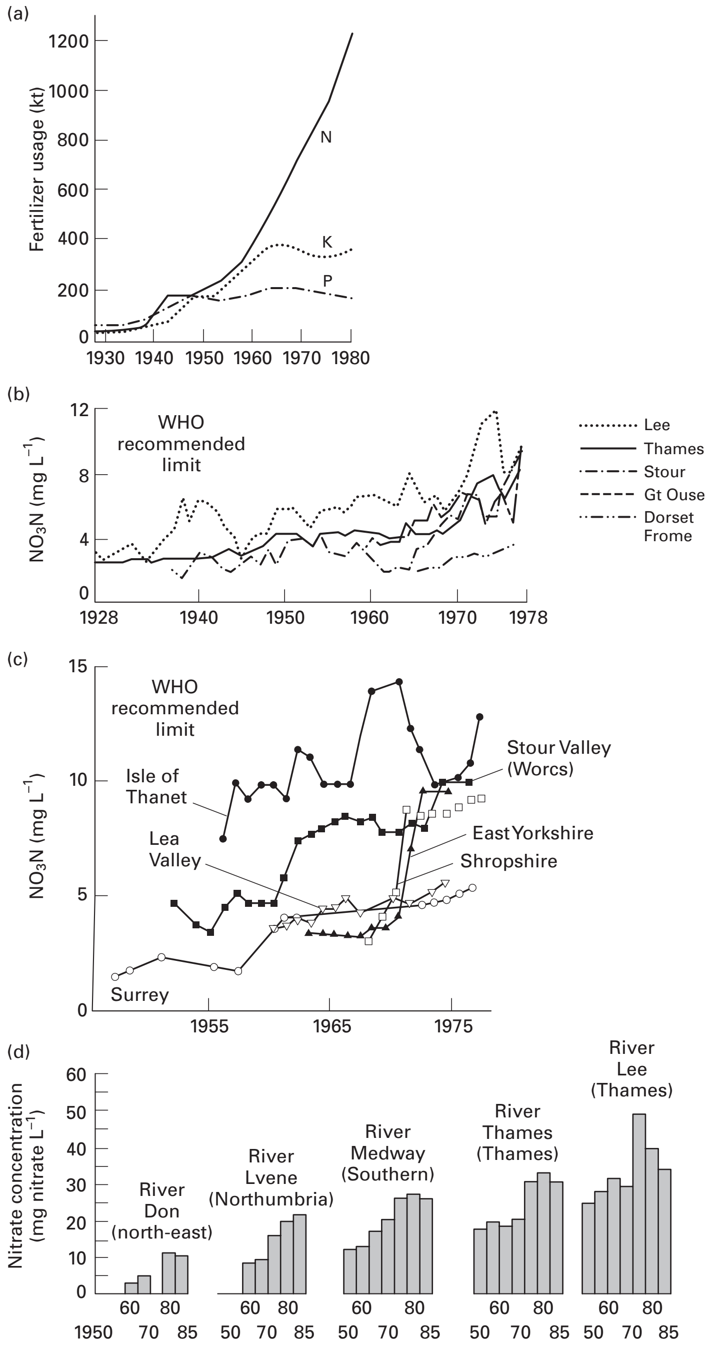

Figure 5.24 Nitrates in surface and groundwaters in the UK: (a) the trends in annual fertilizer usage in the UK during the period 1928–1980; (b) trends in mean annual nitrate concentration in five rivers for which long-term data are available – WHO, World Health Organization; (c) nitrate concentrations in selected public water supply abstraction boreholes in the Cretaceous Chalk and Triassic sandstone aquifers of the UK (Royal Society Study Group, 1983, figures 4, 18, 31); (d) changing nitrate concentrations in five UK rivers. The averages are five-year means (from Department of the Environment statistics, in Conway and Pretty, 1991, figure 4.8).

higher than they were 20 years before. The River Thames, which provides the major supply of London's water, increased its mean annual NO_3 concentration from around 11 mg L^{-1} in 1928 to 35 mg L^{-1} in the 1980s. Trends in nitrogen and phosphorus concentration in lowland regions of North America are not as great as those reported in lowland regions of Britain. This probably reflects the higher population density and greater intensity of land use in Britain (Heathwaite et al., 1996).

Also causing concern is the trend in nitrate concentrations in British groundwaters. Investigations have revealed a large quantity of nitrate in the unsaturated zone of the principal aquifers (mainly Cretaceous Chalk and Triassic sandstone), and this is slowly moving down towards the main groundwater body. The slow transit time means that in many water supply wells increased nitrate concentrations will not occur for 20 to 30 years, but they will then be above acceptable levels for human health (Figure 5.24c).

However, even if an increase in nitrate levels is evident this may not necessarily be because of the application of fertilizers (Burt and Haycock, 1992). Some nitrate pollution may be derived from organic wastes. There has also been some anxiety in Britain over a possible decline in the amount of organic matter present in the soil, which could limit its ability to assimilate nitrogen. Moreover, the pattern of tillage may have affected the liberation of nitrogen via mineralization of organic matter. The increased area and depth of modern plowing accelerates the decay of residues and may change the pattern of water movement in the soil. Finally, tile drainage has also expanded in area very greatly in recent decades in England. This has affected the movement of water through the soil and hence the degree of leaching of nitrates and other materials (Edwards, 1975).

Given the uncertainties surrounding the question of nitrate pollution, and bearing in mind the major advances in agricultural productivity that they have permitted, attempts at controlling their use have not been received with complete favor. Indeed, as Viets (1971) has pointed out, if fertilizer use were curtailed there would be less vegetation cover and increased erosion and sediment delivery to rivers. This, he suggests, would necessitate an increase in land hectarage to maintain production levels which would also cause greater erosion; at the same time the increased plowing would lead to greater nitrate loss from grasslands. Nevertheless some farmers are inefficient and wasteful in their use of fertilizers and there is scope for economy (Cooke, 1977).

In addition to the influence of nitrate fertilizers, the confining of animals on feedlots results in tremendously concentrated sources of nutrients and pollutants. Animal wastes in the USA are estimated to be as much as 1.6 billion tonnes per year, with 50% of this amount originating from feedlots. It needs to be remembered that 1000 head of beef produce the equivalent organic load of 6000 people (Sanders, 1972). The number of cattle fed on feedlots in the USA has increased rapidly, partly because per capita consumption of meat has moved sharply upward, and partly because the confinement of cattle on small lots, on which they are fed a controlled selection of feeds, leads to the greatest possible weight gains with the least possible cost and time (Bussing, 1972). Cattle feedlot runoff is a high-strength organic waste, high in oxygen-demanding material, and has caused many fish kills in rivers in states such as Kansas. In North Carolina and Virginia industrial style hog and poultry operations have caused large waste spills, especially during severe storms, and these too have caused massive fish kills.

Pesticides are another source of chemical pollution brought about by agriculture. There is now a tremendous range of pesticides and they differ greatly in their mode of action, in the length of time they remain in the biosphere, and in their toxicity. Much of the most adverse criticism of pesticides has been directed against the chlorinated hydrocarbon group of insecticides, which includes DDT and Dieldrin. These insecticides are toxic not only to the target organism but to other insects too (that is, they are nonspecific). They are also highly persistent. Appreciable quantities of the original application may survive in the environment in unaltered form for years. This can have two rather severe effects: global dispersal and the 'biological magnification' of these substances in food chains (Manners, 1978). This last problem is well illustrated for DDT in Figure 5.25.

Changes in surface-water chemistry may be produced by the washing out of acids that pollute the air in precipitation. This is particularly clear in the heavily industrialized area of northwestern Europe, where these is a marked zonation of acid rain with pH values that often fall below 4 or 5. A broadly comparable situation exists in North America (Johnson, 1979). Very considerable fears have been expressed about the possible effects that acid deposition may have on aquatic ecosystems, and particularly on fish populations. It is now generally accepted that decades of increasing lake and river acidification caused fish kills and stock depletion. Fishless lakes now occur in areas such as the Adirondacks in the northeast USA. Species of fish vary in their tolerance to low pH, with rainbow trout being largely intolerant to values of pH below 6.0, while salmon, brown and brook trout are somewhat less sensitive. Values of 4.0–3.5 are lethal to salmonids, while values of 3.5 or less are lethal to most fish. Numerous

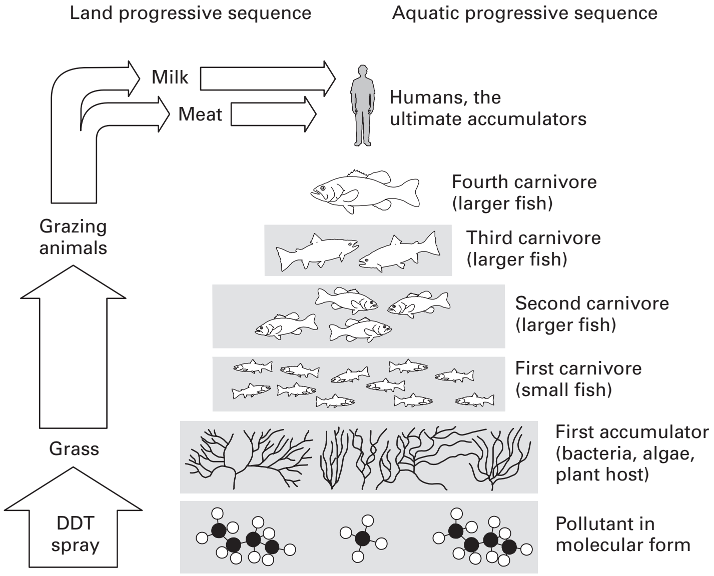

Figure 5.25 Biological concentration occurs when relatively indestructible substances (dichlorodiphenyltrichloroethane (DDT), for example) are ingested by lesser organisms at the base of the food pyramid. An estimated 1000 kg of plant plankton are needed to produce 100 kg of animal plankton. These in turn are consumed by 10 kg of fish, the amount needed by one person to gain 1 kg. The ultimate consumer (man or woman) then takes in the DDT taken in by the 1000 kg of the lesser creatures at the base of the food pyramid, when he or she ingests enough fish to gain 1 kg (after Strandberg, 1971, figure 2).

lacustrine molluscs and crustaceans are not found even at weakly acid pH values of 5.8–6.0, and crayfish rapidly lose their ability to recalcify after molting as the pH drops from 6.0 to 5.5 (Committee on the Atmosphere and the Biosphere, 1981).

Fish declines and deaths in areas afflicted by acid rain are not solely caused by water acidity per se. It has become evident that under conditions of high acidity certain metal ions, including aluminum, are readily mobilized, leading to their increasing concentration in freshwaters. Some of these metal ions are highly toxic and many mass mortalities of fish have been attributed to aluminum poisoning rather than high acidity alone. The aluminum adversely affects the operation of fish gills, causing mucus to collect in large quantities; this eventually inhibits the ability of the fish to take in necessary oxygen and salts. In addition, aluminum's presence in water can reduce the amount of available phosphates, an essential food for phytoplankton and other aquatic plants. This decreases the available food for fish higher in the food chain, leading to population decline (Park, 1987).

Fortunately, however, during the 1980s and 1990s rates of acid deposition decreased over large portions of North America and Europe (Stoddart et al., 1999; Cooper and Jenkins, 2003), and some recovery in streams and lakes has resulted. Reversal of acidification, while not universal, has been noted, for example, in the English Lake District (Tipping et al., 2000), in Scandinavia (Fölster and Wilander, 2002), in central Europe (Vesely et al., 2002), and in the English Pennines (Evans and Jenkins, 2000). In Europe, recovery has been strongest in the Czech Republic and Slovakia, moderate in Scandinavia and the UK, and weakest in Germany (Evans et al., 2001). The period required for recovery may in some areas be considerable. In the Adirondacks of the eastern USA recovery may take many decades because, on the one hand, they have been exposed to acid deposition for long periods of time so that they have been relatively depleted of substances that can neutralize acids, and on the other their soils are thin and so can offer less material to neutralize the acid from precipitation (US General Accounting Office, 2000).

Mining can also create serious chemical pollution. In the western USA, the forest service estimates that between 20,000 and 50,000 mines are currently generating acid on forest service lands, having an impact upon 8000–16,000 km of stream. In the eastern USA more than 7000 km of stream are affected by acid drainage from coal mines (US Environmental Protection Agency, 1994).

In Britain, coal seams and mudstones in the coal measures contain pyrite and marcasite (ferrous sulfide). In the course of mining the water table is lowered, air gains access to these minerals and they are oxidized.

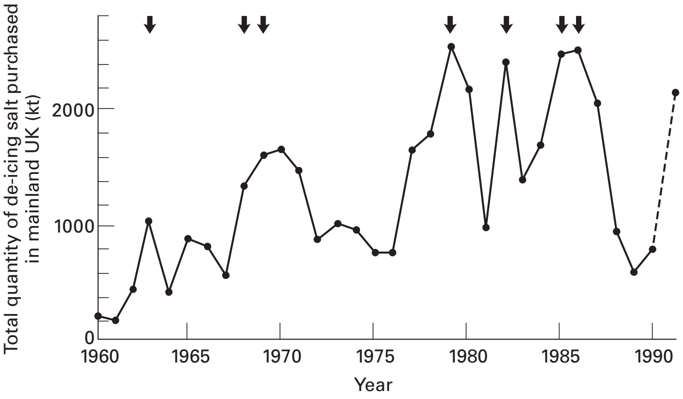

Figure 5.26 Estimates of the total quantity of de-icing salt purchased annually in mainland Britain during the period 1960–1991. Arrows highlight severe winters. Data provided by ICI (in Dobson, 1991, figure 1.1).

Sulfuric acid may be produced. Should mining cease, as is the situation in the coalfields of Britain, pumping may cease, groundwater may rise through the worked mine, and acid derived from it may discharge into more and more surface waters.

As a consequence, mine drainage waters may be very acid and have pH values as low as 2 or 3. They have high sulfate and iron concentrations, they may contain toxic metals such as arsenic and cadmium, and, because of the reaction of the acid on clay and silicates in the rocks, they may also contain appreciable amounts of calcium, magnesium, aluminum, and manganese. Following reactions with sediments or mixing with alkaline river waters, or when chemical or bacterial oxidation of ferrous compounds occurs, the iron may precipitate as ferric hydroxide. This may discolor the water and leave unsightly deposits (Rodda et al., 1976: 299). Some of the reactions involved in the development of what is called acid rock drainage (ARD) or acid mine drainage (AMD) have been set down by Down and Stocks (1977: 110–11).

1 Oxidation of the sulfide (usually FeS_2) in a wet environment producing ferrous sulfate and sulfuric acid

$$2FeS_2 + 2H_2O + 7O_2 \rightarrow 2FeSO_4 + 2H_2SO_4$$

2 Ferrous sulfate, in the presence of sulfuric acid and oxygen, can oxidize to produce ferric sulfate, especially in the presence of the bacterium *Thiobacillus ferro-oxidans*

$$4FeSO_4 + 2H_2SO_4 + O_2 \rightarrow 2Fe_2(SO_4)_3 + 2H_2O$$

3 The ferric iron so produced combines with the hydroxyl $(OH)^-$ ions of water to form ferric hydroxide, which is insoluble in acid and precipitates

$$Fe_2(SO_4)_3 + 6H_2O \rightarrow 2Fe(OH)_3 + 3H_2SO_4$$

The nature of acid drainage from mines and the remedial measures that can be adopted to deal with it are discussed by Robb and Robinson (1995).

Rock salt (sodium chloride) has been used in increasing quantities since the Second World War for minimizing the dangers to motorists and pedestrians from icy road and pavements. With the rise in the number of vehicles there has been a tendency throughout Europe and North America for a corresponding increase in the use of salt for de-icing purposes (see, e.g., Howard and Beck, 1993). Data for the UK between 1960 and 1991 are shown in Figure 5.26 and demonstrate that while there is considerable interannual variability (related to weather severity) there has also been a general upward trend so that in the mid-1970s to end-1980s more than two million tonnes of de-icing salt were being purchased each year (Dobson, 1991). Data on de-icing salt application in North America are given by Scott and Wylie (1980). They indicate that the total use of de-icing salts in the USA increased at a nearly exponential rate between the 1940s and the 1970s, increasing from about 200,000 tonnes in 1940 to approximately 9,000,000 tonnes in 1970. This represented a doubling time of about five years. Runoff from salted roads can cause ponds and lakes to become salinized, concrete to decay, and susceptible trees to die.

Similarly, storm-water runoff from urban areas may contain large amounts of contaminants, derived from

Table 5.12 Comparison of contaminant profiles for urban surface runoff and raw domestic sewage, based on surveys throughout the USA. Source: Burke (1972, table 7.36.1)

*Constituent**	*Urban surface runoff*	*Raw domestic sewage*
Suspended solids	250–300	150–250
BOD	10–250	300–350
Nutrients:		
total nitrogen	0.5–5.0	25–85
total phosphorus	0.5–5.0	2–15
Coliform bacteria (MPN 100 mL^{-1})	10^4–10^6	10^6 or greater
Chlorides	20–200	15–75
Miscellaneous substances:		
oil and grease	Yes	Yes
heavy metals	10–100 times sewage concentration	Traces
pesticides	Yes	Seldom
other toxins	Potential exists	Seldom

*All concentrations are expressed in mg L^{-1} unless stated otherwise: BOD, biochemical oxygen demand; MPN, most probable number.

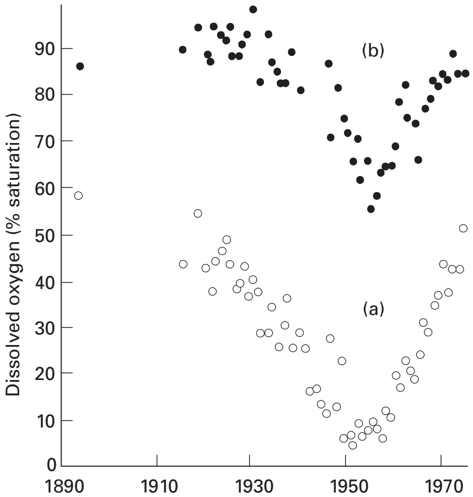

Figure 5.27 The average dissolved oxygen content of the River Thames at half-tide in the July–September quarter since 1890: (a) 79 km below Teddington Weir; (b) 95 km below Teddington Weir (after Gameson and Wheeler, 1977, figure 4).

litter, garbage, car-washings, horticultural treatments, vehicle drippings, industry, construction, animal droppings, and the chemicals used for snow and ice clearance. Comparison of contaminant profiles for urban runoff and raw domestic sewage, based on surveys throughout the USA, indicates the importance of pollution from urban runoff sources (Table 5.12). In New York City some half million dogs leave up to 20,000 tonnes of pollutant feces and up to 3.8×10^6 L of urine in the city streets each year, all of which is flushed by gutters to storm-water sewers. Taking Britain as a whole, dogs deposit 1000 tonnes of excrement and three million gallons of urine on the streets every day (Ponting, 1991).

Nonetheless, it would be unfair to create the impression that water pollution is either a totally insoluble problem or that levels of pollution must inevitably rise. It is true that some components of the hydrological system – for example, lakes, because they may act as sumps – will prove relatively intractable to improvement, but in many rivers and estuaries striking developments have occurred in water quality in recent decades. This is clear in the case of the River Thames, which suffered a serious decline in its quality and in its fish as London's pollution and industries expanded. However, after about 1950, because of more stringent controls on effluent discharge, the downward trend in quality was reversed (see Figure 5.27), and many fish, long absent from the Thames, are now returning (Gameson and Wheeler, 1977). Likewise, a long-term study of the levels of many heavy metals in seawater off the British Isles suggests that levels are generally stable and that concentrations do not seem to be increasing (Preston, 1973).

A similar picture emerges if one considers the trend in the state of Lake Washington near Seattle, USA. Studies there in 1933, 1950, and 1952 showed steady increases in the nutrient content and in associated growth of phytoplankton (algae). These resulted from the increasing levels of untreated sewage pumped into the lake from the Seattle area. A sewage diversion project, started in 1963 and completed in 1968 (see Figure 5.28), resulted in a significant decrease in the sewage input to the lake and was reflected in a rapid decline in phosphates, plankton, and turbidity, and a less marked decline in nitrate levels. There also appears to have been some improvement in pollution levels in the Great Lakes since the mid-1970s (Figure 5.29), as indicated by phosphorus loadings, and DDT and PCB levels.

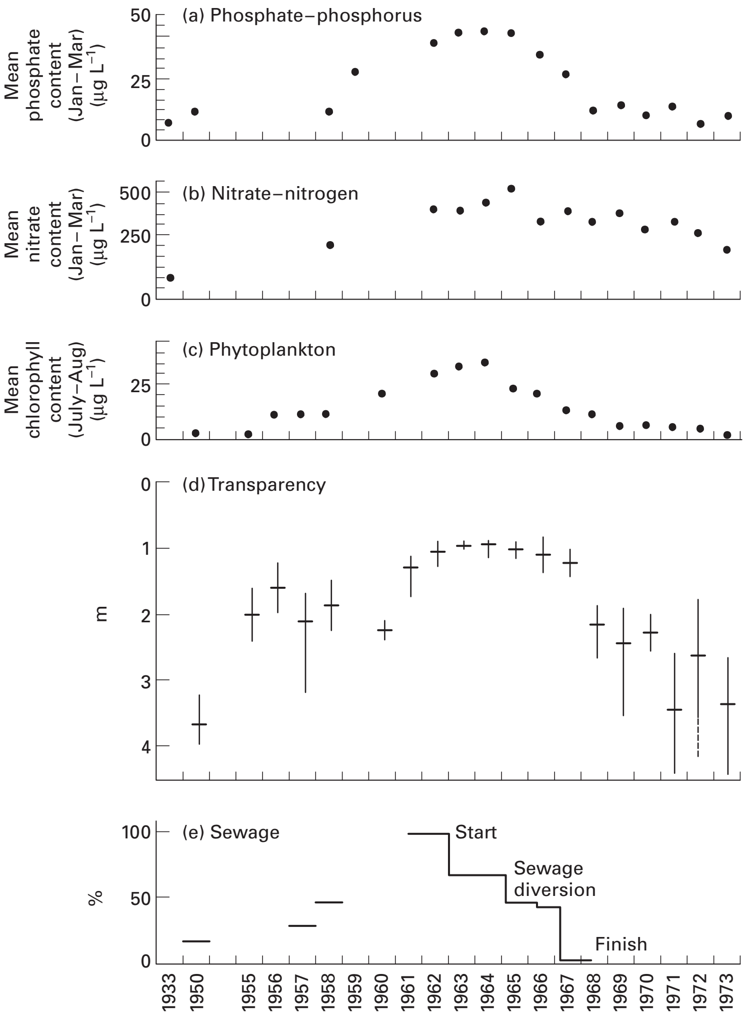

Figure 5.28 Changes in the state of Lake Washington, USA, associated with levels of untreated sewage from 1933 to 1973. The relative amount of treated sewage entering the lake is shown as a percentage of the maximum rated capacity of the treatment plants, 76×10^6 L per day (after Edmonson, 1975, figure 3).

One very important way of reducing the input of pollutants to stream courses is to provide a buffer zone of vegetation between them and the fields from which the pollution comes. Alternatively, bans can be instituted to prevent fertilizer applications in particularly sensitive zones with respect to pollutants such as nitrates.

Deforestation and its effects on water quality

The removal of tree cover not only may affect river flow and stream-water temperature, it may also cause changes in stream-water chemistry. The reason for this is that in many forests large quantities of nutrients are cycled through the vegetation, and in some cases (notably in humid tropical rain forest) the trees are a great store of the nutrients. If the trees are destroyed the cycle of nutrients is broken and a major store is disrupted. The nutrients thus released may become available for crops, and shifting cultivators, for example, may utilize this fact and gain good crop yields in the first year after burning and felling forest. Some of the nutrients may, however, be leached out of the soils, and appear as dissolved load in streams. Large increases in dissolved load may have undesirable effects, including eutrophication (Hutchinson, 1973), soil salination and a deterioration in public water supply (Conacher, 1979).

A classic but, it must be added, extreme exemplification of this is the experiment that was carried out in

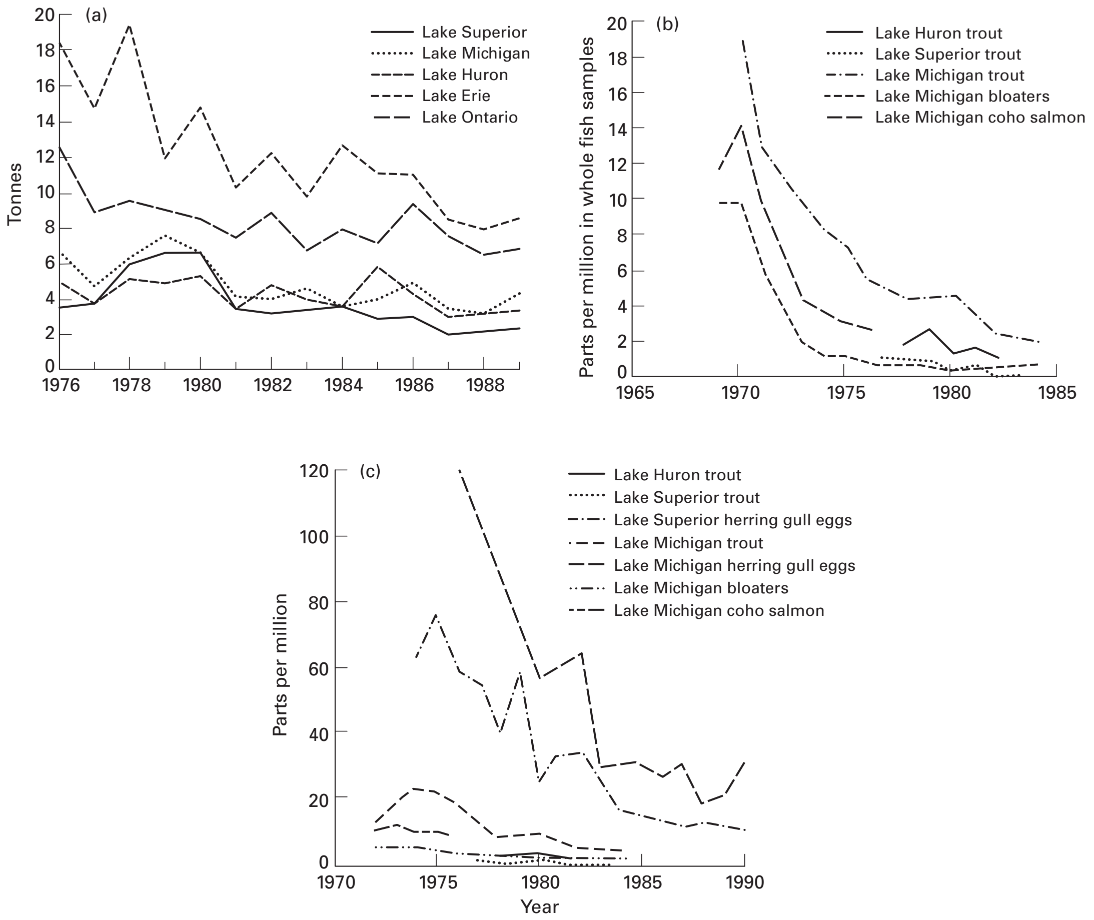

Figure 5.29 Changes in water pollution in the Great Lakes of North America: (a) estimated phosphorus loadings; (b) dichlorodiphenyltrichloroethane (DDT) levels; (c) polychlorinated biphenyl (PCB) levels (after Council on Environmental Quality, 17th (1986) and 22nd (1992) Annual Reports).

the Hubbard Brook catchments in New Hampshire, USA (Bormann et al., 1968). These workers monitored the effects of 'savage' treatment of the forest on the chemical budgets of the streams. The treatment was to fell the trees, leave them in place, kill lesser vegetation and prevent regrowth by the application of herbicide. The effects were dramatic: the total dissolved inorganic material exported from the basin was about 15 times larger after treatment, and, in particular, there was a very substantial increase in stream nitrate levels. Their concentration increased by an average of 50 times.

It has been argued, however, that the Hubbard Brook results are atypical (Sopper, 1975) because of the severity of the treatment. Most other forest clear-cutting experiments in the USA (Table 5.13) indicate that nitrate-nitrogen additions to stream water are not so greatly increased. Under conventional clear-cutting the trees are harvested rather than left, all saleable material is removed, and encouragement is given to the establishment of a new stand of trees. Aubertin and Patric (1974), using such conventional clear-cutting methods rather than the drastic measures employed in Hubbard Brook, found that clear-cutting in their catchments in West Virginia had a negligible effect on stream temperatures (they left a forest strip along the stream), pH, and the concentration of most dissolved solids.

Even if clear-cutting is practiced, there is some evidence of a rapid return to steady-state nutrient cycling because of quick regeneration. As Marks and Bormann (1972) have put it:

Table 5.13 Nitrate-nitrogen losses from control and disturbed forest ecosystems. Source: modified after Vitousek et al. (1979)

Site	*Nature of disturbance*	*Nitrate-nitrogen loss (kg ha^{-1} year^{-1})*	
		Control	*Disturbed*
Hubbard Brook	Clear-cutting without vegetation removal, herbicide inhibition of re-growth	2.0	97
Gale River (New Hampshire)	Commercial clear-cutting	2.0	38
Fernow (West Virginia)	Commercial clear-cutting	0.6	3.0
Coweeta (North Carolina)	Complex	0.05	7.3*
H. J. Andrews Forest (Oregon)	Clear-cutting with slash-burning	0.08	0.26
Alsea River (Oregon)	Clear-cutting with slash-burning	3.9	15.4
Mean		1.44	26.83

*This value represents the second year of recovery after a long-term disturbance. All other results for disturbed ecosystems reflect the first year after disturbance.

Because terrestrial plant communities have always been subjected to various forms of natural disturbances, such as wind storms, fires, and insect outbreaks, it is only reasonable to consider recovery from disturbance as a normal part of community maintenance and repair.

Likewise Hewlett et al. (1984) found no evidence in the Piedmont region of the USA that clear-cutting would create such extreme nitrate loss that soil fertility would be impaired or water eutrophication caused. They point out that rapid growth of vegetation minimizes nutrient losses from the ecosystem by three main mechanisms. It channels water from runoff to evapotranspiration, thereby reducing erosion and nutrient loss; it reduces the rates of decomposition of organic matter through moderation of the microclimate so that the supply of soluble ions for loss in drainage water is reduced; and it causes the simultaneous incorporation of nutrients into the rapidly developing biomass so that they are not lost from the system.

In Britain, a comparison of water chemistry in forested and clear-cut areas in the Plynlimon area of mid-Wales has revealed certain trends (Figure 5.30). The most notable of these is the increase in nitrate levels, which impacts on catchment acidification processes by causing a decrease in pH and releasing toxic metals such as aluminum. Also important is the increase in dissolved organic carbon, which causes discoloration of stream water (Institute of Hydrology, 1991).

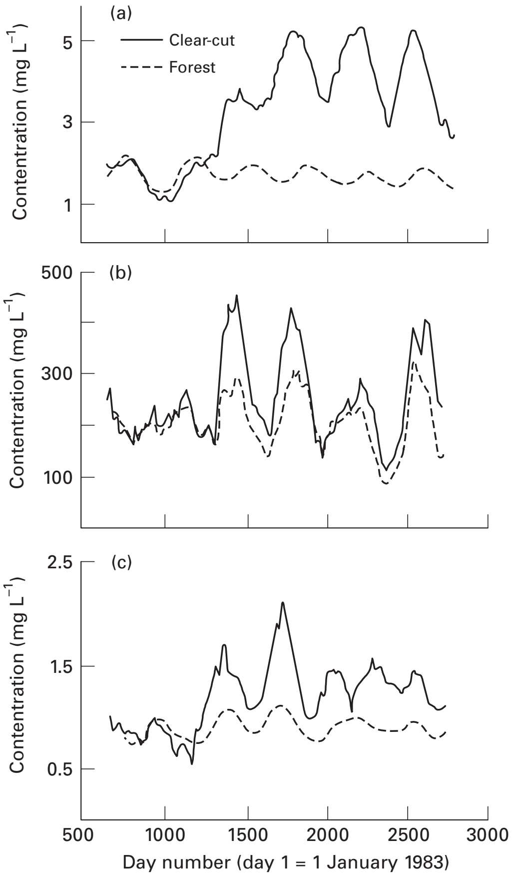

Figure 5.30 Changes in the chemical composition of stream water from clear-cut and forested catchments in mid-Wales, 1983–1990: (a) nitrate (NO_3); (b) aluminum (Al); (c) dissolved organic carbon (DOC) (modified after Institute of Hydrology, 1991, figure 20).

Thermal pollution

The pollution of water by increasing its temperature is called thermal pollution. Many fauna are affected by temperature, so this environmental impact has some significance (Langford, 1990).

In industrial countries probably the main source of thermal pollution is from condenser cooling water released from electricity generating stations. Water discharged from power stations has been heated some 6–9°C, but usually has a temperature of less than 30°C. The extent to which water affects river temperature depends very much on the state of flow. For example, below the Ironbridge power station in England, the Severn River undergoes a temperature increase of only 0.5°C during floods, compared with an 8°C increase at times of low flow (Rodda et al., 1976).

Over the past few decades both the increase in the capacity of individual electricity power-generating units and the improvements in their thermal efficiency have led to a diminution in the heat rejected in relation to the amount of cooling water per unit of production. Economic optimization of the generating plant has cut down the flow of cooling water per unit of electricity, although it has raised its temperature. This increased temperature rise of the cooling water is more than offset by the reduction achieved in the volume of water utilized. Nonetheless, the expansion of generating capacity has meant that the total quantity of heat discharged has increased, even though it is much less than would be expected on a simple proportional basis.

Thermal pollution of streams may also follow from urbanization (Pluhowski, 1970). This results from various sources: changes in the temperature regime of streams brought about by reservoirs according to their size, their depth, and the season; changes produced by the urban heat island effect; changes in the configuration of urban channels (e.g., their width/depth ratio); changes in the degree of shading of the channel, either by covering it over or by removing natural vegetation cover; changes in the volume of storm runoff; and changes in the groundwater contribution. Pluhowski found that the basic effects of cities on river-water temperatures on Long Island, New York, was to raise temperatures in summer (by as much as 5–8°C) and to lower them in winter (by as much as 1.5–3.9°C).

Reservoir construction can also affect stream-water temperatures. Crisp (1977) found, for example, that as a result of the construction of a reservoir at Cow Green (Upper Teesdale, northern England) the temperature of the river downstream was modified. He noted a reduction in the amplitude of annual water-temperature fluctuations, and a delay in the spring rise of water temperature by 20–50 days, and in the autumn fall by up to 20 days. In rural areas human activities can also cause significant modifications in river-water temperature. Deforestation is especially important (Lynch et al., 1984). Swift and Messer (1971), for example, examined stream temperature measurements during six forest-cutting experiments on small basins in the southern Appalachians, USA. They found that with complete cutting, because of shade removal, the maximum stream temperatures in summer went up from 19 to 23°C. They believed that such temperature increases were detrimental to temperature-sensitive fish such as trout (see Figure 5.31). On the other hand, the temporary shutdown of power plants may create severe cold-shock kills of fish in discharge-receiving waters in winter (Clark, 1977). Moreover, an increase in water temperature causes a decrease in the solubility of oxygen that is needed for the oxidation of biodegradable wastes. At the same time, the rate of oxidation is accelerated, imposing a faster oxygen demand on the smaller supply and thereby depleting the oxygen content of the water still further. Temperature also affects the lower organisms, such as plankton and crustaceans. In general, the more elevated the temperature is, the less desirable the types of algae in water. In cooler waters diatoms are the predominant phytoplankton in water that is not heavily eutrophic; with the same nutrient levels, green algae begin to become dominant at higher temperatures and diatoms decline; at the highest water temperatures, blue-green algae thrive and often develop into heavy blooms. One further ecological consequence of thermal pollution is that the spawning and migration of many fish are triggered by temperature and this behavior can be disrupted by thermal change.

Pollution with suspended sediments

Probably the most important effect that humans have had on water quality is the contribution to levels of

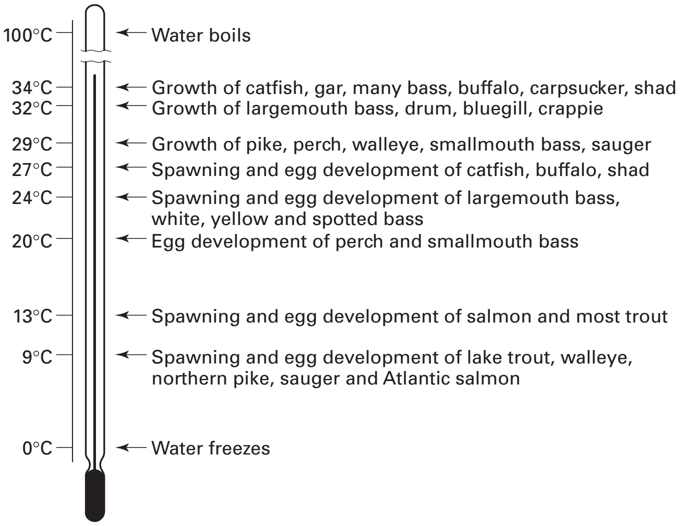

Figure 5.31 Maximum temperatures for the spawning and growth of fish. Heated waste water may be up to 5 to 10°C warmer than receiving waters and consequently the local fish populations cannot reproduce or grow properly. (After J. C. Giddings, *Chemistry, man and environmental change*, Harper and Row; from *Encounter with the Earth* by Leo F. Laporte, figure 13-2. Copyright © by permission of Harper & Row Publishers, Inc.)

suspended sediments in streams. This is a theme that is intimately tied up with that of soil erosion, on the one hand, and with channel manipulation by activities such as reservoir construction, on the other. The clearance of forest, the introduction of plowing and grazing by domestic animals, the construction of buildings, and the introduction of spoil materials into rivers by mineral extraction industries have all led to very substantial increases in levels of stream turbidity. Frequently sediment levels are a whole order of magnitude higher than they would have been under natural conditions. However, the introduction of soil conservation measures, or a reduction in the intensity of land use, or the construction of reservoirs, can cause a relative (and sometimes absolute) reduction in sediment loads. All three of these factors have contributed to the observed reduction in turbidity levels monitored in the rivers of the Piedmont region of Georgia in the USA.

Marine pollution

It is not within the scope of this book to discuss human impacts on the oceans to any great extent. However, it is worth making a few points on this subject, which has been well reviewed by Clark (1997). At first sight, as Jickells et al. (1991: 313) point out, two contradictory thoughts may cross our minds on this issue:

> The first is the observation of ocean explorers, such as Thor Heyerdahl, of lumps of tar, flotsam and jetsam, and other products of human society thousands of kilometers from inhabited land. An alternative, vaguer feeling is that given the vastness of the oceans (more than 1000 billion billion liters of water!), how can man have significantly polluted them?

What is the answer to this conundrum? Jickells et al. (p. 330) draw a clear distinction between the open oceans and regional seas and in part come up with an answer:

> The physical and chemical environment of the open oceans has not been greatly affected by events over the past 300 years, principally because of their large diluting capacity . . . Material that floats and is therefore not diluted, such as tar balls and litter, can be shown to have increased in amount and to have changed in character over the past 300 years.

In contrast to the open oceans, regional areas in close proximity to large concentrations of people show evidence of increasing concentrations of various substances that are almost certainly linked to human activities. Thus the partially enclosed North Sea and Baltic show increases in phosphate concentrations as a result of discharges of sewage and agriculture. The same is true of the more enclosed Black Sea (Mee, 1992).

This can cause accelerated eutrophication – often called ‘cultural eutrophication’ – which can lead to excessive growths of algae. Coastal and estuary water are sometimes affected by algal foam and scum, often called ‘red tides’. Some of these blooms are so toxic that consumers of seafood that have been exposed to them can be affected by diarrhea, sometimes fatally. A thorough analysis of eutrophication in Europe’s coastal waters is provided by the European Environment Agency (2001).

The nature of red tides has recently been discussed by Anderson (1994), who points out that these blooms, produced by certain types of phytoplankton (tiny pigmented plants), can grow in such abundance that they change the color of the seawater not only red but also brown or even green. They may be sufficiently toxic to kill marine animals such as fish and seals. Long-term studies at the local and regional level in many parts of the world suggest that these so-called red tides are increasing in extent and frequency as coastal pollution worsens and nutrient enrichment occurs more often.

Eutrophication also has adverse effects on coral reefs, as explained by Weber (1993: 49):

> Initially, coral productivity increases with rising nutrient supplies. At the same time, however, corals are losing their key advantage over other organisms: their symbiotic self-sufficiency in nutrient poor seas. As eutrophication progresses, algae start to win out over corals for newly opened spaces on the reef because they grow more rapidly than corals when fertilized. The normally clear waters cloud as phytoplankton begin to multiply, reducing the intensity of the sunlight reaching the corals, further lowering their ability to compete. At a certain point, nutrients in the surrounding waters begin to overfertilize the corals' own zooxanthellae, which multiply to toxic levels inside the polyps. Eutrophication may also lead to black band and white band disease, two deadly coral disorders thought to be caused by algal infections. Through these stages of eutrophication, the health and diversity of reefs declines, potentially leading to death.

Likewise it is clear that pollution in the open ocean is, as yet, of limited biological significance. GESAMP (1990), an authoritative review of the state of the marine environment for the United Nations Environment Program, reported (p. 1):

> The open sea is still relatively clean. Low levels of lead, synthetic organic compounds and artificial radionuclides, though widely detectable, are biologically insignificant. Oil slicks and litter are common along sea-lanes, but are, at present, of minor consequence to communities of organisms living in open-ocean waters.

On coastal waters it reported (p. 1):

> The rate of introduction of nutrients, chiefly nitrates but sometimes also phosphates, is increasing, and areas of eutrophication are expanding, along with enhanced frequency and scale of unusual plankton blooms and excessive seaweed growth. The two major sources of nutrients to coastal waters are sewage disposal and agricultural run-off from fertilizer-treated fields and from intensive stock raising.

Attention is also drawn to the presence of synthetic organic compounds – chlorinated hydrocarbons, which build up in the fatty tissues of top predators such as seals that dwell in coastal waters. Levels of contamination are decreasing in northern temperate areas but rising in tropical and subtropical areas due to continued use of chlorinated pesticides there.

The world's oceans have been greatly contaminated by oil. The effects of this pollution on animals have been widely studied. The sources of pollution include tanker collisions with other ships, the explosion of individual tankers because of the build-up of gas levels, the wrecking of tankers on coasts through navigational or mechanical failure, seepage from offshore oil installations, and the flushing of tanker holds. There is no doubt that the great bulk of the oil and related materials polluting the oceans results from human action (Blumer, 1972), although humans should not be attributed with all the blame, for natural seepages are reasonably common (Landes, 1973). Paradoxically, human actions mean that many natural seepages have diminished as wells have drawn down the levels of hydrocarbons in the oil-bearing rocks. Likewise, the flow of asphalt that once poured from the Trinidad Pitch Lake into the Gulf of Paria has also ceased because mining of the asphalt has lowered the lake below its outlet.

Of the various serious causes of oil pollution, a more important mechanism than the much-publicized role of tanker accidents is the discharge of the ballast water taken into empty tankers to provide stability on the return voyage to the loading terminal (Pitt, 1979). It is in this field, however, that technical developments have led to most amelioration. For example, the quantity of oil in tanker ballast water has been drastically reduced by the LOT (load on top) system, in which the ballast water is allowed to settle so that the oil rises to the surface. The tank is then drained until only the surface oil in the tank remains, and this forms part of the new cargo. In the future large tankers will be fitted with separate ballast tanks not used for oil cargoes, called segregated or clean ballast systems. Given such advances it appears likely than an increasing proportion of oil pollution will be derived from accidents involving tankers of ever increasing size, such as the spillage of 300×10^6 L that came from the wreck of the *Amoco Cadiz* in 1978. Even here, however, some progress has been made. Since 1980 there has been a reduction in the number of major oil spills, partly as a consequence of diminished long-distance oil transport to western Europe.

Points for review

What are the ecological effects of dams?
How do humans modify river channels?
To what extent do land cover changes lead to changes in river regimes?
Why should we be concerned about changes in groundwater levels?
Assess the causes and trends in nitrate pollution of water.

Guide to reading

Clark, R. B., 2001, *Marine pollution* (5th edn). Oxford: Clarendon Press. The standard work on this important topic.
Downs, P. W. and Gregory, K. J., 2004, *River channel management*. London: Arnold. A comprehensive treatment of river channels, human impacts, and river system management techniques.
Gleick, P. H. (ed.), 1993, *Water in crisis: a guide to the world's freshwater resources*. New York: Oxford University Press. A compendium of information on trends in water quality and consumption.
Kabat, P. and 9 others (eds), 2004, *Vegetation, water, humans and climate*. Berlin: Springer. A high-level research collection that investigates in particular the effects of vegetation change on climate and hydrological processes.
Petts, G. E., 1985, *Impounded rivers: perspectives for ecological management*. Chichester: Wiley. A treatment of the many consequences of dam construction.