4 Rivers

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4.1 Introduction

Water plays a key role in the transfer of mass and energy within the Earth system. Incoming solar radiation drives evaporation of about 434 000 $km^3\ a^{-1}$ from the ocean surface and 71 000 $km^3\ a^{-1}$ from the land surface, while precipitation delivers about 398 000 $km^3\ a^{-1}$ of water to the ocean and 107 000 $km^3\ a^{-1}$ to the land surface. The balance is redressed through the flow of 36 000 $km^3\ a^{-1}$ of water from the land to the oceans via rivers (data in Berner and Berner, 1996). Environmental change affecting any of these water transfers produces changes in runoff and river flows, hence in the rivers themselves.

Changing climate is intensifying the global hydrological cycle, leading to significant changes in precipitation, runoff and evapotranspiration (Huntington, 2006; Bates *et al*., 2008; see also Chapter 1). Intensification of the hydrological cycle is likely to mean an increase in hydrological extremes (IPCC, 2001). Changes in the frequency distribution of precipitation alter water flows and water availability in the surface environment leading, in turn, to a change in river regimes.

These factors are superimposed upon the effects of human actions associated with land use and with the attempt to control water for various uses that have directly changed river channels and the quality of water flowing in them. Land surface condition mediates quantity of water and the amount and calibre of sediment delivered to rivers which, in turn, influences river sedimentation, morphology and stability. Humans also manipulate the terrestrial hydrological cycle deliberately by construction of reservoirs, abstractions of water for human use, and discharges of water into river courses. Moreover, we directly modify watercourses by realigning them, by river 'training' works, by dredging, by fixing banks and building dykes. All these effects exert a dominating influence over the condition of rivers and of riverine and riparian ecosystems.

This chapter explores some of those effects on waterways and their ramifications. The argument will be that humans are modifying the terrestrial hydrological cycle and waterways in profound ways, indeed have been doing so for a long time, in the course of land use and in order to exploit water resources and to secure protection from water hazards. In comparison with the summary effects of these activities, the direct effects of climate change will remain relatively modest. Climate change will have important regional effects on the total water supply which will be critical where water supply is marginally adequate or already inadequate. However, the occurrence and quality of water and the condition of waterways are, in general, overwhelmingly dominated by human actions.

The chapter will pursue this thesis by considering water in uplands and the origin of runoff to rivers, then the controls and condition of river channels, river sediments and sedimentation, and the important topic of water storage in reservoirs. Contemporary issues of river 'restoration' are also considered briefly for this, in truth, represents a further manipulation of rivers.

4.2 Land surface: runoff production

4.2.1 The hillslope hydrological cycle

Until relatively recently, river engineers took the view that the headwaters of a drainage basin were nothing more than passive source areas for runoff. Being mainly concerned with downstream water management, in particular with flood forecasting, they felt able to ignore the exact processes responsible for generating the flood runoff. However, there were always other hydrologists with an interest in the process of runoff production. These interests have converged, especially since the advent of physically based computer simulation models of flood runoff.

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Moreover, it is highly relevant in the context of this chapter that an interest in river flows is invariably linked to concerns about the potential of the land surface to modulate the relation between precipitation and runoff production.

At the same time as L. K. Sherman was developing a numerical flood forecasting method (Sherman, 1932), the unit hydrograph, R. E. Horton, a hydraulic engineer working mainly in New York State, was much concerned with the impact of runoff from agricultural land on flood generation, soil erosion and sediment transport. Horton pioneered research on links between water infiltration into the soil ('infiltration capacity'), overland flow and erosion (Horton 1933, 1945). At much the same time, in the same region but in the rather different hydrological environment of the Appalachian forests, Charles Hursh showed that the source areas of storm runoff were different in forested lands compared with croplands. He identified the need to establish the relation between forest condition and streamflow in places where erosion was of minor importance (Hursh and Brater, 1941). Only then, Hursh argued, would it be possible to fully understand links between agricultural land use, runoff and erosion. Burt (2008) provides a detailed review of the process studies of Horton, Hursh and others in the establishment of a theory of runoff production.

The pathways taken by hillslope runoff draining to the nearest river channel determine many of the characteristics of the landscape, the uses to which land can be put and the strategies required for sustainable land use management (Dunne, 1978). Many factors influence the exact pathways involved at any location: vegetation cover, soil and bedrock properties, land use and land management practices, as well as the characteristics of the local climate, notably the intensity and duration of rainfall. Nevertheless, as far as storm runoff is concerned, the framework laid down by Horton and Hursh continues to provide a broad framework within which runoff production can be analysed, both in terms of the amount and timing of runoff, and the source areas within the river basin.

The partial source area model: infiltration-excess overland flow

Horton considered that the process of infiltration divided rainfall into two parts, which thereafter pursue different courses: one part moves quickly to the stream channel across the land surface as overland flow and generates storm runoff; the other part infiltrates the soil and flows slowly through soil and bedrock to sustain longer-term 'baseflow'.

High-intensity rain may produce overland flow immediately, while lower-intensity rain may produce overland flow only once infiltration capacity has declined as the soil wets up; low-intensity rainfall may well produce no surface runoff at all. Horton argued that surface runoff would be widespread across a river basin, but we have subsequently learned that this is unlikely to be the case except for small areas where infiltration capacity is relatively uniform and low. Infiltration capacity varies widely across space, as well as through time, producing wide variation in surface runoff production. Betson (1964) captured this localised runoff condition in his *partial area* model, which remains the best guide to the location of runoff source areas for infiltration-excess overland flow. In contrast to the *variable source area* model described below, partial source areas of overland flow appear relatively fixed in location during a given storm event. There may be important changes in infiltration capacity over time in some situations (e.g. in a tilled field over a yearly cultivation cycle) but this is not true for the ultimate 'Hortonian' runoff surface, an urban area, where impermeable surfaces present an unchanging pattern of runoff generation over long periods.

The variable source area model: saturation-excess overland flow

The occurrence of subsurface stormflow must be recognised in order to understand saturation-excess overland flow. Subsurface stormflow may happen in one of two phases: rapid flow through large structural pores or macropores (Jarvis, 2007), and slow seepage through small pores within the soil matrix. Hydrologists have tended to emphasise the latter, although the occurrence of macropore flow can be dominant in certain situations such as peat soils, forest soils and drained clay soils (see below). Lateral subsurface flow through the soil matrix occurs in any situation where soil permeability declines with depth. It was originally thought that subsurface flow was too slow to generate storm runoff but, in fact, rapid responses can be produced via 'capillary fringe' effects, whereby only a small amount of water needs to infiltrate the soil to raise the water table significantly. Significant subsurface flow may occur within a few hours of heavy rainfall on steep slopes with permeable soil which allows subsurface drainage to reach the stream channel relatively quickly (Anderson and Burt, 1978). Such delayed peaks in subsurface flow are particularly encouraged by the convergence of flow into hillslope hollows. If soil water accumulates more quickly than it can drain, then the soil profile may become completely saturated, with the result that water exfiltrates the soil to produce saturation-excess overland flow. The source areas for subsurface flow and saturation-excess overland flow are essentially the same, therefore, in locations where soil water tends to accumulate: at the foot of any slope, especially those of concave form; in areas of thin

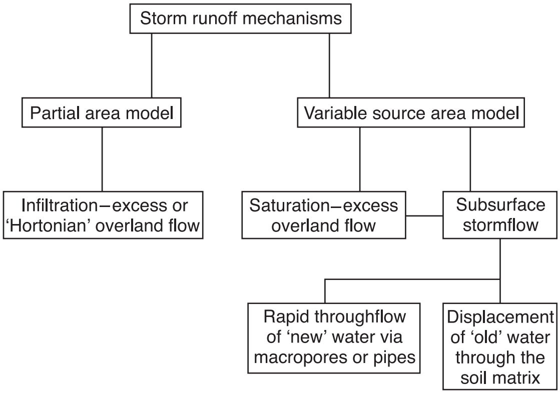

FIGURE 4.1. The partial area and variable source area models for runoff generation.

soils; and, as noted above, in hillslope hollows. Working at the same location as Hursh, J. D. Hewlett (1961) first described the *variable source area* model of storm runoff generation for saturation-excess overland flow. These localised zones of soil saturation expand during a storm, as rainfall adds water to the soil, and seasonally, as soils wet up after the dry season – hence the adjective 'variable'.

The two source area concepts (Fig. 4.1) of storm runoff generation pertain to contrasting process environments: infiltration-excess overland flow (the partial area model) dominates in intensively farmed areas where soil infiltration capacity is likely to be reduced by unfavourable land management practices, and in semi-arid regions. In contrast, saturation-excess overland flow (the variable source area model) tends to dominate in catchments where farming activity is low intensity or non-existent and infiltration capacity remains high.

4.2.2 Effects of human activity

Agriculture and runoff

Given the importance of overland flow for erosion, there have been many studies of infiltration in agricultural soils (see review by Rawls *et al*., 1993). Infiltration capacity depends on soil surface condition and the factors which affect this include soil properties, surface cover and land management practices.

The general relation between soil texture and final minimum infiltration capacity is shown in Table 4.1; fine-textured soils tend to have lower infiltration rates given the general link between texture and pore size distribution.

However, vegetation cover and land use are also crucial influences on infiltration rates, which can consequently vary widely for the same soil in time and space. Table 4.2 shows results from an area of silty clay loam soil; the effect of land use on infiltration capacity is immediately apparent. Under favourable conditions (e.g. woodland soil), silty soils can have a high infiltration capacity, but they are easily compacted; infiltration then falls significantly, and infiltration-excess overland flow occurs even in low intensity rainfall. Very low infiltration capacity can occur if wet soils are compacted by grazing or heavy machinery at inappropriate times. Bare soil is not necessarily the worst-case scenario: freshly ploughed soil has a very high infiltration capacity, for example. However, bare ground is

TABLE 4.1. *Final infiltration rates by Hydrologic Soil Group in relation to soil texture*

US Soil Conservation Service Hydrologic Soil Group	US Department of Agriculture soil textures included in Group	Final infiltration rate (mm hr^{-1})
A	Sand, loamy sand, sandy loam	>7.6
B	Silt loam, loam	3.8–7.6
C	Sandy clay loam	1.3–3.8
D	Clay loam, silty clay loam, sandy clay, silty clay, clay	0–1.3

Source: Based on information contained in Rawls *et al*. (1993).

TABLE 4.2. *The effect of land use on surface runoff at Slapton, Devon, UK*

Land use	Rainfall intensity (mm hr^{-1})	Infiltration rate (mm hr^{-1})
Woodland soil*		180
Permanent pasture*		9 (range: 3 – 36)
Freshly ploughed soil*		50
Temporary grass	12.5	12.3
Barley	12.5	11.0
Rolled, bare soil	12.5	4.0
Lightly grazed permanent pasture	12.5	5.9
Heavily grazed permanent pasture	12.5	0.1

* Results obtained using a rainfall simulator except where indicated by an asterisk.
Source: Data from Heathwaite *et al*. (1990), Burt *et al*. (1983) and Burt and Butcher (1985).

vulnerable to compaction by heavy rain and remains so until a good level of crop cover becomes established (Burt and Slattery, 1996). A 30% cover is often said to be 'safe', although this widely quoted yardstick seems to have no scientific basis.

Understanding spatial and temporal variations of infiltration capacity is thus a complex task. The precise chronology of soil surface changes, even for a single field, varies from season to season, depending on the succession of crops, and management of the crop and inter-crop intervals. More importantly perhaps, inter-annual variation in both erosivity (the tendency to cause erosion) and erodibility (the susceptibility of soil to erosion) depends on climatic conditions. There is a 'window of opportunity' during which a young crop is vulnerable to runoff and erosion as a result of surface sealing by heavy rainfall; whether or not this happens depends entirely on whether heavy rain falls when the crop cover is sparse or non-existent. For example, Boardman *et al*. (1995) describe an erosion event for a maize crop in southern England caused by an unusually heavy thunderstorm for the time of year (late spring). Maize is, in any case, a crop giving rise to conditions of high erodibility, given the wide spacing of rows, but heavy rainfall when the crop had just emerged meant that the soil surface was particularly vulnerable, especially because tillage had formed a fine tilth which was easily sealed by raindrop impact. Even when the soil surface condition is unlikely to generate infiltration-excess overland flow, compacted lines of soil formed by the passage of vehicles ('wheelings' or 'tram lines') may still produce large volumes of surface runoff. Thus, crop management practices (e.g. spraying pesticides or spreading fertiliser) can be damaging even when there is in effect a complete crop cover.

Agricultural land is often drained in order to increase productivity, usually to allow change on clay soils from grassland to arable. Open ditches are dug to extend the channel network while underground drainage in the form of tile drains, pipes traditionally constructed of clay tiles or, nowadays, corrugated plastic, is used to drain excess water from the plant root zone to the nearest channel, usually a drainage ditch. The question of the impacts of agricultural drainage on runoff production and flood peaks has been of interest for a long time. Robinson (1990) summarised the results from many different studies. Because drained soils tend to have a higher capacity to store water, infiltration will increase, reducing surface runoff. Drainage tends to reduce peak flows from clay catchments by decreasing antecedent storage, but may increase peak flows from more permeable soils because of more rapid drainage. Peak discharge decreases because water flows more slowly through the soil to reach the drainage system than it would as surface runoff. However, the overall volume of water lost (surface runoff and tile flow combined) from a drained field may increase (5–15%) compared with fields with surface drainage only; in effect, subsurface discharge increases at the expense of evaporative losses.

Robinson noted that the type of drainage scheme might also be important, with secondary practices such as mole drains or subsoiling giving higher peaks than pipe drains alone, while open ditches produce higher peaks than subsurface drains. Ground condition, due to both agricultural practices and cracking in heavy clay soils, may also be important in controlling the response but, in general, drainage tends to modify the timing of runoff and the peak flow rather than the volume of runoff from a given storm. Soil wetness can also influence the speed of throughflow in cracked clay soils; if the soil is dry, water will infiltrate the soil matrix but if the soil is already saturated, water will flow rapidly through the macropores to the drainage system.

At the catchment scale, it might be thought that land drainage would tend to increase flooding because of its impact on peak flow rates. However, drainage schemes are implemented at the field scale. At larger scales complexities arise because of the effects of routing of the outputs from individual fields, with or without drainage, to a site at risk of flooding. The relative timing of different runoff sources to the stream channel will then be important. It could be that a drainage scheme, by speeding up runoff from an area that before drainage had contributed water directly to the hydrograph peak, would have the effect of reducing the flood peak. Conversely, speeding up runoff from an area that prior to drainage had lagged behind the hydrograph peak could act to increase the flood peak (Beven *et al*., 2004). Substantial controversy has raged in Europe over whether field drainage has contributed to an increase in the incidence of river floods. The resolution appears to be that, while the duration of intermediate flows may have been extended, drainage has no detectable effect on major flooding, which is controlled by the excessive amounts of precipitation that arrive in a drainage basin in a limited time (see Mudelsee *et al*., 2003).

Land drainage in peatlands

The hydrological impacts of land drainage in peatlands are much the same as in poorly drained clay soils where intensive agriculture is practised, but both the reasons for drainage and the environmental context are somewhat different in these marginal areas. In the United Kingdom, large tracts of peaty soil in the uplands were drained in the second half of the twentieth century, both to increase productivity (extensive sheep grazing and game) and for coniferous forestry. At the Coalburn catchment in northern England, ribbon plough drainage (creation of large furrows roughly 1 m wide, 75 cm deep and 5 m apart) was carried out in 1972 prior to forest planting. There were significant increases in storm runoff and decreases in the time to peak immediately following drainage, presumably because the generating area for surface runoff was greatly increased. There was a recovery to pre-drainage responses after about 10 years, probably the result of forest canopy closure and a decrease in the efficiency and effectiveness of the surface drains (Robinson *et al*., 1998).

The impact of open drainage on the hydrological response of peatland catchments was first investigated by Conway and Millar (1960). They concluded that streamflow production in blanket peatlands, catchments that naturally produce large volumes of storm runoff very quickly, was even more rapid where artificial drainage had taken place; there was increased sensitivity to rainfall with peak flows both higher and earlier. Holden *et al*. (2006) showed that, 50 years later, while still 'flashy', the drained catchments produced less overland flow but more throughflow because of long-term changes in peat structure. However, the percentage of rainfall converted to storm runoff was even higher. Whether open ditching in peaty headwater catchments increases the flood risk downstream remains an open question but David and Ledger (1988), studying the effect of plough drainage of deep peat prior to planting with conifers, found that the open drains affected 30% of the area and 50% of the vegetation cover, and acted as major source areas for rapid surface runoff. It is not known whether ditch blocking will allow peat structure to recover eventually. If it does, there might be modest reductions in the speed and volume of stormflow response. A new runoff transition may be imminent, however, inasmuch as areas drained and planted in the second half of the last century are scheduled for harvest early this century.

Urbanisation

In some ways, the effect of urbanisation on runoff generation is simply an extreme form of the changes seen under intensive arable agriculture: the replacement of a permeable, vegetated land cover with a largely impermeable surface with scattered patches of permeable ground. In fact, the percentage of impermeable surface is rarely more than 60%, even in a highly built-up area, but this is still two orders of magnitude more than would be found in a typical rural catchment. Thus, large amounts of surface runoff are generated in urban areas (Endreny, 2005). Because the natural drainage network is greatly extended via roads, underground pipes and culverts, runoff reaches the perennial channel network very quickly. Storm runoff response is greatly enhanced therefore, with higher and earlier flood peaks. Rapid convergence through the drainage system of this increased runoff brings greater risk of flash flooding, especially when downstream drainage capacity is restricted by culverts that are old and unable to cope with extreme events. Moreover, flood protection measures along main river channels can have the unforeseen effect of preventing local drainage into the main channel, generating localised flooding outside the dykes. The quality of urban storm runoff is also very poor and the ecological status of urban watercourses is very likely to be poor too, especially where concrete culverts have replaced natural channels.

Given the problems associated with urban storm runoff, there has been much interest recently in sustainable urban drainage systems (SUDS: www.ciria.org/suds/index.html). Drainage systems are developed in line with the ideals of sustainable development; a balanced approach takes into account quantity, quality and amenity issues. SUDS seek to manage runoff as close to the point of origin as possible through a variety of techniques that attenuate the runoff response via storage ponds, buffer strips and the use of porous surfaces for infiltration. SUDS are more sustainable than traditional drainage systems because they manage peak runoff, reducing the downstream impact of urban runoff, protecting water quality, encouraging infiltration and groundwater recharge (where appropriate), and enhancing the in-stream ecology of urban channels.

Forest management and runoff

Forests cover a substantial portion of Earth's surface and have long been recognised as the principal source of high-quality surface water. They are subject to radical alteration, either in the course of forestry practice or through clearance for other land uses. Forest hydrology is affected by both deforestation and afforestation (not always mirror images in their impact) (National Research Council, 2008). The presence of a tree canopy completely alters the near-surface climate and, because of this, many micrometeorological studies have complemented hydrological research, especially in relation to the study of interception and evaporation (Calder, 1990). Forest harvest imposes a transient but possibly significant effect on runoff which has been extensively studied in deciduous and coniferous northern forests which were the principal sites of industrial forestry well into the twentieth century. Variable findings remain controversial, probably because of the dual role of forests both as interceptors of incoming precipitation, which is then evaporated or transpired back to the atmosphere, and as reservoirs of water in forest soils that contribute to runoff over some time (see Chapter 12).

Forest harvest removes the trees, potentially increasing the total water supply and altering the timing and magnitude of peak flows. Transient increases in water yield of up to 30% have been reported, but the effect rapidly dissipates as new growth occurs and the augmentation of runoff rarely persists beyond a decade (Bruijnzeel, 2005). On a global scale, Bosch and Hewlett (1982) collated the results of 94 experimental studies; they showed that forest removal consistently increased runoff but that the magnitude of the phenomenon varied regionally according to forest type, landscape character and the character of the climate.

Extreme flow effects, much as in agricultural landscapes, have been found to be variable, depending upon antecedent weather, the position of forest harvest in the landscape, and effects on the drainage network of roads and work sites. There is an emerging consensus that effects on extreme flows have more to do with disturbance of the drainage network than with vegetation manipulation.

In recent decades, attention to the effects of forest manipulation has shifted to the tropics, where deforestation proceeds at rates between 0.5% and 1.0% per annum (data from Food and Agriculture Organization, 2005; see also Chapter 8) in contrast to the temperate zone where forest cover is today increasing (see Chapter 2: Fig. 2.6). The implications for tropical hydrology of these rates of change are reviewed in Bonell and Bruijnzeel (2005). For a number of reasons, there is no consensus on the hydrological results at large scale. Firstly, the land conversion may entail the establishment of plantation forestry, or agroforestry, or land clearance for traditional agriculture, each with different hydrological effects. Secondly, it is clear that, at large scale, tropical forests in part create their own climate, so that regional deforestation tends to reduce precipitation with the result that all of the principal elements of the hydrological cycle may decrease in magnitude (see Costa in Bonell and Bruijnzeel, 2005).

4.2.3 Perspective

Changing climate certainly will change the quantity and timing of precipitation around the world. A warmer atmosphere will carry more moisture and a more energetic atmosphere will deliver increased amounts and intensity of storm precipitation in many places. But not in all places – the changing trajectory of weather systems will lead to reduced precipitation in some locations, and changing seasonal occurrence of precipitation will have significant effects on water resources.

Runoff is the residual left from precipitation after evaporation has occurred. In a warmer atmosphere, that quantity will increase too. Hence, some regions will experience increased precipitation yet decreased runoff. The volume and timing of runoff will be further modulated by changing seasonal snow occurrence, and it will eventually be affected by the response of native vegetation to a changed climate. Predicting changes in runoff as the result of expected climate change is therefore a difficult matter (see Bates *et al*., 2008).

In comparison, it is known that human activities have pervasive impacts on runoff to streams. These effects can be summarised under four major categories:

(a) manipulation of land cover, which affects interception and transpiration losses;
(b) working and trafficking on the land surface, which affects the infiltration capacity of soils;
(c) creation of impermeable surfaces; and
(d) installation of land drainage measures.

These actions have various effects. Mostly, the manipulation of surface cover leads to increases in the volume of runoff; working the land and the creation of impermeable surfaces mostly affects the balance of surface and subsurface drainage, leading to more rapid drainage and a larger volume of runoff, while land drainage measures mostly increase the volume of runoff. The effect on peak flows is complex, since that depends upon the structure of the entire drainage network, as well as on the timing and volume of water delivery from individual land units.

These effects have been developing for thousands of years. For at least a millennium they have had regionally major effects, and within the last two centuries they have become intense everywhere humans have settled. Yet the pace of change has been subtle and, until the mid twentieth century, they remained largely overlooked. Whilst climate change over the next century may have a more immediately noticeable effect on water supply, the cumulative impact on the hydrology by human modification of Earth's surface over the course of human history has undoubtedly far surpassed prospective changes, and will continue.

4.3 River channels: function and management

4.3.1 The form of river channels

River channels are the conduits that drain runoff from the surface of the land. Water flowing over the land surface is capable of eroding soil and even rock material, so that rivers carry and redistribute sedimentary materials as well. In the short term, the sediment transporting activity of rivers creates the channels in which streams and rivers flow and it affects the quality of water in the channels; in the very long term, it creates the landscape.

Channelled water flows originate in upland areas wherever topographic declivities cause soil drainage to converge. Concave hollows on hillslopes are typical sites of channel initiation, but much of the initial concentration of flow occurs in the subsurface in soil macropores (see Section 4.2.1) and comes to the surface at springs and seepage zones – places where subsurface flow convergence creates saturated conditions at the surface. The drainage area required for channel inception varies over Earth's surface according to climate and land surface condition (Dunne, 1978).

The conditions that govern the form and stability of river channels include the volume and timing of the water that flows through the channel, the volume and calibre of the sediment that is carried by the stream, the character of the material that forms the bed and banks of the channel, and the gradient of the valley down which the river flows. The volume and timing of water sets the scale of the channel – determines how large the channel must be in order to convey the larger flows – while the volume and calibre of the sediment set the morphological style of the channel – whether it is a wide and shallow, gravel-bed channel, or a deep and narrow, silt-bound one. Bed and bank materials, which may largely consist of the sediment transported by the stream, are also important determinants of channel form and stability, since only flows that can erode the materials locally forming the channel boundary can cause a change in the shape or position of the channel. Finally, the topographic gradient sets the potential rate at which the energy of the water must be dissipated by the river as it flows downhill. The stability of the river depends upon a balance being achieved between the rate at which the potential energy of the water is expended and the rate at which that energy is consumed in doing the work of moving the water and sediment load over the more or less rough and irregular boundary of the channel.

A simple summary of the scale of river channels is expressed by the so-called equations of downstream hydraulic geometry, which relate channel width and depth to the 'channel forming flow', Q, usually taken to be some relatively large flow such as the bankfull flow. These equations take the form

$$w = aQ^b \tag{4.1}$$

where $b = 0.50$, and

$$d = cQ^f \tag{4.2}$$

where $0.33 \leq f \leq 0.40$; and wherein w is water surface width, $d = A/w$ is the hydraulic mean depth, A is the cross-sectional area of the flow, and Q is the discharge. Since $Q = wdv$,

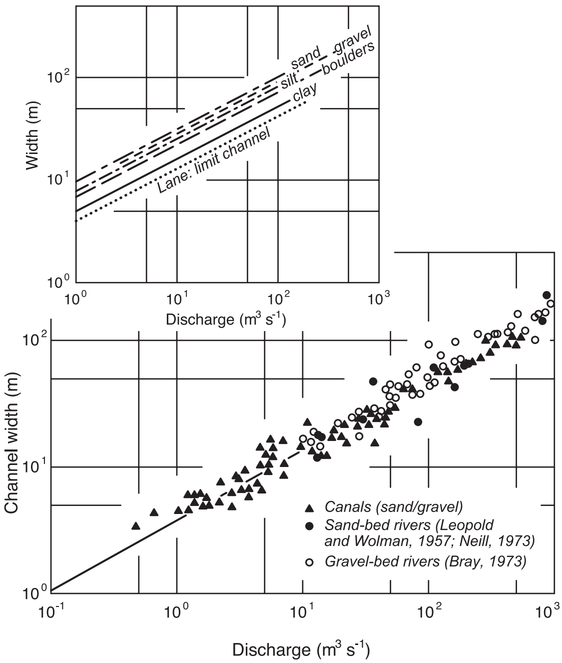

FIGURE 4.2. Scale relation (downstream hydraulic geometry) for alluvial rivers. Inset: variation of hydraulic geometry with materials (modified from Lane, 1957).

wherein v is the mean velocity, the relations above induce a third hydraulic geometry relation,

$$v = kQ^m \tag{4.3}$$

where $m = 1.0 - f - b$; the product $a\ c\ k = 1.0$ and individually vary according to the materials through which the channel flows and the sediments are transported. Figure 4.2 illustrates the channel width equation – the principal scale relation.

The governing conditions vary systematically through a drainage basin in proportion as channels become larger. Headwater streams are small (since they drain a small area) and relatively steep (since water seeks the steepest available line of descent). Because they are steep, they may evacuate most of the sediment supplied to them and flow in channels eroded to bedrock, or through residual materials too large for the stream to move. Farther downstream, channels become larger as tributaries join together in the usual tree-like network; they also become flatter, and tend to deposit a part of their increasing sediment load. Hence, the channels begin to flow in sediments that they may have transported to the site. Such channels are *alluvial* channels. Figure 4.3 illustrates these trends, which are also expressed in the hydraulic geometry, and shows important correlative changes that occur in the drainage system.

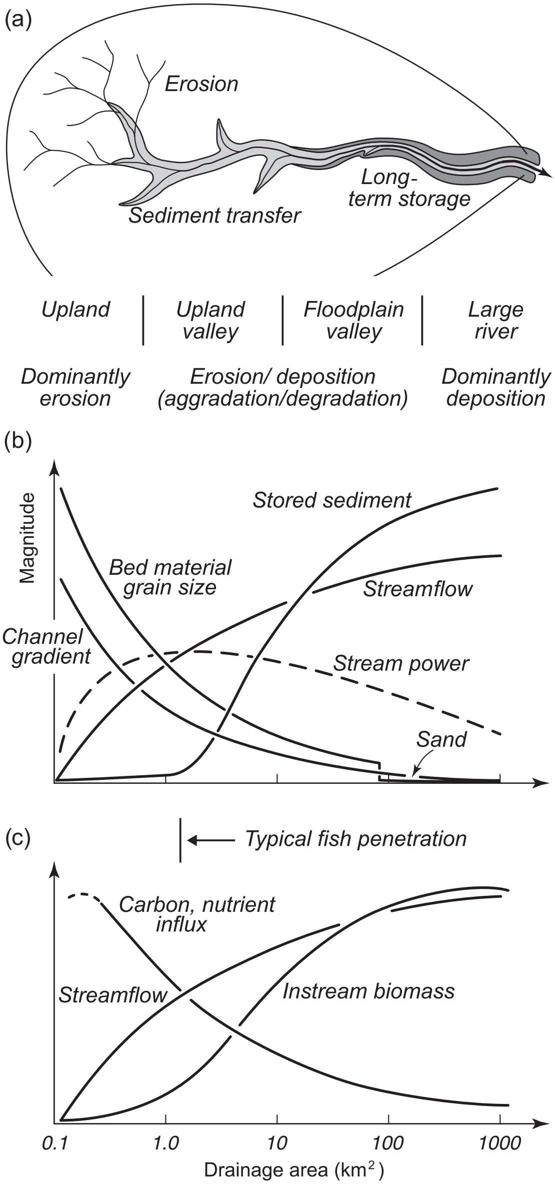

FIGURE 4.3. Variation of flow and river channel properties through the drainage system. (a) Drainage basin map, showing zones of distinctive sediment behaviour (only a fraction of the upland channels is shown); (b) pattern of variation through the drainage basin of principal quantities related to flow, sediment and river morphology; (c) pattern of variation of some ecological quantities that are systematically related to the structure of the drainage system. Area is intended to indicate only the approximate scale. Topography will cause details to vary greatly in individual drainage basins. (Modified from Schumm, 1977.)

This large-scale organisation of the fluvial system permits us to identify an important first order distinction between upland river channels and 'trunk' channels. The former are small, relatively steep, and formed primarily by erosion of the stream into its substrate. Their function is to collect runoff from the land surface and funnel it into the fluvial drainage system. An important variation occurs in flat terrain, where headwater wetlands may drain through channels that are flat, have little erosive capacity and are bounded largely by organic materials. Upland channels occupy about 80% of the total length of the drainage system, simply in view of their high frequency in the landscape. Trunk channels collect water and sediment from upland tributaries and move them toward an end point in a lake or the sea. Sediment is deposited and stored temporarily along the way since most flows are not capable of maintaining the larger part of the sediment load in transport over the reduced valley gradient. Hence, these channels tend to be alluvial ones. A further subdivision can be made between 'transport reaches', those mid-course reaches, often in relatively confined valleys, through which much of the sediment load is moved relatively rapidly, and 'storage reaches', those distal reaches where sediments are deposited and may remain for a long period of time. Such sediment accumulations are the major floodplains and deltas that one finds along the lower course of most major rivers, where much human settlement occurs.

A more detailed view of the function of the fluvial system is gained by considering the pattern of delivery of water through the drainage system and the pattern of sediment movement (see Fig. 4.4). Water arrives relatively rapidly in upland channels (see Section 4.2 above) and drains rapidly. Hence, runoff is highly variable in these channels. Sediment is also delivered very episodically to these channels, either from overbank during periods of overland runoff, or directly from adjacent hillside slopes when slope failures occur. Channels are, accordingly, directly 'coupled' to the adjacent slopes. Flow variation through the year may be of order 100–300 times (becoming infinite in channels that dry up for part of the year), and sediment fluctuations may easily be of order 1000 times. Because they are small, extreme flows and sediment delivery events may create rapid – one might say, 'catastrophic' – changes in such channels. Farther downstream, the integration of drainage from many tributaries, not all of them producing equally extreme runoff simultaneously, modulates the variability of flow, while the deposition of the largest and least mobile sediment grains promotes relatively less extreme variation in onward transport. In the distal parts of large rivers, extreme attenuation may occur, so that flow variations may be reduced to order 3–10 times through the year and sediment fluctuations to order 10–30 times. Alluvial deposits isolate the channels from the adjacent hillsides so sediment delivery to the channels occurs purely by transport along the river from upstream, or by streambank erosion.

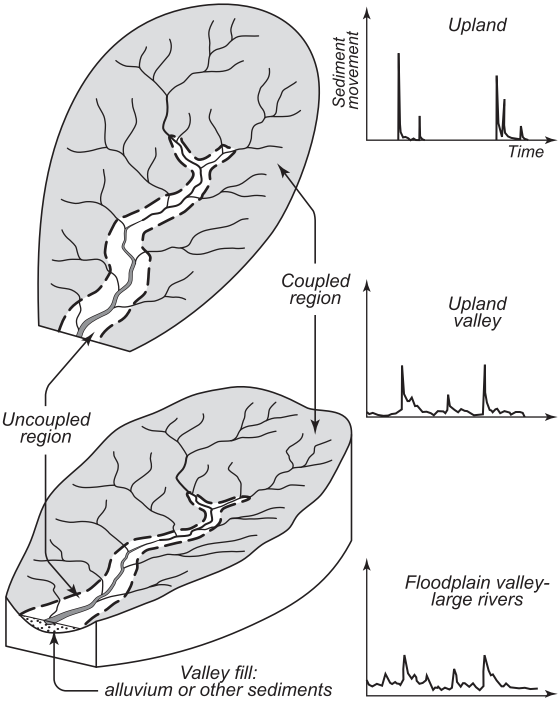

FIGURE 4.4. Schematic view of the drainage network, illustrating the domain of upland channels, where hillslopes are directly coupled to drainage channels, and valley trunk channels, which are buffered from adjacent hillslopes by stream deposits. The graphs show conceptually the variability of flow and sediment transport through the drainage network, sediment transport being more variable even than the flow.

This introductory discussion of function in river systems leads to two conclusions of great importance for understanding the climatic and human impacts on river systems:

- variations occur in the details of river form and function in different parts of the world according to climate, which determines hydrology, and to topography, which determines the available energy gradient for the river;
- drainage basins can be divided into upland and trunk divisions, between which river character changes dramatically.

As an example of the former, we can compare rivers that drain the humid, steep mountains of central Europe with those draining the north European lowlands. Climate – except insofar as it is modulated by altitude – is not too different, but the steepness of the former region creates rivers that transport abundant coarse sediment and typically have wide gravel channels which, in their natural state, are more or less laterally unstable as the coarse sediments are deposited within the channel. In contrast, headwaters of rivers that rise within the North European plain (that is, excepting those with alpine headwaters) mobilise very limited quantities of largely fine organic sediments and flow in relatively deep, narrow channels that may have substantial stability so long as their banks are not severely disturbed.

The second conclusion leads us to recognise that the origins of runoff and sediment on the land surface chiefly control the character of upland river channels, hence that human land use is the major factor that may disturb them whereas, along trunk channels, direct human manipulation of the river (damming it; confining it for flood protection, or to reclaim adjacent land; modifying the channel to improve navigation; diverting significant volumes of water for water resources development purposes) has major impacts on the river.

The history of human impact on river channels in both respects is long and the cumulative impact is large. Relatively few rivers in the world today present anything like their appearance of even 1000 years ago, and humans have been the major driver of change.

4.3.2 Effects of human activities on river morphology

Reinforcement of river banks

One of the earliest modifications of river channels to suit human purposes was the systematic raising and reinforcement of the banks to provide protection against flooding and to protect land by discouraging the lateral movement of the channel. These actions increase the security of people occupying river floodplains which, since the dawn of civilisation, have been the most attractive areas for human settlement because of the richness of the soil for plant growth, the large diversity of plant and animal resources located there, the relative ease of communication (by water or by land), and ready access to the water – arguably the most important of all natural resources.

There is a deep contradiction in these actions, which were expanded with dramatic effect after the advent of powered machinery, and which serve to isolate the river from its floodplain. Most obviously, the isolation of the floodplain from the river eliminates its flood storage function and creates even higher flood peaks within the channelway. More fundamentally, the reason for the resource richness of river floodplains is the connection with the river (Junk *et al*., 1989). Alluvial soils in floodplains are mixtures of riverborne sediment and organic material that sequester abundant nutrients and to which additions are made each time the river floods. Biological diversity is promoted by the lateral shifts of the river within its floodplain, which erode away mature to decadent floodplain habitats and replace them with fresh deposits and early ecological succession. An active floodplain is a palimpsest of habitats collectively supporting a high diversity of species (Ward *et al*., 2002). In the long-term view, the floodplain is part of the river: it is the accumulation of sediments on their way through the fluvial system that has entered long-term but, nevertheless, temporary storage. Severing the river from its floodplain ends the regular exchange of water, sediment and nutrients, and severely constrains the exchange of organisms between the two, to the long-term detriment of biodiversity and productivity in the floodplain and the river.

Hardening riverbanks – freezing the position of the river – causes further problems in the channel. If the river transports significant volumes of bed material, that material must be deposited within the constricted channelway, aggrading the bed and creating, again, higher floodwater levels. Furthermore, there will be only limited possibility for aquatic habitat renewal within the laterally constrained channel, leading to a substantially less productive aquatic ecosystem. In effect, the river has been transformed into a ditch.

Modification of channel form

A more ambitious extension of bank modification entails modifying the entire river channel – replacing the original channel by a more or less regular one. There is a wide variety of reasons to do so. This action, accompanied by the construction of strong banks, fixes the position of the channel, thereby protecting occupied riverine land and/or improving access to riverfront lands; navigation is improved; and resources in the form of sand and/or gravel dredged from the river may be provided. The latter activity is widespread in those parts of the world (generally, beyond the margins of Pleistocene glaciation) where high-quality aggregate resources are scarce on the terrestrial surface.

Extensive channel modification commenced in northwestern Europe in the seventeenth century. Purposes included the drainage of wetlands in the attempt to reduce insect-borne diseases, land reclamation and protection, rationalisation of riparian land holdings, and navigation improvements. The history of modification of some of Europe's largest rivers is recounted in Petts *et al*. (1989). Hundreds of kilometres of major rivers, and thousands of kilometres overall, have been forced into rectilinear or gently curved channels with fixed banks. The channels are relatively narrow so that flows are swift and deep to overcome tendencies for sediment to be deposited. Ecologically, they are relatively barren.

One of the most dramatic examples of channel redesign has occurred on the Mississippi River of the USA. Following earlier practice, 14 meanders were cut off between 1929 and 1942 to improve navigation on the lower river and two natural cutoffs occurred (Winkley, 1994). The reach was shortened by 240 km, or about 45%, which more than doubled the gradient in some subreaches. Subsequent bank stabilisation has essentially fixed the reach at about 70% of its former length. As the sandy alluvial channel adjusts to these changes, there has been bed erosion in upstream and mid-reaches and sediment deposition downstream (Biedenharn *et al*., 2000). The interpretation of these tendencies is made more complex by the changing sediment load delivered to the river as the result of changes in land management in the drainage basin (see Section 4.4.3 for sediment effects).

Today, large-scale channel rectification for flood protection, navigation and water resource control is under way in China, where the importance of flood protection in the summer monsoon areas, the value of waterborne commercial transport and the need for construction materials are all critical spurs for such developments.

Again, the long-term effects may be counterproductive. The replacement of the varied natural topography of the riverbed by an often highly regular cross-section decimates the habitat diversity for aquatic organisms. River channelisation is inevitably followed by a reduction in riverine biodiversity (for perspectives, see Benke, 1990; Sparks, 1995).

More fundamentally, along alluvial rivers (where these actions are most frequent) the change in river channel dimensions that accompanies channelisation or dredging has the effect of replacing the equilibrium cross-section of the channel – that cross-section taken up by the channel as the stable form for the imposed water and sediment loads, and described by the equations of hydraulic geometry – by a channel that is too wide and/or too deep. The river begins to reduce its section by sedimentation so that continuous and possibly costly maintenance activity must be undertaken in order to maintain the engineered channel.

Modifying the flow regime

Damming a river and/or diverting water initiates the most dramatic set of changes of all human actions. Firstly, the hydrological regime may be more or less radically altered, depending on the size and purpose of the project. Early instances, the construction of weirs to trap fish and weirs to direct water to mill-races, effected negligible modification to the river regime. Later, dams constructed for water resource control, for flood control and, most of all, for hydroelectric power generation, have had increasingly radical impacts. The twentieth century has seen a massive project of dam building (see Section 4.5) which has modified a large fraction of all the major rivers of the world.

Today, 60% of the world's large river systems are affected by dams (Nilsson *et al*., 2005), 36% of these basins covering 52% of their aggregate area being 'strongly affected' according to the criteria of Dynesius and Nilsson (1994), with ongoing developments in many large river basins, worldwide.

Dams inundate more or less extensive land areas, they induce sedimentation and aggradation upstream of the impoundment, and they change the water and sediment regimes downstream, often inducing erosion and degradation of the riverbed (Petts, 1984; Brandt, 2000). Flooding extensive areas produces large transient changes in water quality as various substances are desorbed from the drowned soil. Large power dams are often located along the uppermost trunk channels of a river system – where there is still a significant drop that can be controlled for power generation, but where flow is already quite large. They interrupt passage of aquatic organisms along the river – most notably, anadromous fish – and they stop the transfer of organic nutrients from the extensive network of upland channels where nutrient recruitment is prolific, to the downstream trunk channels, where diverse aquatic ecosystems rely on the nutrient influx. Riverine ecosystems are severely disrupted by dams (Petts, 1984; Ligon *et al*., 1995).

In 1967, a major dam was closed on the upper Peace River in northwestern Canada establishing what was, at the time, the fifth largest hydropower project in the world. A continuing study of the adjustment of the 1200-km long river channel downstream shows that full adjustment will proceed according to the ability of the river to redistribute sediments along its course. With the highly regulated flow regime, it is expected that this will require of order 1 ka (Church, 1995), although the bulk of the adjustment will occur within the first century. Similar figures have been estimated by Williams and Wolman (1984) for large projects in America.

Major end point deltas may be significantly impacted by upstream dams because of the reduction in sediment supply. The Nile Delta is one such example. Since the closure of the Aswan dams, the shoreline of the delta has been significantly eroded (Stanley, 1988; see Section 4.5.2 for further details). With the closure of the Three Gorges Dam on Changjiang (the Yangtze River of China), a similar drastic reduction in the downstream sediment budget has been detected and similar effects are anticipated in its delta (Yang *et al*., 2007).

Diversions and canals

Water is sometimes diverted from one drainage basin to another via tunnels, pipes or open channels. The purpose may be delivery of water for resource use in an area of need, or it may be to focus hydroelectric power generation facilities. Canals serve to facilitate freight navigation or to transfer water. Both types of development modify the basic hydrological network.

The direct impact of water diversion is modification of the hydrological regime in both the contributing and receiving waterway. A consequent physical impact is enhanced erosion or sedimentation along one or the other waterway, since sediments are never diverted in proportion to the water diversion. The effects on aquatic ecology that attend the construction of diversions and canals may be serious. The constructed channels represent new routes for the migration of aquatic organisms, which may move either independently, or by attachment to boat traffic along the system. This may lead to species invasions that significantly change the pre-existing ecosystem in the receiving waters.

The heyday of canal building across drainage boundaries occurred in the nineteenth century, before the establishment of high-volume overland transport. Today, most major developments for inland waterborne transport involve modification of single drainage lines, such as the mid-twentieth-century St. Lawrence Seaway into the Great Lakes of eastern North America, or the continued development of the Mississippi–Missouri–Ohio system of the USA. Old-established cross-drainage connections remain a significant ecological concern, however. So, for example, the Chicago drainage canal (properly, the Chicago Sanitary and Ship Canal), which connects the Great Lakes with the Mississippi system, is a major concern for the potential spread into the Great Lakes of a number of major pest organisms that have appeared in the Mississippi system.

An important class of diversions is redirection of water into canals for agricultural irrigation. Perhaps the most famous large-scale diversions were constructed in the Indus basin of then British India (today, divided between Pakistan and India) in the late nineteenth and early twentieth centuries. Similar canals were constructed, as well, in the Nile delta. From these exercises much of the modern theory of river channel behaviour – including the hydraulic geometry – was derived. Water diversion has induced siltation and reduction in size of the river channels, and dramatic modification of water quality (see further discussion in Section 4.5.2).

Diversions for hydroelectric power development and for water resource development continue. The most ambitious development underway in the world today is in China, where the South–North Water Transfer Project is under construction to refurbish the ancient Grand Canal – a 1794-km canal running northeast from Hangzhou (Qiantang River) to Beijing – to supply water, largely from Changjiang (Yangtze River), to the heavily agricultural North China Plain and, especially, to the water-starved capital region

(Stone and Jia, 2006). Most of the rivers between Changjiang and Beijing are, today, virtually 100% diverted for water resource use, with the result that their channels are dry for much of the year. This fate befell even Huanghe (Yellow River) until steps were taken to maintain minimum flows in the lower river.

4.3.3 Perspective

Humans have modified river channels for their particular purposes – protection from floods and command of water resources – for at least 3000 years. Works on a large scale were engineered more than two millennia ago in the Szechwan basin of China. Widespread river channel modifications were undertaken in Europe from the seventeenth century, and large-scale and extensive modification of river channels followed on the development of powered earth-moving and dredging machinery from the mid nineteenth century on. There is a significant reassessment under way today of the wisdom of such large-scale modifications of rivers in the industrial countries (see Section 4.6), but such developments continue unabated in the developing world, where the human condition and the need to control water resources for survival and development generally preclude such rethinking.

The impact of these developments on hydrology and on the rivers is extreme. Channel changes that will accompany the hydrological changes that follow regional or global climate change are predictable using the equations of hydraulic geometry. Thus the relative change in width is related to the change in discharge by

$$\frac{dw}{w} = \frac{b \cdot dQ}{Q} \tag{4.4}$$

where $b = 0.5$ and similarly for d and v; that is, the fractional change in river width will be one-half the fractional change in formative flow – a 20% increase in the magnitude of flood flows will create a 10% increase in the regime width of the river. The exponents b, f (Eq. 4.2) and m (Eq. 4.3) give the fractional changes to be expected in width, depth and mean velocity, respectively.

In comparison, human engineering may alter the size of channels and the flow through them by factors of 2 or more, and may impose artificially simple and fixed geometries on channels. Most of the world's major rivers today are more or less effectively controlled and regulated by human action and, in regions of intense human settlement, nearly all channels have been fixed in position and simplified. The human impact dramatically exceeds the foreseeable consequences of hydroclimatic change and urgently requires comprehensive study to understand the effects at landscape scale on ecosystems, on resource provision, and on human society itself.

4.4 Fluvial sediment transport and sedimentation

4.4.1 Water quality

Water quality refers to the physical and chemical condition of water. In relation to natural waters, it includes the physical properties of the water (temperature, colour, transparency, odour), the content of dissolved minerals (solutes), the quantity and character of particulate matter – both organic and inorganic – carried in the water, and the microbial organisms present in the water. Natural waters always contain some burden of solutes, particulate matter and organisms, and the range may be very wide, but human actions may dramatically augment and change these burdens.

Solutes appear in natural waters as the result of rock weathering, so the chemical character of the water reflects regional geology. Waters draining felsic rock terrains such as granites are acidic in character; ones draining basic rocks such as carbonates are alkaline. Inorganic particulate matter also derives from rock weathering and soil erosion. Mineral grains and rock fragments carried in streams may vary in size from colloidal (<0.5 μm) to boulders of order 1 m in diameter. The latter are moved only on steep gradients in exceptional events. Organic matter comprises plant and animal parts delivered from overbank and transported through the stream system, and organic matter created in the water column and on the streambed – including remains of aquatic organisms, faecal material and metabolites. Living microorganisms that are included in water quality determinations are principally aquatic bacteria.

Humans pervasively affect water quality by land use, which changes water routes and residence times on the land surface and in the soil (see Section 4.2), the exposure to foreign materials, and the direct entrainment of soil materials into runoff. Further, humans inadvertently or deliberately dump materials into water bodies as a means of disposal. The effects exceed those of natural environmental change by orders of magnitude.

The character and stability of rivers – the geomorphology of rivers – is most strongly influenced by the particulate sediment load that they carry, and so that will be the focus of this section.

4.4.2 The fluvial sediment cycle

Mineral particulate matter in rivers is closely tied to the geomorphology of the landscape since this material is the product of erosion of the land surface. Sediments originally mobilised on the land surface may be moved directly into

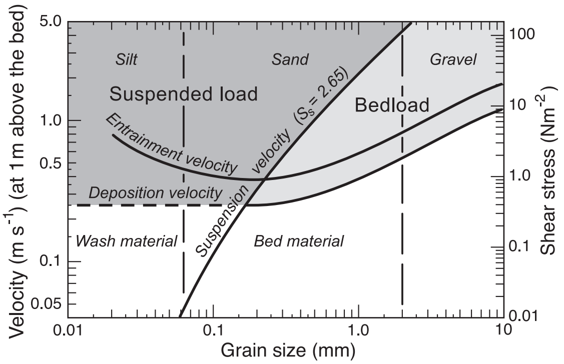

FIGURE 4.5. Diagram to illustrate the water flows necessary to transport particulate sediments of different size and the mode of transport (modified from Sundborg, 1967). S_s is the sediment specific weight.

the river system by surface runoff, or they may go back into storage at field edges or slope base before reaching a stream. Once in a stream, sediments may move a short distance and then be deposited into storage in the channel or overbank on a floodplain surface, or they may move a long way through the system without being redeposited. The distance that material moves is inversely related to grain size – smaller materials, more easily moved by the force of flowing water, are apt to move longer distances in shorter time. Stream systems are, accordingly, sediment sorting machines. Large materials are left behind in upland streams and valleys: fine materials move into floodplains along trunk valleys, to end point deltas, or directly into the receiving water body.

Sorting through the system is reinforced by two processes. Firstly, the manner in which sediment is transported has an important influence on how far and how quickly it moves. Sediments in transport can be divided into two classes. Larger materials move as 'bedload', by sliding or rolling over the bed: the submerged weight of the grains is carried mainly by the bed. Finer grains move in suspension in the water column: their weight is borne by upwardly directed turbulent eddies in the flow, which compensate the settling velocity of the grain. The finer materials move much farther, once entrained. Indeed, very fine material (silt and clay) may move much of the entire distance through the stream system directly to the receiving water body. Accordingly, such material is called 'wash material', in contradistinction to 'bed material', sediment that is found in the bed and lower banks of the channel and determines channel form. Figure 4.5 shows the division of materials according to their mode of transport and persistence in the river channel.

A second process that reinforces sorting is the character of sediment storage places and the amount of time that sediments spend in them. Materials transported as bedload are deposited in bars within the channel, while finer materials are deposited either interstitially within the coarser deposits on river bars, or overbank on floodplain surfaces. The farther the deposition occurs from the central axis of the channel, the longer the material is apt to remain in storage. We are left with two principles for sediment transfer through the river system:

- coarser grains, which move principally as bedload, move relatively short distances in single events and are stored in the channel, where they are apt to be soon re-entrained;
- finer materials, which move intermittently or mainly in suspension, move relatively long distances in single events and are stored toward the channel edges or overbank, where they are apt to remain for a protracted period.

Storage of sediments along the channel can vary from the time between successive sediment entraining flows on bar edges, to periods of years to decades if they are buried deeply within the bars. Overbank storage can vary from periods of years near the channel to millennia near the back of wide floodplains. Figure 4.6 gives a schematic view of the sediment transfer system based on these principles.

An important ancillary process is rock weathering, which is particularly important in the wet–dry, possibly freeze–thaw, environment of river channels and floodplains. Larger materials that enter storage may relatively rapidly be weakened and may break down to finer materials when they are re-entrained into the flow. The net result of these processes is that, although finer sediments are more highly mobile than larger ones, their total time of passage through the fluvial system may not be too strongly different, except that the larger materials will have been eliminated by weathering.

Sediment transfer through the drainage basin nevertheless requires a long time: the virtual velocity of sediments (i.e. the average rate of progress of the sediments, including rest periods) through a drainage basin is on the order of m a^{-1} so that, in large drainage basins, transit time through the basin may be many thousands of years (this is the reason why the adjustment to a dam on a large river may require many centuries to complete). Within this period, important modulations of climate and land surface condition may create significant changes in sediment yield; changes that are buffered by the rate at which sediments move into or out of storage along the river system.

Sediments may be entrained into the river system from two sources: the land surface, or the bed and banks of the river. Sediments go into storage in the channel or in alluvial fan, floodplain or delta deposits of the river itself. During periods when there is a relatively large delivery of sediment

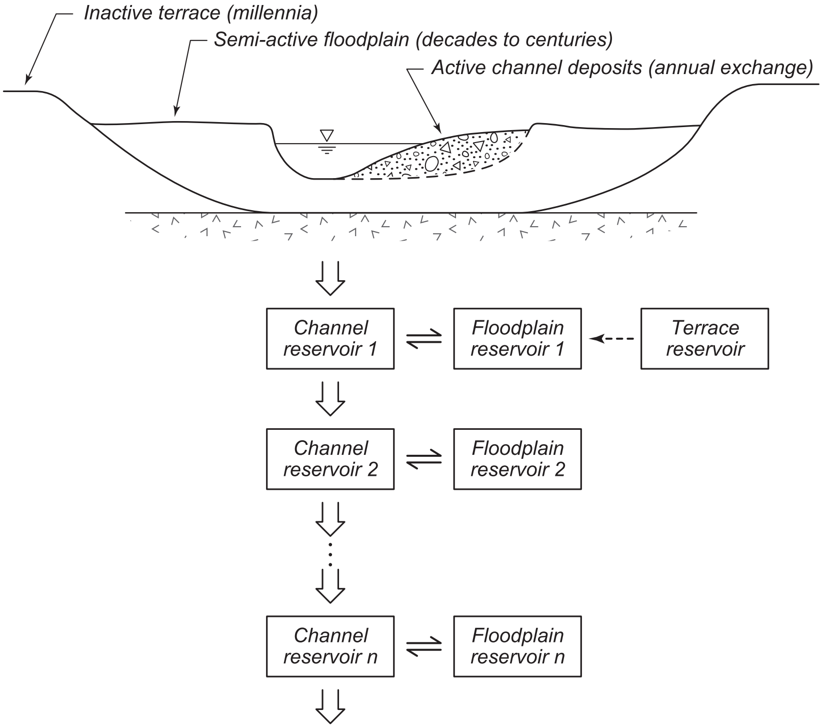

FIGURE 4.6. Cascade diagram of fluvial sediment 'reservoirs'; characteristic storage times given in parentheses.

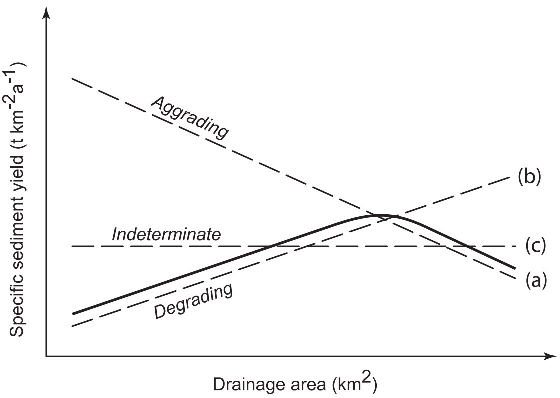

FIGURE 4.7. Trends of sediment yield through the drainage system, illustrating (a) aggrading and (b) degrading patterns. The heavy line illustrates a common pattern whereby degradation of upland channels (net sediment export) is balanced by aggradation along trunk rivers (loss of sediment into floodplain storage). Line (c) indicates a system in sediment yield equilibrium throughout.

from the land surface, there is a net transfer of sediment into storage along the river system – the system is said to be 'aggrading'. During periods when sediment delivery from the land surface is relatively small, the rivers re-entrain material from channel beds and banks and total fluvial storage is reduced – the system is said to be 'degrading'. The tendency of a drainage basin to be aggrading or degrading can be measured by calculating the specific sediment yield – the sediment yield per square kilometre of contributing drainage area. If this declines down the system, then sediment mobilised from the land surface must be lost to storage along the drainage line, and the system is aggrading; in the reverse case, the system is degrading (Church *et al.*, 1999) (Fig. 4.7).

Simple trends of aggradation/degradation are unlikely to hold throughout a large drainage system, for aggradation in one part of the system directly implies degradation wherever the sediment originates. If the sediment originates on the land surface, then the *fluvial* system may indeed exhibit a consistent trend, but if sediment is originating somewhere in the drainage system, then it may be going back into storage farther down the system, hence upstream degradation followed by downstream aggradation is a common landscape signal (as is observed in the Mississippi River example discussed in Section 4.3.2).

The most significant pulse of sediment from the land surface into the fluvial system in recent Earth history was the end-Pleistocene mobilisation of sediment at the time of northern hemisphere deglaciation. This 'paraglacial' sediment pulse was rapidly exhausted in small upland basins, but it dispersed through the larger fluvial system over several millennia (Church, 2002) (see Chapter 2, Section 2.5.9). Lesser pulses of sediment delivery are created by more mundane events, including wildfire, or an individual major landslide on a hillside slope.

Inasmuch as soil is strongly retained by the root systems of vigorous vegetation cover, the condition of the vegetation on the land surface is a prominent modulator of sediment entrainment from the land surface. Since humans both manipulate vegetation in a comprehensive way and directly disturb the soil in the course of forestry, farming and construction activities, we are by far the most important agent influencing sediment mobilisation from the land surface today and, thereby, sediment transfer through the fluvial system.

4.4.3 Effects of human activities on fluvial sedimentation

Agricultural land use

Agriculture in most systems of practice entails the virtually complete replacement of the natural vegetation by managed covers. Where these covers consist of perennial, continuous cover (such as pasture), soil may be well conserved, but most of the world's arable lands are bared for part of the year and crops frequently provide only fractional surface cover. In addition, arable soils are often compacted by heavy machinery, and recently ploughed soils of certain textures may undergo surface sealing as the result of rainsplash (see Section 4.2). The net result may be a significant increase in surface runoff and the effect may be further reinforced by certain ploughing patterns. In these circumstances, soil erosion by runoff can be increased dramatically. The severity of the soil loss may depend on the timing of rainfall in relation to crop planting (see Slattery and Burt, 1996, and Section 4.2.2 for further discussion).

Trimble (1983, 1999) has shown that, in the American Midwest, ploughing of the land between 1850 and 1940 yielded large volumes of sediment to river channels. Upland channels underwent massive aggradation and regional sediment yield followed the curve (a) of Fig. 4.7. Since the late 1930s, the implementation of soil conservation practices has reduced field erosion dramatically. Sediment stored in the upland channels has been re-entrained and is moving into higher order tributaries. The uplands now exhibit a type (b) sediment yield pattern, while regional sediment yield follows the pattern of upland degradation and valley aggradation. Throughout the period, however, less than 10% of all the sediment mobilised was transferred as far as the regional trunk stream, the Mississippi River. Nevertheless, by looking at long-term floodplain aggradation rates inferred from floodplain stratigraphy in the American Midwest, Knox (1989) has determined that average sedimentation rates post-European settlement have been 10–100 times greater than the preceding rates here.

Meade (1982) demonstrated a similar historical pattern of agriculturally dominated sediment yield in the southeastern US Piedmont and coastal plain whereby rivers experienced massive sedimentation between 1750 and *c.* 1900 as forests were cleared, with large sediment yields to the ocean. Hundreds of mill-dams along the smaller streams contributed significantly to sediment trapping, floodplain construction and changes in stream channel character (Walter and Merritts, 2008). During the twentieth century, improved agricultural practice and reafforestation of much of the land reduced sediment influx and the rivers are degrading. There appears, then, to have been a major spike in sediment yield associated with early modern agriculture, a spike that has been largely attenuated with the development of improved land management practices, although sediment losses from agricultural fields have by no means been eliminated.

Nor is modern agriculture exceptional. Examples of agriculturally related soil loss so severe as to cause social collapse are found around the ancient world. Examples come from such different environments as Mesopotamia, prehispanic Central America and Easter Island. Montgomery (2007) has recently given a comprehensive summary of this history.

Forest land use

Forestry has been widely regarded as a significant source of increased sediment yield to fluvial systems (National Research Council, 2008). In fact, in most forest management systems, the effect is highly transient. Three distinct effects are experienced (see Chapter 12 for further discussion). During the preparations for forest harvest, road construction and other site preparations may interrupt natural drainage lines, create exposed road embankments and excavations, and establish important sources of surface runoff and fine-sediment production on unmetalled road surfaces. During harvest, direct disturbance of forest soil by heavy machinery or by log handling may substantially increase soil erodibility. After harvest, the exposure of the forest soil and the decay of root systems may leave soil susceptible to surface erosion or to landslides on hillside slopes. There is a restricted window during which soils may be particularly prone to erosion which ends once a new, young forest is securely established. The time period for this may vary from 5 to 15 years, depending on both forest and site characteristics. During this period, the chance effect of particularly severe weather may be an important factor determining whether or not significant erosion actually occurs. Along river channels, harvesting trees to the streambank may have particularly drastic effects on streambank strength and hence on fluvial erosion. On a regional

TABLE 4.3. *Sediment mobilisation and yield from hillside slopes*

Process	Mobilisation rate		Yield rate to stream channels	
	Forested slopes	Cleared slopes	Forested slopes	Cleared slopes
Normal regime				
Soil creep (including animal effects)	$1\ m^3\ km^{-1}\ a^{-1*}$	2 ×	$1\ m^3\ km^{-1}\ a^{-1*}$	2 ×
Deep-seated creep	$10\ m^3\ km^{-1}\ a^{-1*}$	1 ×	$10\ m^3\ km^{-1}\ a^{-1}$	1 ×
Tree throw	$1\ m^3\ km^{-2}\ a^{-1}$	–	–	–
Surface erosion: forest floor	$<10\ m^3\ km^{-2}\ a^{-1}$		$<1\ m^3\ km^{-2}\ a^{-1}$	
Surface erosion: landslide scars, gully walls	$>10^3\ m^3\ km^{-2}\ a^{-1}$ (slide area only)	1 ×	$>10^3\ m^3\ km^{-2}\ a^{-1}$ (slide area only)	1 ×
Surface erosion: active road surface	–	$10^4\ m^3\ km^{-2}\ a^{-1}$ (road area only)	–	$10^4\ m^3\ km^{-2}\ a^{-1}$ (road area only)
Episodic events				
Debris slides	$10^2\ m^3\ km^{-2}\ a^{-1}$	2–10 ×	to $10\ m^3\ km^{-2}\ a^{-1}$	to 10 ×
Rock failures: falls, slides	No consistent data: not specifically associated with land use			

* These results reported as $m^3\ km^{-1}$ channel bank. All other results reported as $m^3\ km^{-2}$ drainage area.
Source: Generalised results after Church and Ryder (2001), Table 1.

basis, the relative importance of these effects can be gauged from a summary of experience in the Pacific Northwest of North America (Table 4.3).

In well-managed forest harvest operations, erosion associated with initial access and road building is found to be most severe, and mostly associated with the disturbance to natural drainage routes.

Mining and quarrying

Unlike agriculture and forestry, which are distributed across the landscape, mining and quarrying are carried out at individual sites of limited extent. In landscape terms, they are point developments. While huge volumes of material may be moved, very little of it (except product) leaves the site. What does leave the site may, however, be highly troublesome since, by specific purpose, mining is focussed upon materials that are rare in Earth's surface environment and are therefore apt to be toxic to many organisms. Consequently, the complete control of drainage is an important activity at properly designed mining operations. In some parts of the world, however, mine wastes are directly dumped into river systems. Historical mine wastes have often been dumped into rivers, however, and today contaminate floodplain soils (e.g. Lewin and Macklin, 1987).

Waste materials, particularly the waste products of ore concentrating processes, are often slurries that are routed to ponds (called 'tailings' ponds) where the solids settle. The ponds are sealed so that water is recovered for treatment and the solids secured. A significant problem, however, is that mine sites usually are active and supervised for a period of only decades' length, whereas the waste materials remain on the site for ever. After the mine is closed, supervision of wastes ends and there is a significant risk that, eventually, the containment may be breached by natural processes. A number of such failures have been experienced in recent years (see, for example, Grimalt *et al.* (1999) on the 1998 spill in Aznalcóllar, Spain, into the Guadiamar River; Macklin *et al.* (2003) on the 2000 Tisza River inundation in Romania) with disastrous consequences for aquatic and riparian ecosystems.

Placer mining and gravel borrowing

River sediments may deliberately be disturbed or removed for the recovery of precious metals – principally gold – or for industrial use of the river sediments. Placer mining turns over river sediments without, usually, removing the bulk of the material from the river. This activity does, however, mobilise large volumes of fine sediment sequestered amongst coarser materials on the streambed, significantly increasing the fine-sediment load of the river downstream, often with significant impact on fisheries.

Sand and gravel mining from riverbeds has often been presented as renewable resource exploitation. The fact, however, is that almost everywhere rivers have been exploited for aggregate resources the volumes removed have exceeded sediment recruitment by up to an order of magnitude. The result is destabilisation of the channel (Lagasse *et al.*, 1980) and a dramatic change in river morphology, leaving what is essentially a degraded ditch. Accordingly, riverine ecosystems collapse and are replaced by dramatically less productive ones (Kondolf, 1998).

Urban land conversion

On a global basis, urban land conversion is possibly the most severe sedimentary disturbance today. But, like forestry, its initial effects are transient. Urban land conversion and, similarly, the construction of modern communication routes, entails denuding the land surface, exposing the soil for a period of months at least, and the movement and temporary storage of significant amounts of soil. These activities may lead to very large increases in sediment mobilisation and delivery to stream systems (Wolman, 1967; Trimble, 1997).

Developed urban lands are largely covered with unerodible materials, while landscaping of the remaining soil surfaces usually imparts high stability to them. Hence, after urban conversion, sources of sediments become very low. However, a substantial variety of more or less exotic materials is generated in urban areas by industrial, commercial and domestic activities and released deliberately or inadvertently into the surface environment, where it is entrained in urban building and street runoff. Combustion products, petroleum products, paint and metal fragments, fertilisers, pesticides and pharmaceuticals all find their way into the runoff and subsequently into waterways where they may strongly affect water quality.

The contaminant burden is added to by deliberate disposal of industrial and domestic wastes into rivers. This burden includes many synthesised materials that are wholly foreign to the natural environment. Once in the environment, many of these materials are adsorbed onto fine mineral particulates and eventually settle out of the water column with the sediments, to be stored in riverbottom or floodplain sediments. If the contaminant burden of the river is subsequently reduced, a reverse chemical gradient is established from the sediments into the water column and the sequestered material may then be resorbed back into the water. The definitive clearance from a river system of particular contaminants may take a long time. Since rivers were often regarded as natural sewers in the nineteenth and early twentieth centuries, there are many instances of this problem today (see, for example, Wiener *et al.* (1984) on contamination of the upper Mississippi River system).

4.4.4 Perspective

Humans influence riverine water quality and sediment burden in many ways. Comparisons between natural and contemporary sediment loads are difficult to establish because there are no pre-modern (that is, pre-industrial) measurements of riverine sediment loads and, in any case, it is likely that agriculture has had some influence for a very long time, though probably much less than is achieved by modern industrial agriculture in a crowded world. In the absence of measurements Syvitski *et al.* (2005) have attempted to compare contemporary and pre-industrial sediment loads in the world's rivers by modelling pre-industrial sediment yields. They estimate the pre-industrial suspended sediment yield to the oceans of the world's rivers to be 14 000 Mt a^{-1}. In comparison, they estimate the modern yield to be 16 200 Mt a^{-1} – an increase of 16%. However, reservoirs trap approximately 22% of the load, so that the sediment yield to the world ocean is claimed to be reduced to 12 600 Mt a^{-1}.

These figures are based on the sediment yields of relatively large rivers. Given the pervasive influence of human activity in increasing sediment loads, most river systems today exhibit aggradation along their middle and lower courses. Indeed, so pervasive is this phenomenon that, until recently, it was supposed that the regional signal of aggradation (curve (a) in Fig. 4.7) was the standard signal for riverine sediment mechanics everywhere. Wilkinson and McElroy (2007) estimate that as much as 75 000 Mt a^{-1} is being mobilised, mostly from agricultural fields (see Fig. 1.16 in Chapter 1). It is probable, then, that substantially more sediment is being mobilised in headwater regions than is accounted for by statistics based on large river systems. This makes humans incomparably the most important geological agent remaking the surface of Earth today.

4.5 Water control: dams and diversions

4.5.1 Introduction

For centuries the landscape moulded by moving water has been modified dramatically by management and storage of the water (Plate 8). To this day politicians, technocrats and floodplain inhabitants continue to promote large storage dams. Thus, for example, the number of dams along the upper Yangtze River increased from very few in 1950 to approximately 12 000 by the late 1980s and continues to increase (Xu *et al.*, 2006). The purpose for storing water is to hold it during peak flows and then release it during low flows, thus, as the US Bureau of Reclamation (1946) put it, transforming 'a natural menace into a national resource'. But this statement is not entirely appropriate. If the natural water cycle is modified by humans then impacts follow. In addition to storing water, the sediment and nutrients in motion with the river flow are trapped in the reservoir.

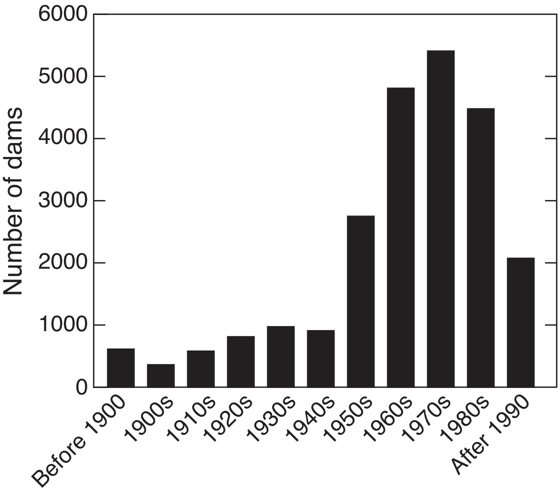

FIGURE 4.8. Numbers of high dams (>15 m high) constructed in the world by decade, excluding China (data of the International Commission on Large Dams).

The downstream river, built from its own sediment, no longer has any building material, but the clear water retains erosive power, resulting in bed lowering (channel incision), bank erosion and changes to riparian vegetation. One of the most dramatic impacts has been the sediment starvation of river deltas – a most striking example being the sinking Mississippi Delta whose flood-protection dykes could not hold back the high waters due to Hurricane Katrina of 2005 (Martin, 2007). Of significance is the combination of deltaic deterioration due to sediment starvation brought on by reservoir storage coupled with global warming causing a rise in sea levels. Such additive impacts have not been accounted for during the planning of large dams; in fact, planners and politicians have scarcely addressed combinations of impacts at all.

The diversion and storage of water developed slowly, beginning *c.* 8 ka BP with the inception of regular crop planting and communal settlements. Within the most recent 200 years, the management of water for multiple uses has become so complex that serious water disputes have resulted between countries as well as communities. The progressive construction of major infrastructure such as dams, canals, flood dykes and pump stations was usually initiated on a small scale, but as the infrastructure expanded, the control of water became a significant component of a region's resource management programme.

The number of high dams (more than 15 m high) has exploded over the last half century (Fig. 4.8). This surge in dam construction has proceeded with inadequate impact analysis and new problems are identified with regularity. The ponding of water behind dams, the spreading of water over fields and the conveyance of floods between dykes has changed fluvial processes and transformed local landscapes. Then, as the landscapes changed, the rainfall and evaporation changed, causing progressive change in local climate. The system is not static. The following discussion presents, through a number of examples, the complexity of landscape changes and the many causative factors. In order to examine the impacts to environments, water resource developments in several large basins (the Colorado, the Indus and the Nile) will be described with illustrations of landscape changes. In addition, future scenarios of the Nile, Mekong and Huanghe (Yellow) rivers will be speculated upon.

4.5.2 Some case studies

Colorado River

The Colorado River basin drains 632 000 km^2. The river originates in Wyoming and Colorado and flows into the Gulf of California in Mexico (Figure 4.9). The Colorado River landscape consists of canyons in the upper basin, floodplains along the lower reaches, and an extensive delta at its lower end. Much of the basin is arid, with less than 80 mm of precipitation per year (Cohen, 2002). The river's reported average annual flow varies with the investigator and source of information – Meko *et al.* (1995) estimated a long-term mean flow of 530 m^3 s^{-1}, based on tree ring records, while Owen-Joyce and Raymond (1996) estimated 590 m^3 s^{-1} based on the past century of instrumental record. Earlier, the US Bureau of Reclamation (1946) had estimated that there was 690 m^3 s^{-1} available for use annually but this value has now been acknowledged to be too high.

Diversion works for irrigation were begun in the late nineteenth century, but it was not until the completion of the Hoover Dam in 1935 that water was stored and flows and sediment downstream were significantly modified. An accidental diversion occurred in 1905 during spring floods which created the inland Salton Sea. Eventually, the Imperial Dam and the All-American Canal were completed to keep the Colorado River flowing toward the irrigated farms of Imperial Valley. The historical sediment load delivered to the delta was about 160 M t a^{-1} (van Andel, 1964) but the present load is almost zero (Carraquiry and Sanchez, 1999). The annual volume of water reaching the Gulf of California has been reduced to about 140 m^3 s^{-1} (Cohen, 2002) since the Glen Canyon Dam was completed in 1963. These dramatic changes to water and sediment have brought about the following significant environmental changes:

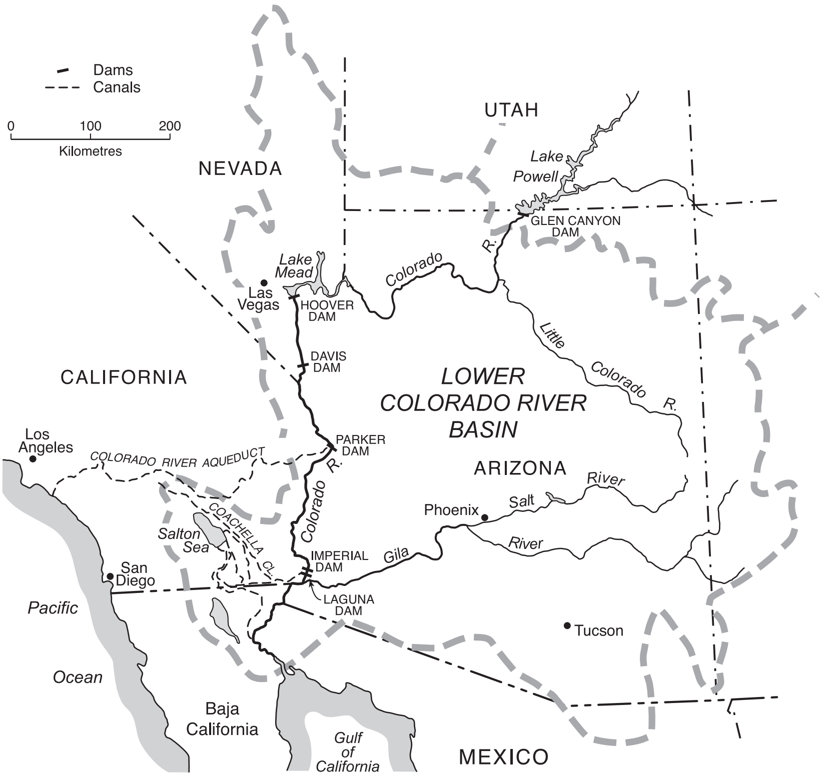

FIGURE 4.9. Map of the lower Colorado River basin.

- reversal of the slow accumulation of deltaic sediment as tidal action now removes more sediment from the delta than arrives;
- inversion of the salinity gradient in the upper Gulf of California so that there is now higher salinity in its northern (proximal) part (Lavin *et al*., 1998);
- collapses in several fisheries, namely totoaba, the pacific sharp-nose shark and the shrimp fishery (these events have also been attributed partially to illegal and unreported catches).

It is interesting to note that, despite major modifications to the delta ecosystem, new growth of wetland habitat has emerged after small releases of water from upstream reservoirs (Pitt *et al*., 2000) and in response to the El Niño events of 1982 and 1993 (Lozano, 2006). The fisheries crisis has also been addressed by Lozano, who concluded after simulation studies that a small flow increase – only 1% – may produce an increase of around 10% in the total biomass of the upper Gulf. This indication suggests that further human intervention might trigger significant improvements to the marine ecosystem and to fish species.

The impacts to the middle reaches of the multi-dam Colorado River as reported by the National Research Council (1987) are many. An important summary finding was that, because of the participation of various agencies, with different missions and budgets, the planning process for the Glen Canyon Environmental Study (GCES) did not treat the ecosystem as a whole. The GCES recommendations were aimed at strengthening the database and adopting an ecosystem approach to river management, but they were not adopted by the operating authorities. Subsequently, a controlled flood was created by allowing a release of 1274 $m^3 s^{-1}$ from the Glen Canyon Dam in 1996 in an attempt to restore beaches and rehabilitate habitat. This initiative gathered together an interdisciplinary team of scientists who subsequently published their findings in Webb *et al*. (1999). Conclusions from this research included the following:

- encroachment of riparian vegetation on sand bars (as the result of the cessation of sedimentation) limited use of the bars as campsites;
- after many flow releases sand moved from emergent sand bars to eddy zones, thereby filling aquatic habitats;
- clear, cold water releases changed the trophic structure of the aquatic ecosystem such that the productivity of trout increased; and
- maximising the rainbow trout fishery and habitat for the endangered Humpback chub proved to be mutually exclusive.

FIGURE 4.10. Map of the Indus River basin, showing the principal tributaries and the principal elements of the Indus water control projects.

The findings on the primary sedimentation process below the Glen Canyon Dam were, however, subsequently contested by Rubin *et al*. (2002) and it appears that research over a longer period is required.

In summary, the main landscape changes have been the transformation of the delta from a deposition feature to an eroding system, the reversal of the salinity gradient in the Gulf of California with higher salinity within its northern zone, and changes in flow and sedimentation through the Grand Canyon that have important ecological effects. The prime causative factor has been the construction of large dams (Hoover and Glen Canyon) resulting in trapping of sediment.

The Indus basin projects

An example of changes to basin-wide environment brought on by the construction of dams coupled with extensive irrigation is found in the Indus River system in Pakistan. The Indus and its main tributaries (Sutlej, Ravi, Chenab, Jhelum and Beas) rise in the Karakorum Range of the Himalayas. The mountains were created by the collision of the Indian Plate with the Asian Plate *c*. 65 Ma BP and subsequent uplift which followed within the last 2 Ma (Pleistocene Epoch). The mountain range forces the monsoon clouds of summer (June to September) to release their moisture in seasonally heavy and persistent downpours and in winter the range prevents cold Tibetan winds from penetrating to the south-facing slopes. The Indus River emerges near Mt Kailash in Tibet, flows northwest and cuts through the Himalayan Range downstream from its confluence with the Gilgit. Thereafter, the river is joined by the main tributaries (Fig. 4.10).

The Indus flows have been modified by dams and diversions constructed under the Indus Water Treaty. Prior to the treaty, the Punjab experienced about 100 years of irrigation development under the British. With partition of the subcontinent into Pakistan and India in 1947, irrigation expanded rapidly under the Indus Water Treaty. Large dams, the Tarbela and the Mangla in Pakistan along with the Bhakra in India, financed through international donors, have also resulted in multi-purpose management of water for irrigation, power, flood control and water supply. The treaty assigned the three western rivers (Chenab, Jhelum and Indus) to Pakistan and the three eastern rivers (Sutlej, Beas and Ravi) to India (Michel, 1967). To replace the waters of the eastern rivers, Pakistan constructed a large system of works, mostly link canals and two high dams, under the Indus Basin Project (Tarar, 1982). The layout of the project is shown in Fig. 4.10. The irrigation system of the Indus Plain now includes two storage reservoirs, 17 barrages, eight link canals and an extensive system of main canals, branches, distributaries and minors.

After the dams, cheap hydropower was used to pump water from the ground to expand the irrigation system. This action resulted in waterlogging and salinisation of soils. Thereafter, drainage systems were added which introduced saline water into the lower rivers. Large barrages diverted the saline water into irrigation systems in the Sind province. Meanwhile, the lower reaches of the Chenab and the Sutlej have shrunk – the widths are much smaller than the widths of these same rivers near the foothills. Nine or ten major link canals transfer flows from the northern rivers to the southern rivers. The expansion of irrigated area has resulted in more salinisation of land and increased evaporation. From anecdotal information, early morning fog is now frequent in northern Pakistan, resulting in cancellation of air flights.

In an attempt to resolve these problems, a multi-agency project (Left Bank Outfall Drain) was initiated in the early 1980s but, after review, the project was rated overall as unsatisfactory (World Bank, 2004). Thereafter, the international donors have proposed another US$785 million to develop a 'National Drainage Program'. Farther downstream, in the Indus delta, the shrunken Indus flows through a single channel with no active distributaries evident. The coastal mangrove zone has shrunk dramatically and both river and coastal fisheries have been impacted. Field inspection indicates new drainage channels to the east of the Indus emptying into the Rann of Kutch. The drainage channels are enlarging their size by headcutting, bringing new water and sediment problems into this tidal zone. Also, destruction of mangroves has impacted local climate and the reduction of silt delivery into the delta has resulted in regular erosion of the delta.

In summary, the introduction of high dams into the upper watershed has provided cheap power for pumping groundwater and, coupled with barrages to divert water, the largest irrigation system in the world. The change to the landscape has been dramatic – vast areas of land have become saline and unproductive while the delta zone is eroding and vegetation is disappearing. The large-scale storage of water has produced problems that, although foreseen prior to the Indus Treaty and acknowledged during the planning and negotiation phase, have been met only slowly with mitigation measures.

The River Nile

For thousands of years, inhabitants of the lower River Nile in Egypt have relied upon the water and its nutrients from the upper basin. The source of water was unknown and Egypt was styled 'a gift of the Nile' (Herodotus). In reality Egypt is a gift of Ethiopia – sediment eroded in Ethiopia is transported down the river and has, through time, filled the floodplain of the Nile Valley with fertile sediment and formed the Nile Delta (Butzer, 1972). The rise of the Egyptian civilisation over a period of about 7 ka was based on annual Nile flows sustaining a prosperous agriculture on the river floodplain and in the delta. Most of the water (about 75%) originates in Ethiopia, and flows down the Blue Nile and the Atbara, while the remainder (25%) originates in the Lake Plateau and flows down the White Nile. During the low flow period in the months March–June, the flow from Ethiopia is low and the White Nile provides about 75% of the total discharge. These flows pass slowly through the Sudd swamps in Sudan and a significant portion of the inflow evaporates.

Proposals for the management of the waters of the River Nile are numerous, with the historical purpose being to feed the floodplain inhabitants and their rulers. An overview of the major river works constructed to 1980 is shown in the profile in Fig. 4.11. Several major river works, mainly dams, were constructed on the Nile with the major impact being downstream from the High Aswan Dam. Prior to the construction of the High Dam many predictions were made and these are contrasted with actual changes in Table 4.4.

After the completion of the High Dam, the water level range in the lower Nile was reduced to about 2 m, with no overflow of the banks. Bank erosion has been significantly reduced since 1950. Studies of the river downstream from the Low Aswan Dam to Cairo indicated that the 1950 eroding bank length was some 500 km, which was 21% of the total bank length. It was reduced to 242 km in 1988 (12% of the reduced, 1988 length). The meandering river path was reduced and out of a total of 150 islands, some 87 joined the main bank, contributing to a substantial reduction in riverine habitat complexity. Also, the bankfull river width was reduced by about 30% from 1950 to 1978 as a result of a flow reduction from 8400 $m^3\ s^{-1}$ to about 2600 $m^3\ s^{-1}$ in post-High Dam conditions (RNPD, 1991).

TABLE 4.4. *Assessment of environmental changes on the River Nile below the High Aswan Dam*

Prediction	Actual change	Reference
(1) Reduced agriculture production	Increase	Sterling (1972)
(2) Devastation of fish in the Mediterranean	Slow decrease followed by increased numbers by 2004	Sterling (1972) Nixon (2004)
(3) River bed to be lowered by 10 to 20 m and bridges would collapse and banks erode	Bed lowering very small; bed is protected by snail shells and gravel; bank erosion reduced	Simaika (1970) RNPD (1991)
(4) Soil fertility reduced by trapping sediment in reservoir	Process is ongoing, with some fertilisers being applied	
(5) Increase in salinity and waterlogging in the delta	Serious problem partially being alleviated by field drains and pumping stations	Waterbury (1979)
(6) Erosion of coastline	Dramatic erosion after closure of High Dam; coastal defence works being constructed	Mobarek (1972)

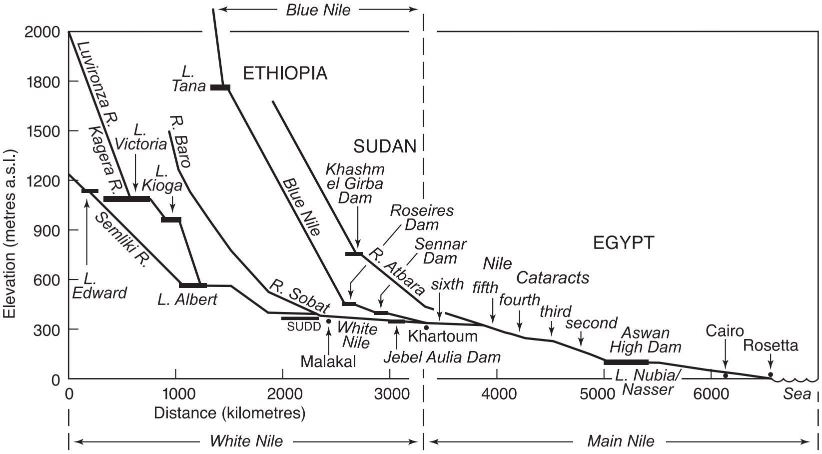

FIGURE 4.11. Long profile of the River Nile showing the principal river control works.

The Nile has become a relatively stable canal. Pre-dam predictions indicated major bed lowering with consequent failure of bridge foundations and landing wharves. However, these predictions did not materialise for a number of reasons:

- the presence of the Low Aswan Dam and six downstream barrages keeps the river bed from being lowered excessively;
- the occurrence of snail shells on the bed directly downstream from several barrages (delta barrages) has armoured the river bed;
- the presence of gravel lenses at locations of wadis entering the main river coarsened and armoured the river bed;
- the significant reduction in flows and velocities resulted in slow removal of bed sediment; and
- the introduction of wind-blown sand into the river caused a rise in the river bed (RNPD, 1991).

Another significant environmental consequence is the erosion of the Nile coastline, primarily as a result of reduced sediment entering this zone. The historical annual sediment load of about 125 Mt a^{-1} has been reduced to about 5 Mt a^{-1}. There is no longer any sediment deposition to perpetuate the growth of the delta. The coastal zone now has to be protected from erosion by large concrete works which are extremely expensive (Mobarak, 1972). The erosion was initially attributed to construction of barrages along the Nile in the nineteenth century but accelerated erosion was noticeable after 1964 with the completion of the High Aswan Dam.

The modification of the sediment budget along the Nile was predictable, but the degree of change to the fluvial landscape (river valley floodplain, delta and coast) were treated as separate topics and predictions were erratic. The changes are closely related to changes in the sediment budget. However, due to the influence of increasing populations reclaiming salt flats in the delta and expanding towns protecting their riverbanks, it is difficult to separate dam-induced impacts from other societal impacts. In summary, changes in sediment budget and river flows led to dramatic changes, some negative and some positive, in landscapes downstream from the High Aswan Dam.

Other significant impacts, such as the decline of fish stocks in the Mediterranean, occurred soon after the construction of the High Dam but, from 1990, the numbers of certain species has increased (Nixon, 2004). The main reason for the larger numbers is that the load of nutrients moving down the Nile – which is predominantly waste from expanding populations – increased, especially downstream from Cairo. As noted by Nixon (2004), the fish are now plentiful but 'may not have the same taste as the pre-dam fish'. Also, waterlogging and salinisation of the soil were predicted but the extent was underestimated.

4.5.3 Twenty-first-century predictions for large water projects

Mekong River

The Mekong River has long been a major water provider for humans, fish and vegetation throughout southernmost China and former Indo-China (Laos, Cambodia, Vietnam, Myanmar and Thailand). The Mekong is the eighth largest river in the world by area with a basin of 795 000 km^2 and an average annual flow of 3800 $m^3\ s^{-1}$ at Luang Prabang. The Cambodian floodplains and the Mekong Delta receive most of the water, with some flooding, and 95% of the sediment load. The upper basin in China and Myanmar contributes 18% of the mean annual discharge – this contribution comes during the dry season and is highly important to the lower Mekong system. Since the 1960s, a number of plans for the development of water resources of the Lower Mekong have been presented (White, 1963; Mekong Committee, 1970), but none of the proposed dams had been constructed until China began its aggressive development of eight hydro projects on the upper river in 1993, commencing with a dam at Manwan.

Upon completion, the eight reservoirs will trap about 50% (about 80 Mt a^{-1}) of the total sediment load of the Mekong River. The impacts of the upper river dams can be grouped under hydrological and geomorphological changes and fisheries impacts. The river downstream from the dams will degrade and could become a rock-cut canyon (Gupta and Liew, 2007). Also, local navigation on the river may be hampered. Because dry-season flows will be increased, the lowest lake elevations in Tonle Sap ('Great Lake') will increase in the future. Large areas of seasonally flooded forest will become permanently flooded, resulting in nutrient changes that will affect the fish. With lower peak flows, the maximum flooded areas will decrease and this will impact on the feeding zone for the fish. Hogan *et al.* (2004) have reported on imperilled species, such as the Mekong giant catfish, and the various action plans to save them.

These impacts, however, may be modified if the Upper Mekong Navigation Improvement Project (blasting away of river rapids) is allowed to continue. The Mekong River Commission has reviewed an additional 12 hydropower stations on the Mekong which would certainly block fish migration. Given the pressures for development, there may be inadequate time to study the cumulative environmental impacts of such developments.

The River Nile water budget and impacts due to proposed water projects on the Nile

Historically, one of the main developments proposed for the River Nile is the Jonglei Canal in Sudan – in fact, most of the canal route has been excavated. The canal project was financed by Egypt in order to gain a larger share of the Nile flows by bypassing the Sudd. However, the decision to proceed with the construction was made without consideration of environmental impacts. Studies had been conducted on prospective changes to the Sudd, but the conclusions were unclear. As reported by Howell *et al.* (1988): 'the project unfortunately started in a highly charged political atmosphere. The sudden announcement in 1974 of its impending implementation caused unfavourable reactions among southern Sudanese…'. This is not the only recent project to be constructed under political circumstances: Egypt recently constructed a pump diversion project to irrigate the low-lying area west of Lake Nasser (Kerisel, 1999). The water allocation to irrigate this area has not been negotiated with upstream countries and environmental questions have been raised. Also, hydro projects are currently under construction on the Tekeze River in Ethiopia and on the Nile at Merowe in Sudan. Both of these projects will modify evaporation losses within the basin – evaporation may be less in Ethiopia than from Lake Nasser and with timing of release flows more water could be delivered to the High Aswan Dam turbines. This matter has yet to be negotiated.

Huanghe (Yellow River), China

Huanghe is unique in the world, its annual total sediment load being one of the highest (1900 Mt a^{-1}) with a mean annual flow of 4000 $m^3\ s^{-1}$ (Zhao *et al.*, 1989). Frequent floods have resulted in countless deaths and an early response of dyke building to reduce flood impacts. The construction of dykes, however, is not a permanent solution, sediment deposited between the dykes necessitating a programme of progressive dyke raising. The dyked riverbed at some locations is 10 to 15 m above the surrounding floodplain. From 600 BC to 1949, the river changed its course across the North China plain and delta countless times (Xu, 1993).

The first major dam on the system was the high Sanmenxia Dam, built with the assistance of Russian engineers. The reservoir filled with sediment in about 6 years and low-level outlets were subsequently bored through the base of the dam to pass sediment-laden flow. The impact of the dam on the downstream landscape was not drastic – portions of the river degraded, resulting in less frequent flooding while, farther downstream, the sand bed has continued to aggrade (Zhao *et al*., 1989). Major changes to the floodplain have, however, been ongoing for centuries with the confinement of the river by flood dykes. The main future impact will be due to the recently completed Xiaolangdi Dam which is located about 200 km downstream from Sanmenxia. This reservoir, being quite large, will trap a reasonable portion of the sediment load and could initiate the lowering of the downstream river bed. Also, the delta zone will be relatively stable resulting in the expansion of Port Tianjin to the north and expanded agriculture. The change to the river landscape due to the two dams may, however, be overwhelmed by recent low flows and by the reduction of upstream sediment loads by extensive construction of hillslope terraces and check dams on the minor tributaries of the Loess Plateau (Hassan *et al*., 2008). It will be difficult to distinguish the impacts of the dams from those of the upstream basin rehabilitation, but neither of these two interferences will 'tame' Huanghe.

Future changes to Huanghe will be dominated by the large-scale inter-basin water transfer from Changjiang (Yangtze River) to Huanghe and farther north to the Beijing area. After a 50-year study the Chinese Ministry of Water Resources announced approval in principle of the General Plan of the South-to-North Water Transfer Project (Shao *et al*., 2003). The first component will be the East Route, which involves a siphon-type structure under Huanghe. A similar structure will be part of the Middle Route, but a number of potential problems, such as canal leakage, liquefaction of sand and frost heave have been identified. Also, along the East Route, water pollution problems already exist in detention lakes that are to be used as part of the transfer system. The pollution could increase if the diverted water is polluted and soil salinisation could result due to a rise in detention lake levels if the canal is to be used for navigation.

The consequences for Huanghe may be difficult to forecast. The ongoing changes due to terracing in the upper watershed are not yet fully understood. Presently, the lower river runs dry, or nearly so, for several months of the year, so there could also be positive impacts if the south water is diverted into the river.

4.5.4 Perspective

The number and magnitude of river diversions and dams has increased dramatically during the last century, but the environmental impact has yet to be fully documented and understood. Dams and reservoirs have direct climatic impacts themselves inasmuch as evaporation from reservoirs changes the water budget of the river, while regional atmospheric humidity and precipitation may be affected. In a regional climate subject to larger-scale changes, water projects associated with dams and diversions may become uneconomical, and may visit hardship upon those depending on the water supply as the actual amount of disposable water may fall below the designed expectation. This outcome has already been experienced in the Colorado River, where the original projects were based on the most optimistic estimates of the river's flow. Today, even the more recent projects are falling short of the expected water supply.

Withal, there is no sign that the rapid pace of human-induced river changes is slowing – new impacts to the environment probably will supersede earlier impacts. The landscape response will become increasingly complex, such that environmental rehabilitation projects will become the norm and realistic prediction of future impacts will become impossible. Damming a river, of course, creates the most radical changes of all in river hydrology, morphology and ecology. No primary effects on a river of regional climate change come close to such a radical reorganisation of the fluvial system.

4.6 River restoration in the context of global change

4.6.1 Introduction

River channels and floodplains have been directly altered for purposes such as bank stabilisation, navigation, flood control, relocation for highways and other infrastructure, in-channel mining for sand/gravel and placer deposits, and for hydropower and water supply impoundments (see foregoing sections and Table 4.5). In addition, changes in catchment land use change runoff and sediment load to rivers, which in turn can induce changes in river channels. To mitigate these impacts, a variety of restoration actions can be taken, some of which fit the notion of 'restoration' of ecological attributes, while others might be better viewed as

TABLE 4.5. *Some human impacts on river channels and restoration approaches*

Activity	Impacts	Restoration approach
Navigation	Straightening	Re-meander: allow sinuosity to redevelop by removing riprap and other constraints, or reconstruct channel with meanders
	Deepening (dredging)	Stop dredging, allow channel bed to recover through aggradation
	Stabilising banks (rock riprap)	Remove or don't maintain bank protection
	Training (groynes)	Remove or don't maintain training features
	Removing large wood	Allow large wood to remain and move through the system, less desirable: build structures with wood cabled to banks
	Removing other roughness features (e.g. blasting bedrock)	Cannot restore directly (may be able to compensate by creating other rough features)
	Cutting off side channels	Open side channels to flow through removal of plugs/weirs
	Altered flow regime	Re-regulate flows to achieve more natural flow regime
Flood control	Reservoir reduces flood peaks	Operate reservoir to increase flood peaks to restore system dynamics
	Levees prevent overbank flooding, depriving floodplain of flows	Set back, breach or remove levees to restore lateral connectivity with floodplain
	Levees concentrate flow, scouring and simplifying channel	Introduce set-back levees to reduce shear stress within levees, allowing gravel bars, vegetation and other hydraulically rough features to develop
Channel relocation	Relocated channel typically straighter than original channel	Enlarge river corridor and increase sinuosity
Bank stabilisation	Channel migration prevented, undercut bank habitat lost, cohesive vertical bank habitat lost, new point bars deposition prevented	Remove bank protection, allow channel migration to occur
	Reduced gravel supply to river channel by reduced bank erosion	Remove bank protection to restore gravel supply from bank, or artificially add gravel to channel
In-channel mining	Direct loss of complex channel features	Cease in-channel gravel mining; allow channel form to recover if adequate sediment load is available
	Incision propagates upstream of mine site via headcut migration	Incision may be controlled with grade control structures, but tendency to incise persists and scour downstream of weirs may create barriers to fish migration
	Incision propagates downstream due to sediment starvation, and tends to continue until sediment supply can balance sediment deficit (often occurs through bank erosion induced by bank undercutting)	Increase supply of coarse sediment to downstream reach to reverse incision
Reservoirs	Trap coarse sediment, release sediment-starved water downstream, inducing	
	bed coarsening, loss of salmonid spawning gravels	Pass sediment through (small) reservoirs via low-level outlets or around reservoirs via

TABLE 4.5. (*cont.*)

Activity	Impacts	Restoration approach
		bypass channels, or add coarse sediment artificially to channel below dam
	Incision, lowered alluvial water tables	Increase coarse sediment supply downstream of dam (as above) or install structures such as artificial logjams to raise water levels in the channel
	Reduce flood peaks, inducing vegetation encroachment and channel narrowing	Mechanically remove vegetation and berms established along the channel margins, and introduce more dynamic flow regime including flushing flows designed to scour seedlings before they can establish mature trees

countermeasures to control incision or accelerated bank erosion (Table 4.5). The degradation of ecological qualities of rivers as a result of global change has been noted in the preceding sections of this chapter. Here we consider the role of river restoration in the context of global change.

4.6.2 Extent and scope of river restoration

River restoration is increasingly popular in North America and Europe. In the United States, over 37 000 individual projects with combined costs exceeding US$15 billion have been completed since 1990 (Bernhardt *et al*., 2005), not including large restoration programmes such as the Kissimmee River (Koebel, 1995) or the Colorado River in the Grand Canyon (National Research Council 1999). Many of these projects can be called 'restoration' in name only, having as principal goals bank stabilisation or imposition of a stable channel of socially preferred form. Remarkably few of these projects have been subject to objective post-project appraisal, severely limiting the potential for the field to mature and for practice to improve, and limiting our ability to assess the overall contribution of restoration projects to river ecosystem vitality (Bernhardt *et al*., 2005).

River 'restoration' in North America has largely become an industry, with a set of standard approaches broadly applied, in many cases without profound understanding of the history and constraints of a particular river (Wohl *et al*., 2005). In Europe, fewer projects have been completed to date, but under the Water Framework Directive (adopted by the European Union Parliament in 2000), EU member states are required to achieve 'good ecological status' in rivers by 2015, prompting strong interest in restoration programmes. Moreover, in some cases, water managers have taken approaches based on best available science that can be viewed as more innovative than the standard approach of their North American counterparts.

To many land managers in North America, 'stream restoration' implies reconstructing channels into the culturally desired form of single-thread meandering channels. In regions where this approach is currently popular, hundreds of such projects have been completed since 1990. While these projects are usually justified by arguments about width–depth ratios and 'stream types' specified by a particular channel classification system, they are usually designed by practitioners without strong academic backgrounds in fluvial geomorphology, who instead apply the classification scheme, which has been criticised by the academic and research community (Simon *et al*., 2006). Moreover, the fact that this approach consistently specifies a single-thread meandering channel (no matter what the context) suggests that there is something deeper at work, that these projects are responding to an ingrained cultural preference for such an ideal channel form (Kondolf, 2006).

In Germany, after early attempts to design and build channel forms and habitats, managers now increasingly attempt to initiate channel dynamics as a more sustainable and less expensive restoration strategy. For example, large wood has been introduced into incised channels in Hesse, Germany, and channel widening to restore multi-thread channel systems and their habitats (and increase flood capacity) has become a popular approach in Austria (Piégay *et al*., 2008). The Drôme River, France, has incised because of reduced sediment supply from the catchment due to rural depopulation, reduced land pressure and afforestation. To counteract negative consequences of sediment starvation and incision, managers are attempting to reactivate sediment sources to restore channel dynamics (Kondolf *et al.*, 2002).

It is useful to consider the full range of human impacts that have degraded river ecosystems, and to compare the trajectories of degradation with trajectories of restoration. We find that, most commonly, the restoration trajectories do not parallel the degradation trajectories because restoration projects tend to tackle only the changes that are easier (logistically, financially and politically) to reverse (Kondolf *et al.*, 2006). For example, Clear Creek (a tributary to the Sacramento River near Redding, California) had two dams blocking salmon migration: Saeltzer was a small dam (*c.* 1912) to divert water for irrigation, while Whiskeytown is a large dam (*c.* 1963) storing water transferred from the Trinity River via penstocks, en route to the Sacramento River as part of the massive Central Valley Project. Both dams blocked migration of salmon, but only Whiskeytown affected high flows that shape the channel. By trapping gravel it created sediment-starved conditions downstream. Restoration of Clear Creek has involved removal of the smaller downstream dam, reconstruction of a reach disturbed by gravel mining to improve fish passage, and injection of gravel into the channel to increase spawning habitat for salmon, relatively easy activities to undertake in the current environment. To date, operation of the larger dam upstream has not been substantially affected, as to do so would affect politically powerful interests and have larger costs (Kondolf *et al.*, 2006). Thus, the trajectory of restoration in Clear Creek does not parallel the trajectory of its degradation, as only some of the changes have been reversed by restoration activities, a common pattern in river restoration projects.

4.6.3 Mitigating the effects of climate change

In North America, the greatest concentration of restoration projects is found in the western Cordillera, driven by programmes to create habitat for anadromous salmon and trout, many runs of which are listed as threatened or endangered. In the southern end of the range of these species, summer water temperatures commonly limit distribution of the fish. Concern about the potential effects of projected temperature increases on habitat suitability for salmon has led to interest among government and non-government agencies (such as the Nature Conservancy) to explore ways to mitigate temperature increases by buffering temperatures at the reach scale. Increased shading and increased hyporheic exchange through increased channel complexity, creating favourable hydraulic gradients to drive surface–groundwater exchange (Poole *et al.*, 2002), are being considered as strategies to maintain some rivers within the temperature tolerance range of salmonids.

4.6.4 River restoration as a developed world activity

Widespread river restoration is a relatively recent phenomenon, mostly restricted to the developed world, reflecting increased demand for environmental quality in affluent, educated societies, and improvements in water quality brought on by environmental legislation such as the Clean Water Act in the United States. Only after water quality improves does it make sense to encourage greater human contact with rivers or attempt to re-establish native (or otherwise socially desirable) ecological communities in rivers. Ironically, much of the improvement in water quality and redevelopment of formerly industrial riverfronts in developed world societies has been made possible by displacement of heavy industries to developing countries where environmental controls are less stringent or unenforced. For example, recent restoration of the riverfront in Pittsburgh, Pennsylvania, was made possible by the closing of steel mills and related industries, most of which moved abroad (Otto *et al.*, 2004). Thus the much-heralded restoration of formerly industrial rivers in North America and Europe is probably at least matched by increased impacts in rivers elsewhere. Rivers in the developing world are affected not only by industry displaced from developed countries, but also by the increasing demands of expanding populations, with concomitant agricultural and industrial development. These trends imply greater loads worldwide of sewage and other pollutants discharged into rivers, as well as extensive land use change and consequent impacts on flow, sediment load and water quality. When we consider the rate of population increase in many developing world cities that lack sewage treatment, and calculate how many sewage treatment plants would be needed to meet current and future needs, it becomes clear that such developed world approaches cannot realistically be employed in this context, but rather that alternative approaches to sanitation need to be developed and employed. Certainly the notion of river restoration as practised in North America today would be irrelevant in this context of heavy practical demands on waterways in the developing world.

4.6.5 Perspective: relative scales of restoration and degradation

Even in a purely developed world context, when we consider the rate of river degradation, river restoration appears very limited in comparison. For example, the CALFED

Bay–Delta Program, encompassing the estuary of the Sacramento River, San Francisco Bay and the Sacramento–San Joaquin Delta (the San Francisco Estuary) and its watershed in northern California, is one of the largest ongoing restoration programmes in the United States, with more than US$500 million invested in restoration projects from 1997 to 2004 (CALFED, 2005). Yet when we look at the results of these and other restoration efforts to date in the context of habitat losses and fish population declines since European settlement in 1850, it is clear that even a restoration effort on this scale will not reverse large-scale historical changes. Many component projects have involved restoration of tidal marsh in the estuary. The Sonoma Baylands, one of the most successful such projects to date, restored 124 ha in 1996. This area is equivalent to less than 0.2% of the estimated 68 000 ha of tidal marsh lost in the San Francisco Estuary since 1850 (Bay Institute, 1998). Collectively, tidal wetland restoration projects in the San Francisco Estuary have restored about 650 ha – about 1% of the tidal marsh habitat lost since 1850 (Bay Institute, 2003). When we consider that there is no guarantee that restoration projects will work as intended, preservation of intact river ecosystems (with still natural processes of flow, sediment, and floodplain connectivity) takes on greater priority.

Most restoration programmes are directed at smaller rivers, within which reasonably affordable engineering effort might have detectably positive results. In the United States, in recent years, this interest has extended to considering the removal of dams of small or moderate scale, most of them constructed in the late nineteenth or early twentieth centuries and now of questionable integrity in any case. Whilst practical restoration efforts might be extended to include most rivers of European scale, this prominently leaves aside many of the largest and most ecologically diverse rivers of the world, on which dam building and navigation improvements have been conducted at too large a scale to consider reversal and, in any case, the 'improvements' are too closely tied to the economy that they serve to consider ending them.

When we take a global view of the improvements in river ecosystems from restoration projects to date, accounting both for improvements in developed nations and continued degradation in the developing world, it is difficult to avoid concluding that river conditions are deteriorating overall in response primarily to increased human pressures on waterways in the developing world, but also because the benefits of the restoration projects undertaken in the developed world are either small relative to historical degradation, or simply cannot be demonstrated due to lack of adequate documentation and monitoring. This is not to say that we should give up on the enterprise of river restoration, but we should not fall into the trap of believing that the world is getting better because we see apparent improvements in some rivers of the developed world. We must ask how we can rigorously assess the actual ecological effectiveness of these projects, how these demonstrated improvements compare with the scale of historical degradation, and how our progress in the developed world scales in light of continued degradation in the developing world. Changing climate adds another layer to this story but, compared with the effects of increased population and increased pressures on river systems, its role is relatively minor.

4.7 Conclusions

There is no question that climate change is affecting the world's rivers. By changing the total volume and seasonal distribution of flow – the consequence of changing patterns of precipitation on to and evapotranspiration from the land surface – riverine water supply is affected in ways that will have an important impact on regional and global economies. The impact in many places will be unfavourable because it will entail a reduction in the availability of already scarce resources, but it may be unfavourable in most places simply because human societies are ill-adapted to deal with change of any kind.

The consequences of climate change for the morphology of the rivers themselves and of the riverine ecosystems that they support will, however, be far, far less dramatic than are the consequences of long-established and ongoing activities of humans. This chapter has sought to establish this fact by describing consequences for rivers of human activities on the land surface which affect the formation of runoff, the quality of water and the supply of sediment to rivers, and the consequences of direct human manipulation of river channels for diverse reasons. We have closed the chapter with some brief remarks on the limited efficacy of human efforts at 'restoration' or, at least, habilitation of rivers.

A great deal remains to be learned about how humans might properly manage rivers (and, on a crowded planet, active management will remain necessary). One thing is clear. Humans interfere with rivers at all stages from runoff formation on the land surface to the discharge of water through river estuaries and deltas to the world ocean. A successful approach to river management must be an approach that integrates all of the processes and effects through the drainage system. This was a prominent theme in the development-oriented society of the mid twentieth century. It needs to return with a much stronger emphasis upon the conservation and appropriate use of the resources that the world's rivers represent (see Newson, 1997). It will require us to learn far more about the hydrology, geomorphology and ecology of rivers than we know at present. The factors contributing to change in local, regional and global environments – primarily directed by human activities – come to a critical focus on water and waterways.

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