1 Landscape and landscape-scale processes as the unfilled niche in the global environmental change debate: an introduction

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1.1 The context

Whatever one's views, it cannot be doubted that there is a pressing need to respond to the social, economic and intellectual challenges of global environmental change. Much of the debate on these issues has been crystallised around the activities of the IPCC (Intergovernmental Panel on Climate Change). The IPCC process was set up in 1988, a joint initiative between the World Meteorological Organization and the United Nations Environment Programme. The IPCC's First Assessment Report was published in 1990 and thereafter, the Second (1996), the Third (2001) and the Fourth Assessment Report (2007) have appeared at regular intervals. Each succeeding assessment has become more confident in its conclusions.

The conclusions of the Fourth Assessment can be summarised as follows:

(a) warming of the climate system is unequivocal;
(b) the globally averaged net effect of human activities since AD 1750 has been one of warming (with high level of confidence);
(c) palaeoclimate information supports the interpretation that the warmth of the last half century is unusual in at least the previous 1300 years;
(d) most of the observed increase in globally averaged temperature since the mid twentieth century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations; and
(e) continued greenhouse gas emissions at or above current rates will cause further warming and induce many changes in the global climate system during the twenty-first century that would very likely be larger than those observed in the twentieth century. Details of the methodology used to reach these conclusions can be found in Appendix 1.1.

The IPCC assessments have been complemented by a number of comparable large-scale exercises, such as the UNEP GEO-4 Assessment (Appendix 1.2) and the Millennium Ecosystem Assessment (Appendix 1.3) and, for example, at a more focussed level, the Land Use and Land Cover Change (LUCC) Project (Appendix 1.4) and the World Heritage List (Appendix 1.5). There is no doubting the effort, value and significance of these enormous research programmes into global environmental change (Millennium Ecosystem Assessment, 2005; Lambin and Geist, 2006).

1.1.1 Defining landscape and appropriate temporal and spatial scales for the analysis of landscape

It is important to establish an appropriate unit of study against which to assess the impacts of global environmental change in the twenty-first century and to identify those scales, both temporal and spatial, over which meaningful, measurable change takes place within such a unit. The unit of study chosen here is that of the landscape. There are strong historical precedents for such a choice. Alexander von Humboldt's definition of 'Landschaft' is the 'Totalcharakter einer Erdgegend' (Humboldt, 1845–1862). Literally this means the total character of a region of the Earth which includes landforms, vegetation, fields and buildings. Consistent with Humboldt's discussion, we propose a definition of landscape as 'an intermediate scale region, comprising landforms and landform assemblages, ecosystems and anthropogenically modified land'.

The preferred range of spatial scales is 1–100 000 km^2 (Fig. 1.1). Such a range, of six orders of magnitude, is valuable in two main ways:

(a) individual landforms are thereby excluded from consideration; and

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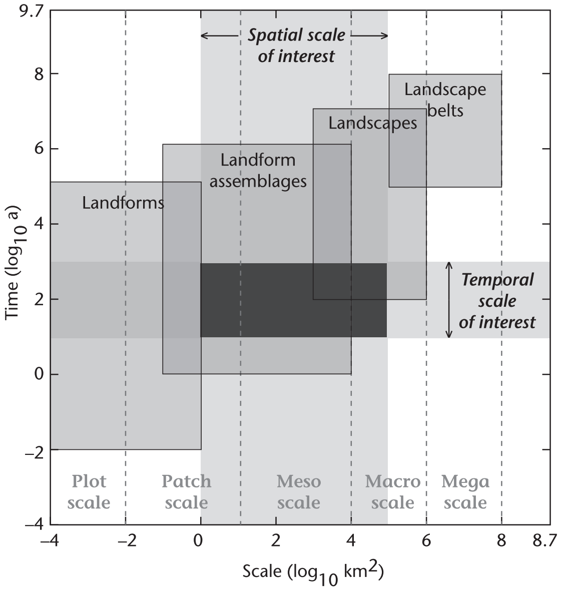

FIGURE 1.1. Spatial and temporal scales in geomorphology. On the *x*-axis, the area of the surface of the Earth in km² is expressed as 8.7 logarithmic units; on the *y*-axis, time since the origin of the Earth in years is expressed as 9.7 logarithmic units.

(b) landscape belts (*Landschaftgürtel*) and biomes, which provide an organising framework for this volume, are nevertheless so large that their response to environmental disturbance is impossible to characterise at century or shorter timescales.

The preferred range of timescales is decades–centuries (Fig. 1.1). These are intermediate temporal scales that are relevant to human life and livelihoods (and define timescales required for mitigation and adaptive strategies in response to environmental change). The determination of the future trajectory of landscape change is unthinkable for projections into a more distant future. Nevertheless, as is argued below, an understanding of changes in landscapes and biomes over the past 20 000 years (i.e. since the time of maximum continental ice sheet development over North America and Eurasia) provides essential context for a proper understanding of current and near-future landscape dynamics.

1.1.2 The global human footprint and landscape vulnerability

The human imprint on the landscape has become global (Turner *et al*., 1990a; Messerli *et al*., 2000) and positive feedbacks between climate, relief, sea level and human activity are leading in the direction of critical system state 'tipping points'. This is both the threat and the opportunity of global environmental change. Some of the implications of arriving at such a tipping point are that gradual change may be overtaken by rapid change or there may even be a reversal of previously ascertained trends. A few examples of the most vulnerable landscapes, in which small environmental changes, whether of relief, sea level, climate or land use, can produce dramatic and even catastrophic response, are listed here:

(a) Low-lying deltas in subsiding, cyclone-prone coasts are highly vulnerable to changes in tropical storm magnitude and/or frequency. It is clear that societal infrastructure is poorly attuned to disaster response in such heavily populated landscapes, in both developed (e.g. Hurricane Katrina, Mississippi Delta, August 2005) and developing (Cyclone Nargis, Irrawaddy Delta, May 2008) countries;

(b) Shifting sand dunes respond rapidly to changing temperature and rainfall patterns. Dunes migrate rapidly when vegetation is absent; the vast areas of central North America, central Europe and northern China underlain by loess (a mixture of fine sand and silt) are highly vulnerable to erosion when poorly managed, but are also an opportunity for continuing intensive agricultural activity guided by the priority of the ecosystem;

(c) Glacier extent and behaviour are highly sensitive to changing temperatures and rising sea level. In most parts of the world, glaciers are receding; in tropical regions, glaciers are disappearing altogether, with serious implications for late summer water supply; in Alaska, British Columbia, Iceland, Svalbard and the Antarctic Peninsula glaciers are surging, leading to catastrophic drainage of marginal lakes and downstream flooding. Transportation corridors and settlements downstream from surging glaciers are highly vulnerable to such dynamics;

(d) Permafrost is responding to rising temperatures in both polar and alpine regions. In polar regions, landscape impacts include collapse of terrain underlain by massive ice and a general expansion of wetlands. Human settlements, such as Salluit in northern Quebec, Canada, are highly vulnerable to such terrain instability and adaptation strategies are required now to deal with such changes; and

(e) In earthquake-prone, high-relief landscapes, the damming of streams in deeply dissected valleys by landslides has become a matter of intense concern. The 12 May 2008 disaster in Szechwan Province, China saw the creation of over 30 'quake lakes', one of which reached a depth of 750 m before being successfully drained via overspill channels. If one of these dams had been catastrophically breached, the lives of 1.5 million downstream residents would have been endangered. Although one example does not make a global environmental concern, the quake lakes phenomenon is representative of the natural hazards associated with densely populated, tectonically active, high-relief landscapes.

1.1.3 Multiple drivers of environmental change

There is an imbalance in the contemporary debate on global environmental change in that the main emphasis is on only one driver of environmental change, namely climate (Dowlatabadi, 2002; Adger *et al*., 2005). In fact, environmental change necessarily includes climate, relief, sea level and the effects of land management/anthropogenic factors *and* the interactions between them. It is important that a rebalancing takes place now, to incorporate all these drivers. Furthermore, the focus needs to be directed towards the landscape scale, such that global environmental changes can be assessed more realistically. Human safety and well-being and the maintenance of Earth's geodiversity will depend on improved understanding of the reciprocal relations between landscapes and the drivers of change.

In his book *Catastrophe*, for example, Diamond (2005) has described a number of ways in which cultures and civilisations have disappeared because, at least in part, those civilisations have not understood their vulnerability to one or more of the drivers of environmental change. Montgomery (2007) has developed a similar thesis with a stronger focus on the mismanagement of soils.

1.1.4 Systemic and cumulative global environmental change

Global environmental change is here defined as environmental change that consists of two components, namely systemic and cumulative change (Turner *et al*., 1990b). Systemic change refers to occurrences of global scale, physically interconnected phenomena, whereas cumulative change refers to unconnected, local- to intermediate-scale processes which have a significant net effect on the global system.

In this volume, hydroclimate and sea level change are viewed as drivers of systemic change (see Sections 1.6 and 1.7 of this chapter below). The atmosphere and ocean systems are interconnected across the face of the globe and the modelling of the coupled atmosphere–ocean system (AOGCM) has become a standard procedure in application of general circulation models (or GCMs). A GCM is a mathematical representation of the processes that govern global climate. At its core is the solution to a set of physical equations that govern the transfer of mass, energy and momentum in three spatial dimensions through time. The horizontal atmospheric resolution of most global models is between 1°–3° (~100–300 km). Processes operating at spatial scales finer than this grid (such as cloud microphysics and convection) are parameterised in the model. In the vertical direction, global models typically divide the atmosphere into between 20 and 40 layers.

Topographic relief, and land cover and land use changes, by contrast, are viewed as drivers of cumulative change (see Sections 1.8 and 1.9). The patchiness of relief and land use and difficulties of both definition and spatial resolution make the incorporation of their effects into GCMs a continuing challenge. Nevertheless, developments in global climate modelling over the past decade have seen the improvement in land-surface modelling schemes in which an explicit representation of soil moisture, runoff and river flow routing has been incorporated into the modelling framework (Milly *et al*., 2002). This trend, coupled with the widespread implementation of dynamic vegetation models (in which vegetation of different plant functional types is allowed to grow according to prevailing environmental conditions) has resulted in a generation of models into which such a range of complex interacting processes are embedded that they have become termed global *environmental* models instead (Johns *et al*., 2006).

1.1.5 The role of geomorphology

In these contexts, geomorphology (from the Greek *geo* Earth and *morphos* form) has an important role to play; it involves the description, classification and analysis of the Earth's landforms and landscapes and the forces that have shaped them, over a wide range of time and space scales (Fairbridge, 1968). In particular, geomorphology has the obligation to inform society as to what level of disturbance the Earth's landforms and landscapes can absorb and over what time periods the landscape will respond to and recover from disturbance.

In this book, we have chosen to view geomorphology (changing landforms, landform systems, landscapes and landscape systems) as dependent on the four drivers of environmental change, namely climate, relief, sea level and human activity, but also as an independent variable that has a strong effect on each of the drivers at different time and space scales. The relationship in effect is a reflexive one and it is important to avoid the implication of unique deterministic relations.

Two important intellectual strands in geomorphology have been so-called 'climatic' and 'process' geomorphology; they have tended to focus on different spatio-temporal scales of inquiry.

1.2 Climatic geomorphology

Climate's role in landscape change has long been of interest to geomorphology. Indeed in the continental European literature this was a theme that was already well developed by the end of the nineteenth century (Beckinsale and Chorley, 1991). The greatest impetus to climatic geomorphology came from the global climatic classification scheme of Köppen (1901). A clear statement of the concept of climatic geomorphology was made by de Martonne (1913) in which he expressed the belief that significantly different landscapes could be developed under at least six present climatic regimes and drew particular attention to the fact that humidity and aridity were, in general, more important as differentiators of landscape than temperature. The identification of morphoclimatic/morphogenetic regions and attempts to identify global erosion patterns (Büdel in Germany, Tricart in France and Strakhov in Russia) were also important global-scale contributions. Strakhov's map of global-scale erosion patterns is reproduced here (Fig. 1.2) to illustrate the style and scale of this research. He attempted to estimate world denudation rates by extrapolating from sediment yields for 60 river basins. His main conclusions were:

(a) arid regions of the world have distinctive landforms and landscapes;

(b) the humid areas of the tropics and subtropics, which lie between the +10 ºC mean annual isotherm of each hemisphere, are characterised by high rates of denudation, reaching maximum values in southeastern Asia;

(c) the temperate moist belt, lying largely north of the +10 ºC mean annual isotherm, experiences modest denudation rates;

(d) the glaciated shield areas of the northern hemisphere, largely dominated by tundra and taiga on permafrost and lying north of the 0 ºC mean annual isotherm, have the lowest recorded rates of denudation; and

(e) mountain regions, which experience the highest rates of denudation, are sufficiently variable that he was forced to plot mountain denudation data separately in graphical form.

The map is an example of climatic geomorphology in so far as it demonstrates broad climatic controls but perhaps the most important contribution of twentieth-century climatic geomorphology was that it maintained a firm focus on the landscape scale, the scale to which this volume is primarily directed. The weakness of the approach is that regional and zonal generalisations were made primarily on the basis of form (in the case of arid regions) and an inadequate sampling of river basin data. There was a lack of field measurements

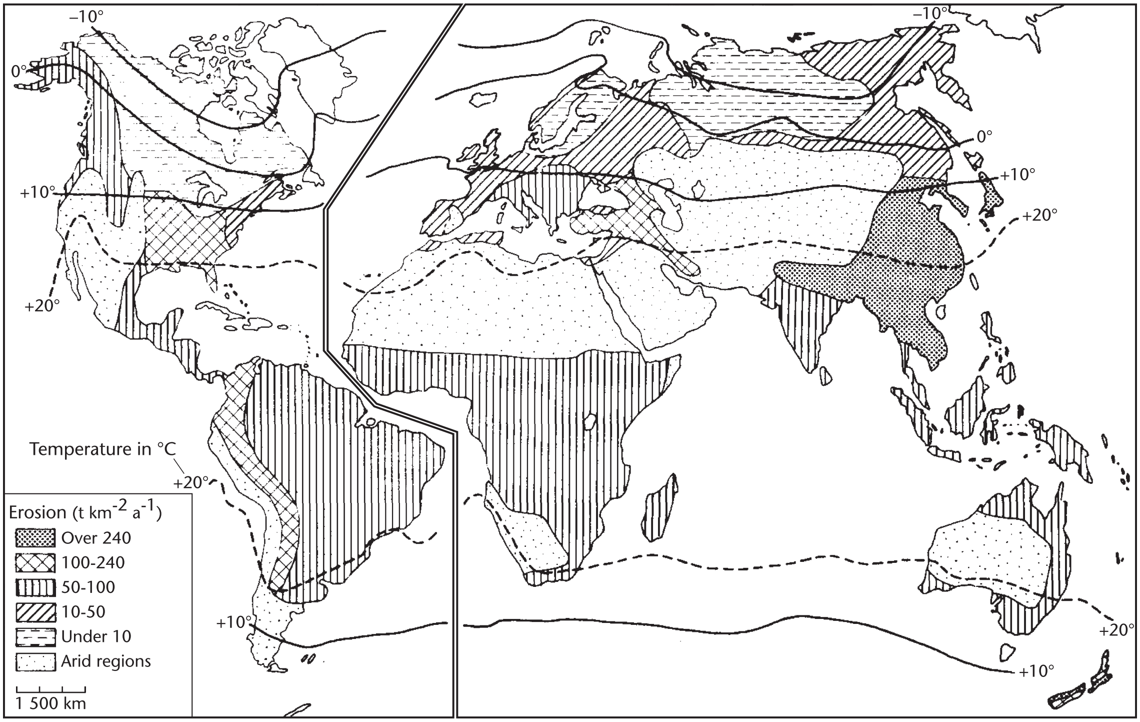

FIGURE 1.2. Climatic geomorphology (modified from Strakhov, 1967).

of contemporary process and no discussion of the scale dependency of key rainfall, runoff and sediment relations.

Whilst one may be critical of these earlier attempts to deal with landscape-scale geomorphology, now is a good time to revisit the landscape scale, with a firmer grasp of the relief, sea level and human activity drivers, for the following reasons:

(a) the development of plate tectonic theory and its geomorphological ramifications has given the study of earth surface processes and landforms a firmer geological and topographic context;
(b) a better understanding of the magnitudes and rates of geomorphological processes has been achieved not only from contemporary process measurements but also from the determination of more precise and detailed records of global environmental change over the last 20 000 years utilising improved chronologies (largely ocean rather than terrestrially based) and benefiting from the development of whole suites of radiometric dating techniques, covering a wide range of half-lives and thus timescales; and
(c) the ability to provide, at a range of scales, quantitative measurements of land surface topography and vegetation characteristics from satellite and airborne remote sensing.

1.3 Process geomorphology

From the 1950s onwards an Anglo-American geomorphology came to be reorientated towards quantitative research on the functional relations between form, materials and earth surface processes. These 'process studies', generally at the scale of the small drainage basin or below, began to determine local and regional rates of surface lowering, or denudation, material transport and deposition and their spatial differentiation. The rates at which these processes take place are dependent upon local relief and topography, the materials (bedrock and soils) involved and, of course, climate, both directly and indirectly through the relations between climate, vegetation characteristics and surface processes. The emphasis on rates of operation of processes led to a greater interest in the role of hydroclimate, runoff and sediment transport both in fluvial and in coastal systems. The role of vegetation in landscape change also assumed a new importance for its role in protecting the soil surface, in moderating the soil moisture and climate and in transforming weathered bedrock into soil (Kennedy, 1991).

1.3.1 Process–response systems

One of the most influential papers in modern geomorphology concerned the introduction of general systems thinking into geomorphology (Chorley, 1962). General systems thinking provided the tool for geomorphologists to analyse the critical impacts of changes in the environmental system on the land surface, impacts of great importance for human society and security. One kind of general system that has proved to be most fruitful in providing explanations of the land surface–environment interaction is the so-called process–response system (Fig. 1.3). Such systems are defined as comparatively small-scale geomorphic systems in which deterministic relations between 'process' (mass and energy flows) and 'response' (changes in elements of landscape form) are analysed with mathematical precision and attempted accuracy. There is a mutual co-adjustment of form and process which is mediated through sediment transport, a set of relations which has been termed 'morphodynamics' and which has been found to be particularly useful in coastal studies (e.g. Woodroffe, 2002).

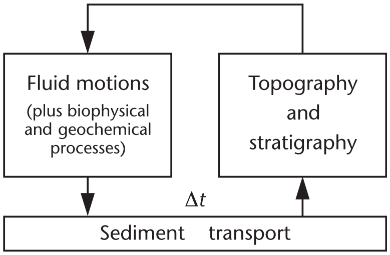

FIGURE 1.3. A simplified conceptual model of a process–response system.

Morphodynamics explains why, on the one hand, physically based models perform well at small spatial scales and over a limited number of time steps but, on the other hand, why model predictions often break down at 'event' and particularly 'engineering' space-timescales. Unfortunately, these are exactly the scales that are of greatest significance in the context of predicting landscape responses to global environmental change and the policy and management decisions that flow from such responses.

1.3.2 The scale linkage problem

The issue of transferring knowledge between systems of different magnitude is one of the most intransigent problems in geomorphology, both in terms of temporal scale and spatial scale (Church, 1996).The problem of scale linkage can be summarised by the observation that landscapes are characterised by different properties at different scales of investigation. Each level of the hierarchy includes the cumulative effects of lower levels in addition to some new considerations (called emergent properties in the technical literature) (Fig. 1.4).

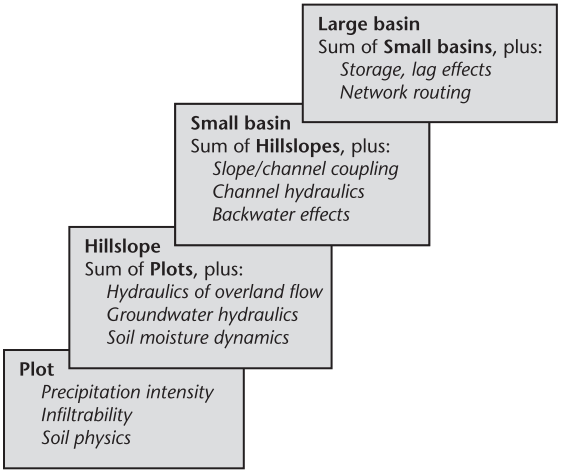

FIGURE 1.4. The scale linkage problem (modified from Phillips, 1999) illustrated in terms of a spatial hierarchy which contains new and emergent properties at each successive spatial scale.

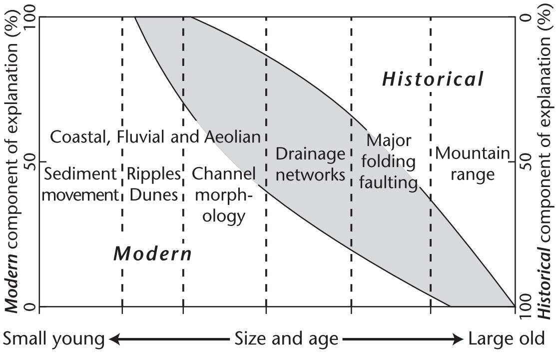

FIGURE 1.5. The relative importance of historical vs. modern explanation as a function of size and age of landforms and landscapes (modified from Schumm, 1985). Note the assumption that size and age are directly correlated, an assumption that is most appropriate for coastal, fluvial and aeolian landscapes, but does not easily fit volcanic and tectonic landscapes.

At the landscape scale, here taken to be larger than the large basin scale in Fig. 1.4, there are further emergent properties which have to be considered such as regional land use and hydrology.

Figure 1.5 combines a consideration of both temporal and spatial scales. At one extreme of very small spatial scale, such as the movement of individual sand grains over very short timescales, the process–response model works well. At the other extreme, large landscapes that have evolved over millions of years owe their configuration almost exclusively to past processes. Discontinuous sediment disturbances have a history of variable magnitude and frequency of occurrence. The practical implication is that, in general, the larger the landscape we wish to consider the more we have to take into account past processes and the slower will be the response of that landscape in its entirety to sediment disturbance regimes. Coastal morphology and drainage networks, which occupy the central part of Fig. 1.5, exemplify the scales of interest in this volume.

1.4 Identification of disturbance regimes

Global environmental change has become a major concern in geomorphology because it poses questions about the magnitude, frequency and kinds of disturbance to which geomorphic systems are exposed. What then are the major drivers of that change? Discussions about the rhythm and periodicity of geological change have spilled over into geomorphology. In his discussion of rhythmicity in terrestrial landforms and deposits, Starkel (1985) directed attention to the fact that the largest disturbance in the geologically recent past is that of continental-scale glaciation (see Plates 1 and 2). Periods of glaciation alternating with warmer episodes define a disturbance regime characterised by varying rates of soil formation and erosional and depositional geomorphological processes during interglacial and glacial stades (Fig. 1.6).

Some of the excitement in the current debate over global environmental change concerns precisely the question of the rate at which whole landscapes have responded to past climate changes and disturbances introduced by tectonism (e.g. volcanism, earthquakes and tsunamis) or human activity.

1.4.1 Landscape response to disturbance

The periodicity of landscape response to disturbance in Fig. 1.6 is controlled by the alternation of glacial and interglacial stades. The magnitude and duration of this response is a measure of the sensitivity and resilience of the landscape. In the ecological and geomorphic literature, this response is commonly called the system vulnerability. Conventionally, human activity has been analysed outside

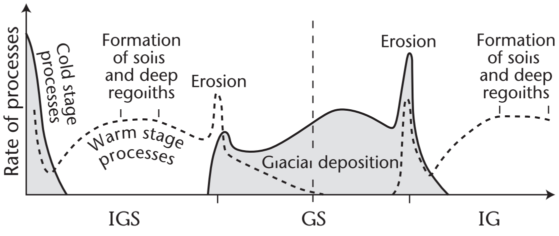

FIGURE 1.6. Periodicity of erosion and sedimentation (modified from Starkel, 1985). IGS is interglacial stade; GS is glacial stade; and IG is the present interglacial.

the geosystem (and Fig. 1.6 contains no human imprint) but the weakness of this approach is that it fails to recognise the accelerating interdependence of humankind and the geosystem. The IPCC usage of the term ‘vulnerability’, by contrast, addresses the ability of society to adjust to disturbances caused by environmental change. We therefore follow, broadly, the IPCC approach in defining sensitivity, adaptive capacity and vulnerability as follows. ‘Sensitivity’ is the degree to which a system is affected, either adversely or beneficially, by environment-related stimuli; ‘adaptive capacity’ is the ability of a system to adjust to environmental change, to moderate potential damages, to take advantage of new opportunities or to cope with the consequences; and ‘vulnerability’ is the degree to which a system is susceptible to, or unable to cope with, adverse effects of environmental change. In sum, ‘vulnerability’ is a function of the character, magnitude and rate of environmental change and variation to which a system is exposed, its sensitivity and its adaptive capacity (Box SPM-1 in IPCC, 2001b, p. 6.).

In general, those systems that have the least capacity to adapt are the most vulnerable. Geomorphology delivers a serious and often unrecognised constraint to the feasible ways of dealing with the environment in so far as it controls vulnerability both in the ecological sense (in the absence of direct human agency) *and* in the IPCC sense. A number of unique landscapes and elements of landscapes are thought to be more likely to experience harm than others following a perturbation. There are seven criteria that have been used to identify key vulnerabilities:

(a) magnitude of impacts;
(b) timing of impacts;
(c) persistence and reversibility of impacts;
(d) estimates of uncertainty of impacts;
(e) potential for adaptation;
(f) distributional aspects of impacts; and
(g) importance of the system at risk.

In the present context, such landscapes are recognised as hotspots with respect to their vulnerability to changes in climate, relief, sea level and human activities. We think immediately for example of glaciers, permafrost, coral reefs and atolls, boreal and tropical forests, wetlands, desert margins and agricultural lands as being highly vulnerable. Some landscapes will be especially sensitive because they are located in zones where it is forecast that climate will change to an above average degree. This is the case for instance in the high arctic where the degree of warming may be three to four times greater than the global mean. It may also be the case with respect to some critical areas where particularly substantial changes in precipitation may occur. For example, the High Plains of the USA may become markedly drier. Other landscapes will be especially sensitive because certain landscape forming processes are particularly closely controlled by thresholds, whether climatic, hydrologic, relief, sea level or land use related. In such cases, modest amounts of environmental change can switch systems from one state to another (Goudie, 1996).

1.4.2 Azonal and zonal landscape change

The overarching problem of assessing probable landscape change in the twenty-first century is approached here in two main ways. A group of chapters which are ‘azonal’ in character concern themselves with ways in which geomorphic processes are influenced by variations in mass, energy and information flows, and this self-evidently includes human activity. These azonal chapters deal with land systems that are larger than individual slopes, stream reaches and pocket beaches, but generally smaller than continental-scale regions. By comparison, the zonal chapters use whole biomes as their organising principle, similar to those used in the Millennium Ecosystem Assessment (2003) (Plate 3). In these chapters also, environmental change is driven, not only by hydroclimate, relief and sea level but also by human activity.

In addition to understanding the terrestrial distribution of biomes, it is also important to recognise the broad limits to coral reef and associated shallow water ecosystems, such that the upper ocean’s vulnerability to global environmental change can also be assessed (Fig. 1.7).

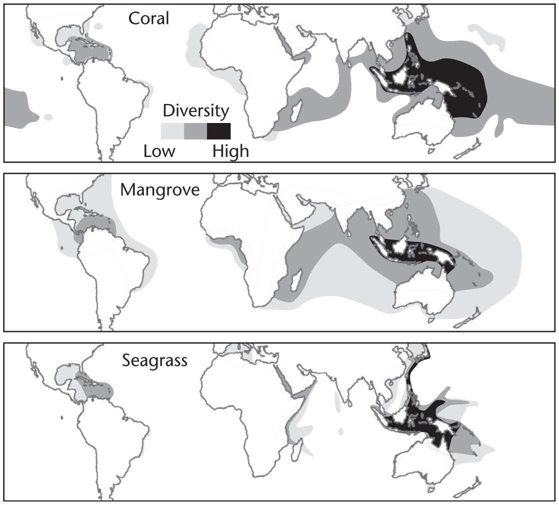

FIGURE 1.7. Global distribution of coral reefs, mangroves and seagrass. Scale of diversity ranges from 0–10 genera (low); 10–25 genera (medium); and >50 (high) (modified from Veron, 1995).

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The decision to structure the book chapters using a bottom–up (azonal) and a top–down (zonal) approach reflects the fact that both approaches have complementary strengths.

1.5 Landscape change

Geomorphology emphasises landscape change under the influence of climate, relief, sea level change and human activity (Chorley *et al*., 1984) and does so at a range of space and timescales. With respect to temporal scales, attention is confined in this volume to the last complete glacial–interglacial cycle and forward towards the end of the twenty-first century (Fig. 1.8). The reasons for the selection of these end points are that they include one complete glacial–interglacial cycle (see Chapter 14), and thus the widest range of climates and sea levels in recent Earth history. This period includes the rise of *Homo sapiens sapiens*; and extends forward to a time when future landscapes can be modelled with some confidence and for which credible scenarios of landscape change can be constructed.

Included in this timescale are the closing stages of the Pleistocene Epoch (150 000 to 10 000 years ago); the Holocene Epoch (10 000 years BP until the present) and a recent, more informally defined, Anthropocene, extending from about 300 years ago when human impact on the landscape became more evident, and into the near future. The comprehensive ice core records from Greenland (GISP and GRIP) and from Antarctica (Vostok and EPICA) (Petit *et al*., 1999; EPICA, 2004) (Fig. 1.8); lake sediments from southern Germany (Ammersee) (Burroughs, 2005) (Fig. 1.9) and elsewhere; and a number of major reconstructions of the climate of the last 20 000 years using past scenarios (Plates 1 and 2) provide a well-authenticated record of the Earth's recent climatic history.

The record of changing ice cover and biomes since the Last Glacial Maximum (LGM) has been reconstructed by an international team of scientists working under the general direction of the Commission for the Geological Map of the World (Petit-Maire and Bouysse, 1999; Plates 1 and 2). The authors stress that the maps are tentative but contain the best information that was available in 1999. The maps depict the state of the globe during the two most

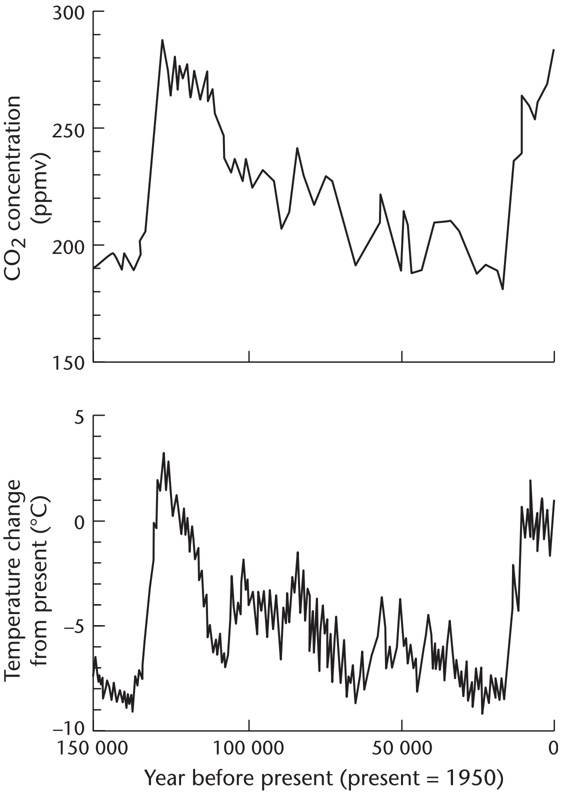

FIGURE 1.8. Climate records from East Antarctica (Vostok ice core) covering the last glacial–interglacial cycle (modified from Petit *et al*., 1999). Note the rapid warming followed by a gentler, stepped cooling process and also the close correlation of temperature and CO_2.

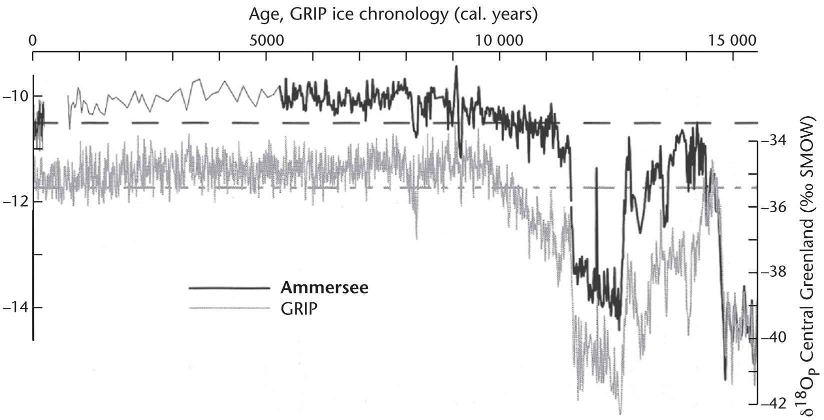

FIGURE 1.9. A comparison of the record from Ammersee, in southern Germany, and the GRIP ice core from Greenland showing the close correlation between the Younger Dryas cold event from 12.9 to 11.6 ka BP at the two sites (from von Grafenstein *et al*., 1999).

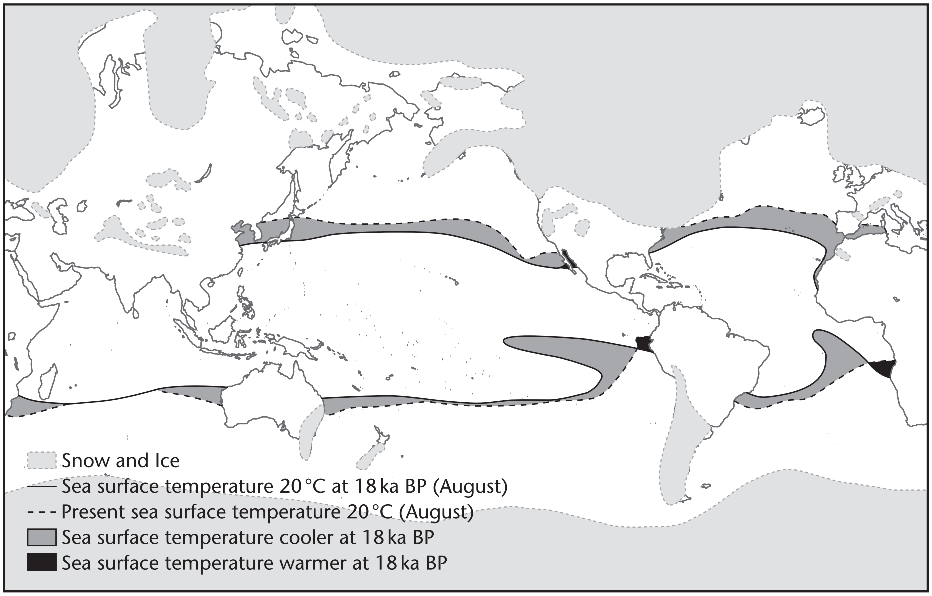

FIGURE 1.10. Changing tropical ocean temperatures, LGM to present (modified from CLIMAP, 1976 and Spencer, 1990).

contrasted periods of the last 20 ka. The LGM was the coldest (*c.* 18 ka ± 2 ka BP) and the Holocene Optimum (HOP) was the warmest (*c.* 8 ka ± 1 ka BP) period. These periods were only 10 ka apart and yet there was a dramatic reorganisation of the shorelines, ice cover, permafrost, arid zones, surface hydrology and vegetation at the Earth's surface over that interval. Thus within a 10-ka time-span (in many places less) the two vast ice sheets of Canada and Eurasia, which reached a height of 4 km and covered about 25 million km^2, disappeared; 20 million km^2 of continental platform were submerged by the sea; biomes of continental scale were transformed and replaced by new ones; and humans could no longer walk from Asia to America nor from New Guinea to Australia nor from France to England.

It is also interesting to compare these shifts in the terrestrial landscape with change in sea surface temperatures over the same period of time. In particular, in the tropical oceans, these changes were relatively small – as illustrated by the change in the 20 ºC isotherm (which provides a broad limit to coral growth) – with the greatest changes being in the variable strength of the equatorial upwelling systems on the eastern margins of the ocean basins (Fig. 1.10).

1.5.1 The Last Glacial Maximum

First of all, there needs to be a caveat with respect to the timing of the LGM (Plate 1). There is strong evidence that the maximum extent of ice was reached in different places at different times. The ice distribution that is mapped corresponds to the maximum extent during the time interval 22 ka to 14 ka years BP, which covers the global range within which the maximum is believed to have occurred. During the LGM, mean global temperature was at least 4.5 °C colder than present. Permafrost extended southwards to latitudes of 40–44º N in the northern hemisphere (although in the south, only Patagonia and the South Island of New Zealand experienced permafrost). Mean sea level was approximately 125 m lower than at present. Large areas of continental shelf were above sea level and colonised by terrestrial vegetation, particularly off eastern Siberia and Alaska, Argentina, and eastern and southern Asia. New Guinea was connected to Australia, the Persian Gulf dried up and the Black Sea, cut off from the Mediterranean Sea, became a lake.

There was a general decrease in rainfall near the tropics. Loess was widespread in periglacial areas and dunes in semi-arid and arid regions. All desert areas were larger than today but in the Sahara there was the greatest southward extension of about 300–400 km. Surface hydrology reflected this global aridity except in areas that received meltwaters from major ice caps, such as the Caspian and Aral seas. Grasslands, steppes and savannas expanded at the expense of forests.

1.5.2 The record from the ice caps and lake sediments

The transition between the LGM and the Holocene was marked by a partial collapse of the Laurentide/Eurasian ice sheets. This led to a surge of icebergs, recorded in the sediments of the North Atlantic by the last of the so-called Heinrich events (thick accumulations of ice-rafted sediments) around 16.5 ka. There followed a profound warming around 14.5 ka (Fig. 1.9) which coincided with a rapid rise in sea level (see Section 1.7), presumably associated with the break-up of part of the Antarctic ice sheet (Burroughs, 2005).

Between 14.5 and 12 ka BP the mean annual temperature oscillated violently and between 12.9 and 11.6 ka the last great cooling of the ice age (known as the Younger Dryas stade) occurred. Rapid warming continued until around 10 ka but thereafter, the climate seems to have settled into what looks like an extraordinarily quiet phase when compared with the earlier upheavals. The Holocene Epoch is conventionally said to start around 10 ka because the bulk of the ice sheet melt had occurred by that time, but the Laurentide ice sheet, for example, did not disappear until 6 ka BP.

Although climatic fluctuations during the Holocene have been much more modest than those which occurred during the previous 10 ka, there have been fluctuations which have affected glacier distribution in the mountains, treeline limits in the mountains and in the polar regions, and desiccation of the Sahara. The CASTINE project (Climatic Assessment of Transient Instabilities in the Natural Environment) has identified at least four periods of rapid climate change during the Holocene, namely 9–8 ka; 6–5 ka; 3.5–2.5 ka and since 0.6 ka. In terms of landscape history, it is also important to recognise that the mean global temperature may not be the most significant factor in landscape change. Precipitation amounts and soil moisture availability and their variability of occurrence and intensity over space and through time have had a strong influence on regional and local landscape evolution.

1.5.3 The Holocene Optimum

A caveat also needs to be applied with respect to the timing of the HOP (Plate 2). The maximum values of the signals for each of the various indicators of environmental change are far from being coeval. During the HOP, the mean global temperature was about 2 °C warmer than today. By 6 ka BP, mean relative land and sea level was close to that of the present day except in two kinds of environments:

(a) the Canadian Arctic and the Baltic Sea where isostatic (land level rebound after ice sheet load removal) adjustments were at a maximum;
(b) deltas of large rivers, such as the Mississippi, Amazon, Euphrates–Tigris and Yangtze, had not reached their present extent.

The glacier and ice sheet cover cannot be distinguished from that of today at this global scale. Permafrost, both continuous and discontinuous, was within the present boundary of continuous permafrost in the northern hemisphere. Significantly wetter conditions were experienced in the Sahara, the Arabian Peninsula, Rajasthan, Natal, China and Australia, where many lakes that have subsequently disappeared were formed. In Canada the Great Lakes were formed following the melting of the ice sheet and the isostatic readjustment of the land. Rainforest had recolonised extensive areas and the taiga and boreal forest had replaced a large part of the tundra and areas previously covered by ice sheets (Petit-Maire, 1999).

This time-span of 20 000 years has been selected in order to encapsulate the extremes of mean global cold and warmth experienced between the LGM and the HOP, a range that one might expect to contain most of the reasonable scenarios of environmental change over the next 100 years. Certainly, this range defines the ‘natural’ variability of Earth’s landscapes but, notably, little distinctive human impact was discernible at this global scale of analysis.

Recently, however, Ruddiman (2005) has claimed to recognise the effects of human activity in reversing the trends of CO_2 and methane concentrations around 8–5 ka BP. His hypothesis is that clearing of the land for agriculture and intensification of land use during the Holocene has so altered the climate as to delay the arrival of the next glacial episode. This is a controversial hypothesis which requires further testing. If the hypothesis is supported, it emphasises the importance of the warning issued by Steffen *et al.* (2004) against the use of Pleistocene and Holocene analogues to interpret the Anthropocene, the contemporary epoch which is increasingly dominated by human activity and is therefore a ‘no analogue’ situation.

1.6 Systemic drivers of global environmental change (I): hydroclimate and runoff

1.6.1 Introduction

Water plays a key role in the transfer of mass and energy within the Earth system. Incoming solar radiation drives the evaporation of approximately 425×10^3 km^3 a^{-1} of water from the ocean surface and approximately 71×10^3 km^3 a^{-1} from the land surface; precipitation delivers about 385×10^3 km^3 a^{-1} of water to the ocean and 111×10^3 km^3 a^{-1} to the land surface. The balance is redressed through the flow of 40×10^3 km^3 a^{-1} of water from the land to the oceans in rivers (Berner and Berner, 1996). Global environmental change affecting any one of these water transfers will lead

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to changes in runoff and river flows. However, the prediction of changes may not be simple because the role of hydrological processes in the land surface system is complex and involves interactions and feedbacks between the atmosphere, lithosphere and vegetation.

The hydrological cycle is affected by changes in global climate, but also by changes that typically occur on a smaller, regional scale, such as changes in vegetation type and land use (for example the change from forest to agricultural pasture land) and changes in land management. These latter changes may also include reservoir construction, abstractions of water for human use, and discharges of water into river courses and the ocean.

Increasing atmospheric carbon dioxide levels and temperature are intensifying the global hydrological cycle, leading to a net increase in rainfall, runoff and evapotranspiration (Huntingdon, 2006). Changes are projected to occur not only to mean precipitation and runoff, but also to their spatial patterns. Within the tropics, precipitation rates increased between 1900 and 1950 but have declined since 1970. In contrast, mid-latitude regions have seen a more consistent increase in precipitation since 1900 (IPCC, 2007a).

The intensification of the hydrological cycle is likely to mean an increase in hydrological extremes (IPCC, 2001a). Changes to the frequency distribution of rainfalls and flows of different magnitude can have a disproportionately large effect on environmental systems such as river basins, vegetation and aquatic habitats. The reason for this disproportionality is because extreme flows provoke changes when certain thresholds in magnitude or in the duration of runoff are exceeded. There are suggestions that interannual variability will increase, with an intensification of the natural El Niño and North Atlantic Oscillation (NAO) cycles, leading to more droughts and large-scale flooding events. Key questions that this section will address include:

(a) what changes in precipitation, evaporation and consequent runoff have been observed over the historical period; and
(b) what changes are projected under future climate and land use scenarios.

1.6.2 Observed changes in precipitation, evaporation, runoff and streamflow

Surface temperatures

Global mean surface temperatures have increased by 0.74 ºC ± 0.18 ºC over the period 1906–2005, although the rate of warming in the last 50 years of that period has been almost double that over the last 100 years (IPCC, 2007a). With this change in surface temperature comes the theoretical projection that warming will stimulate evaporation and in turn precipitation, leading to an intensified hydrological cycle. In the earliest known theoretical work on the subject, Arrhenius (1896) showed that specific humidity would increase roughly exponentially with air temperature according to the Clausius–Clapeyron relation. Numerical modelling studies have since indicated that changes in the overall intensity of the hydrological cycle are controlled not only by the availability of moisture but also by the ability of the troposphere to radiate away latent heat released by precipitation. An increase in temperature of 1 Kelvin would lead to an increase in the moisture-holding capacity of the atmosphere by approximately 3.4% (Allen and Ingram, 2002). The convergence of increased moisture in weather systems leads to more intense precipitation; however the frequency or duration of intense precipitation events must decrease because the overall amount of water does not change a great deal (IPCC, 2007a).

Pollutant aerosols

In addition to the effects of temperature increases, the effects of pollutant aerosols can be significant. Increases in sulphate, mineral dust and black carbon can suppress rainfall in polluted areas by increasing the number of cloud condensation nuclei. This leads to a reduction in the mean size of cloud droplets and reduces the efficiency of the process whereby cloud droplets coalesce into raindrops (Ramanathan *et al.*, 2001). An additional effect of increased atmospheric aerosol loading is a reduction in the amount of solar radiation that reaches the land surface; this may affect the amount of evaporation and therefore precipitation. The effects of aerosol loading are expected to be highest in highly polluted areas such as China and India and evidence is emerging that aerosol loading may explain the recent tendency towards increased summer flooding in southern China and increased drought in northern China (Menon *et al.*, 2002). Recent analyses indicate that aerosol loading led to a reduction in solar radiation reaching the land surface of 6–9 W m^{-2} (4–6%) between the start of measurements in 1960 and 1990 (Wild *et al.*, 2005). However, between 1991 and 2002, the same authors estimate that the amount of solar radiation reaching the Earth's surface increased by approximately 6 W m^{-2}. This observed shift from dimming to brightening, has prompted Andreae *et al.* (2005) to suggest that the decline of aerosol forcing relative to greenhouse forcing may lead to atmospheric warming at a much higher rate than previously predicted.

Precipitation

Precipitation trends are harder to detect than temperature trends, because the processes that cause precipitation are more highly variable in time and space. Nevertheless, global mean precipitation rates have increased by about 2% over the twentieth century (Hulme *et al.*, 1998). The spatial pattern of trends has been uneven, with much of the increase focussed between 30° N and 85° N. Evidence for a change in the nature of precipitation is reported by Brown (2000), who finds a shift in the amount of snowfall in western North America between 1915 and 1997. Zhang *et al.* (2007) used an ensemble of fourteen climate models to show that the observed changes in the spatial patterns of precipitation between 1925 and 1999 cannot be explained by internal climate variability or natural forcing, but instead are consistent with model projections in which anthropogenic forcing was included.

Runoff

Rates of surface and subsurface runoff depend not just on trends in precipitation, because the water balance for any soil column dictates that runoff is the difference between precipitation and evaporation. When an unlimited amount of water is available at the surface, the rate of evaporation is controlled by the amount of energy available and the water vapour pressure deficit (i.e. the difference between the actual vapour pressure and the vapour pressure at saturation) in the overlying air (Penman, 1948). The amount of energy available depends on the net solar radiation received at the surface. The water vapour pressure deficit depends on the temperature of the air and its specific humidity. The rate of transport of air across the surface exerts a key control on the potential evaporation rate because it determines how readily saturated air is refreshed so that further evaporation can occur. In practice, an unlimited amount of water is available only over persistent open water in oceans, lakes and rivers. Over the land surface, the rate of actual evaporation depends not only on meteorological variables but also on the nature of the vegetation and on the amount of available soil moisture.

Evapotranspiration

Only limited observations of evaporation are available. Sparse records of potential evaporation from evaporation pans show a generally decreasing trend in many regions, including Australia, China, India and the USA (IPCC, 2007a). Roderick and Farquar (2002) demonstrate that the decreasing trends in pan evaporation are likely to be a result of a decrease in surface solar radiation that may be related to increases in atmospheric aerosol pollution. On the other hand, Brutsaert and Parlange (1998) have pointed out that pan evaporation does not represent actual evaporation and that in regions where soil moisture exerts a strong control on actual evaporation any increase in precipitation which drives an increase in soil moisture will also lead to higher rates of actual evaporation.

In any case, at the scale of a river basin, vegetation controls the amount of evaporation from the land surface through its effects on interception and transpiration. A significant fraction of precipitation falling on land can be intercepted by vegetation and subsequently evaporated. The rate of evaporation from intercepted water depends on the vegetation type and structure of the plant canopy; it is normally higher for forest canopies than for grassland. In contrast, transpiration occurs through the evaporation of water through plant stomata. The rate of transpiration depends on available energy and vapour pressure deficit but also on stomatal conductance: the ease with which the stomata of a particular plant species permit evaporation under given environmental conditions. Stomatal conductance depends on light intensity, CO_2 concentration, the difference in vapour pressure between leaf and air, leaf temperature and leaf water content. All of these properties change over timescales relevant to global change, but the most significant variant may be CO_2 concentration (Arnell, 2002).

Increased CO_2 concentration stimulates photosynthesis and may encourage plant growth in some plant species that use the C3 photosynthesis pathway, which includes all trees and most temperate and high-latitude grasses (Arnell, 2002). Carbon dioxide enrichment has the additional effect of reducing stomatal conductance by approximately 20–30% for a doubling of the CO_2 concentration. Thus, for a given set of meteorological conditions, the water use efficiency of plants increases. Considerable uncertainty exists over whether this leaf-scale process can be extrapolated to the catchment scale; in many cases the decreased transpiration caused by CO_2-induced stomatal closure is likely to be offset by additional plant growth (Arnell, 2002).

Trends in streamflow

Only patchy historical data are available to assess global patterns of streamflow. Dai and Trenberth (2002) estimate that only about two-thirds of the land surface has ever been gauged and the length and availability of observed records are highly variable. Detecting trends in streamflow is problematic too, because runoff is a spatially integrated variable which does not easily permit discrimination between changes caused by any of its driving factors. Streamflow and groundwater recharge exhibit a wide range of natural variability and are open to a host of other human or natural influences.

In an analysis of world trends in continental runoff, Probst and Tardy (1987) found an increase of approximately 3% between 1910 and 1975. This trend has been confirmed in a reanalysis of data between 1920 and 1995 by Labat *et al*. (2004). In areas where precipitation has increased over the latter half of the twentieth century, runoff has also increased. This is particularly true over many parts of the USA (Groisman *et al*., 2004). Streamflow records exhibit a wide range of variability on timescales ranging from inter-annual to multi-decadal and for most rivers, secular trends are often small. There is evidence that flood peaks have increased in the USA because increases in surface air temperature have hastened the onset of snowmelt (Hodgkins *et al*., 2003). In many rivers in the Canadian Arctic, earlier break-up of river ice has been observed (Zhang *et al*., 2001).

Caution must be exercised in the interpretation of long-term hydrological trends. Using flow observations made during the last 80–150 years, Mudelsee *et al*. (2003) found a decrease in winter flooding in the Elbe and Oder rivers in Eastern Europe, but no trend in summer flooding. They concluded that the construction of reservoirs and deforestation may have had minor effects on flood frequency. Svensson *et al*. (2006) showed that, in a study of long time series of annual maximum river flows at 195 gauging stations worldwide, there is no statistically significant trend at over 70% of sites. They attributed the lack of a clear signal to the wide ranging natural variability of river flow across multiple time and space scales. Hannaford and Marsh (2006) described a set of benchmark UK catchments defined to represent flow regimes that are relatively undisturbed by anthropogenic influences. Over the past 30–40 years they found a significant trend towards more protracted periods of high flow in the north and west of the UK, although trends in flood magnitude were weaker. However, they pointed out that much of the trend is a result of a shift towards a more positive NAO index since the 1960s. The NAO is a climatic phenomenon in the North Atlantic Ocean and is measured by the difference in sea level pressure between the Icelandic Low and the Azores High. This difference controls the strength and direction of westerly winds and storm tracks across the North Atlantic.

Some component of many observed runoff trends can be explained by changes to environmental properties other than climate. Increases in runoff have resulted from land use change, particularly from the conversion of forest to grassland or agricultural land (Vörösmarty and Sahagian, 2000). The most significant effect of removing trees is the reduction in canopy evaporation; that is, evaporation from water intercepted by the tree canopy and stored on leaves. In the Plynlimon experimental catchments in upland Wales, United Kingdom, Roberts and Crane (1997) found that clearcutting of ~30% of the coniferous forest cover led to an increase in runoff of 6–8%. In snow-dominated catchments, the effects of deforestation are more significant because a large amount of snow is permitted to accumulate if forest is cleared (Troendle and Reuss, 1997). Conversely, abandonment of agricultural land and upland afforestation can reduce the volume of runoff. In the Plynlimon catchments experiment, annual evaporation losses (estimated as the difference between annual precipitation and annual runoff) in the forested Severn catchment were ~200 mm greater than in the grassland Wye catchment. This represents a 15% reduction in the flow (Robinson *et al*., 2000). Most studies of the effects of land cover on the water balance have involved catchment-scale measurements and it is, at present, uncertain whether these findings can be extrapolated to regional and planetary scales.

1.6.3 Projections for future changes

An assessment of the potential impacts of future climate change on precipitation, evaporation, and therefore runoff is a fundamental influence on the strategies adopted by land and river managers. It is impossible to make a reliable prediction of the weather more than about a week in advance, but projections of the statistical properties of future climate can be obtained by using general circulation models (GCMs) to construct climate scenarios (see Section 1.1.4).

Models that encompass an ever-wider range of environmental processes have led to a shift in the goals of climate modelling. Instead of simply providing projections of future average weather, current environmental models provide a powerful tool to examine numerically the complex feedbacks that exist within the Earth system. They have also fuelled studies that fall under the broad title of ‘detection and attribution’, in which historical observed changes in measured environmental variables are partly explained through understanding gained using climate simulations. For example, Gedney *et al*. (2006) attempt to show that statistically significant continent-wide increases in twentieth-century streamflow can be explained by the effect of CO_2-driven stomatal closure on continental-scale transpiration.

In contrast to numerical weather prediction, which is an initial-value problem where governing equations are solved to find the time-evolution of the system given a set of initial conditions, a typical GCM experiment corresponds to a boundary-value problem in mathematics. In a boundary-value problem, boundary conditions for the problem are used to constrain solutions to the governing equations that are consistent with the imposed conditions. For example, the frequency distribution of rainfall magnitudes may be required under different scenarios of atmospheric CO_2 concentration. The detailed trajectory of changes in CO_2 is highly dependent on socioeconomic factors which govern the behaviour of human societies. The IPCC has published a range of plausible alternatives in its Special Report on Emissions Scenarios (SRES) in which the scenarios are defined (Appendix 1.1).

Temperature and precipitation

Globally averaged mean water vapour, evaporation and precipitation are projected to increase with global environmental warming (IPCC, 2007a). Current models indicate that future warming of 1.8–4.0 °C by 2100 (depending on the scenario chosen) will drive increases in precipitation in the tropics and at high latitudes; decreases in precipitation are expected in the subtropics (Plate 4). The intensity of individual precipitation events is predicted to increase, especially in areas seeing greatest increases in mean precipitation, but also in areas where mean precipitation is projected to fall. Summer drying of continental interiors is a consistent feature of model projections (IPCC, 2007a).

Hydroclimate and runoff

Despite some consistent patterns, the spatial response of precipitation to climate change is much more highly variable than that of temperature. Plate 5 shows the spatial pattern of precipitation and other hydrologically related changes projected for the A1B scenario (Appendix 1.1). Runoff is expected to fall in southern Europe and increase in Southeast Asia and at high latitudes. The impact of these changes has been assessed by Nohara *et al.* (2006), who find that in high latitudes river discharge is predicted to increase but in much of Central America, Europe and the Middle East, decreases in river flow are expected.

1.7 Systemic drivers of global environmental change (II): sea level

1.7.1 Introduction

Variations in sea level form part of a complex set of relations between atmosphere–ocean dynamics, ice sheets and the solid Earth, all of which have different response timescales. Thus changes in sea level resulting from global environmental change are, on the one hand, masked by shorter-term variations in the elevation of the sea surface. These fluctuations can be considerable: El Niño–Southern Oscillation (ENSO)-related inter-annual changes in ocean level in the western Pacific Ocean are ~45 cm (Philander, 1990), of comparable magnitude to many estimates of the magnitude of sea level rise to 2100. Furthermore, near-future sea level changes will take place against a backdrop of ongoing geological processes. The geographical variability in Holocene sea level histories has been well established (e.g. Pirazzoli, 1991) and geophysical models have identified large-scale sea level zones, with typical sea level curves, for the near- (Zone I), intermediate- (Zone II) and far-fields (Zones III–VI) in relation to former ice sheets (Clark *et al.*, 1978) (Fig. 1.11).

These differences have implications for future coastal vulnerabilities. Some coasts (in Zones IV and V for example) will have adjusted to coastal processes operating at present, or close to present, sea level for at least 5000 years whereas other regions (Zone II for example) will only have experienced present sea level being reached within the last 1000 years.

At the inter-ocean basin scale, coral reef systems in the Indo-Pacific Reef Province lie in the far-field, with near present sea level being reached at ~6 ka BP. Thereafter, hydro-isostatic adjustments and meltwater migration back to former ice margins, and in some cases local tectonics, resulted in a mid-Holocene sea level high of ~ +1 m, followed by a gradual fall to present mean sea level (Fig. 1.11). In the western Indian Ocean, sea level rose rapidly (6 mm a^{-1}) until 7.5 ka BP then dramatically slowed (to ~1 mm a^{-1}), with near present sea level being attained at 3.0–2.5 ka BP (Camoin *et al.*, 2004); however, in the central and eastern Indian Ocean a mid-Holocene high

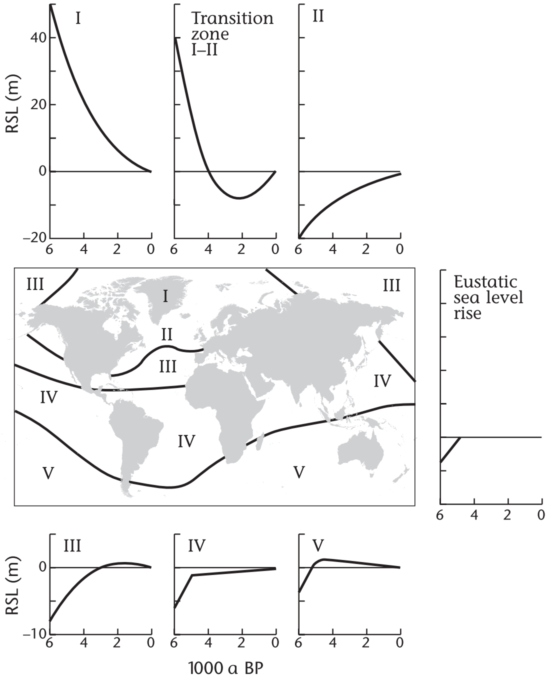

FIGURE 1.11. Sea level regions and associated sea level curves, 6–0 ka BP, assuming no eustatic component after 5 ka BP. RSL, relative sea level (modified from Clark *et al.*, 1978).

stand of ~ +0.5 m has been reported (Woodroffe, 2005; P. Kench, personal communication, 2007). By contrast, the reefs of the Atlantic Reef Province lie within the intermediate field and experienced a decelerating rate of sea level rise through the Holocene, with present sea level being reached only within the last 1000 years (Toscano and Macintyre, 2003) (Fig. 1.11). These different sea level histories go some way to explaining the gross morphological differences between reef provinces. Thus Indo-Pacific reef margins are generally characterised by wide, low-tide-emergent reef flats and, in some locations, by supratidal conglomerates and raised reef deposits. By contrast, in the Atlantic reef province, emergent reef features are lacking and relatively narrow reef crests are backed by shallow backreef environments and lagoons. These differences are of importance: as sea level rises, near-future reef responses will take place over these different topographies.

Finally, at the within-region scale, continuing adjustments to the unloading of ice, reflooding of shallow shelf seas and sedimentation in coastal lowlands in the British Isles since the Last Glacial Maximum have resulted in maximum rates of land uplift of ~1.5 mm a^{-1} on coasts in western Scotland but corresponding maximum subsidence of –0.85 mm a^{-1} on the Essex coast of eastern England (Shennan and Horton, 2002). In Scotland, therefore, sea level rise will be partially offset by uplift whereas in south-east England sea level rise will be additive to existing rates of relative rise.

Long-term trends in coastal erosion – such as along the eastern seaboard of the USA where 75% of the shoreline removed from the influence of spits, tidal inlets, and engineering structures is eroding (Zhang, 2004) and the eastern coastline of the UK where 67% of the shoreline length has retreated landward of the low-water mark (Taylor *et al.*, 2004) – can be reasonably associated with sea level rise over the last 100–150 years. The exact linkage, however, is most probably more event-based. Komar and Allan (2007) have identified increased ocean wave heights along the eastern seaboard of the USA and related them to an intensification of hurricane activity from the late 1990s; they have also argued that increased erosion along the US west coast since the 1970s has been associated with increasing wave heights due to higher water levels and storm intensities (Allan and Komar, 2006). In addition to sea level change and its variability, coastal erosion is also driven by other natural factors, including sediment supply and local land subsidence. Anthropogenic activities can intensify these controls on coastal change. Finally, the impact of such processes depends upon the ability of coastal landforms to migrate to new locations in the coastal zone and to occupy the accommodation space that becomes available (or not) to them (Fitzgerald *et al.*, 2008). These issues, and many more, are dealt with in Chapters 5, 6 and 7.

1.7.2 Recent sea level rise

Global sea level has been rising at a rate of ~1.7–1.8 mm a^{-1} over the last century, with an acceleration of ~3 mm a^{-1} during the last decade (Church *et al.*, 2004; Church and White, 2006) (Fig. 1.12). The total twentieth-century rise was 0.17 ± 0.05 m (IPCC, 2007a).

Observations since 1961 indicate that the oceans have been absorbing 80% of the heat added to the climate system, causing the expansion of seawater and perhaps

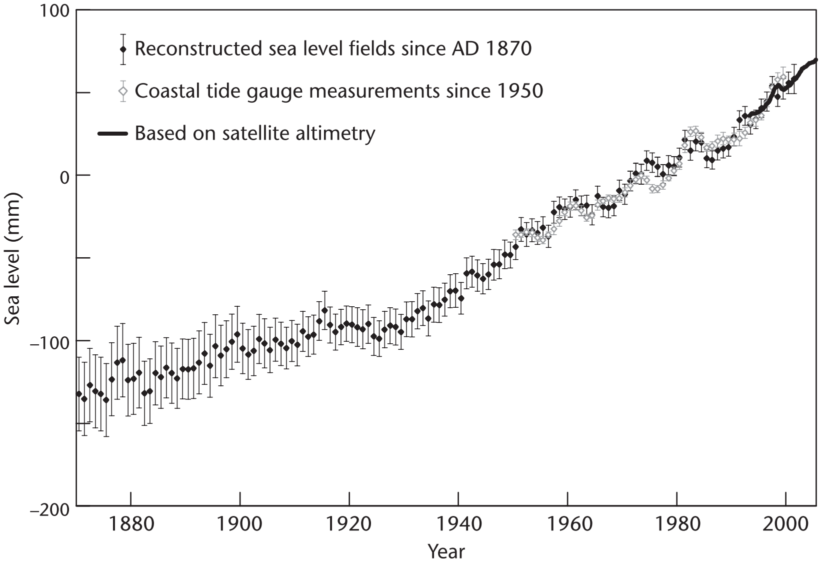

FIGURE 1.12. Annual averages of global mean sea level (mm), 1870–2003. Sea level fields have been reconstructed since 1870; coastal tide gauge measurements are available since 1950; and altimetry estimates date from 1993.

TABLE 1.1. *Observed rate of sea level rise and estimated contributions from different sources, 1961–2003 and 1993–2003*

Source of sea level rise	Rate of sea level rise (mm a^{-1})[a] 1961–2003	1993–2003
Thermal expansion	0.42 ± 0.12	1.6 ± 0.5
Glaciers and ice caps	0.50 ± 0.18	0.77 ± 0.22
Greenland ice sheet	0.05 ± 0.12	0.21 ± 0.35
Antarctic ice sheet	0.14 ± 0.41	0.21 ± 0.35
Sum of individual climate contributions to sea level rise	1.1 ± 0.5	2.8 ± 0.7
Observed total sea level rise	1.8 ± 0.5	3.1 ± 0.7
Difference (observed minus sum of estimated climate contributions)	0.7 ± 0.7	0.3 ± 1.0

[a] Data prior to 1993 are from tide gauges and after 1993 are from satellite altimetry.

Source: From IPCC (2007a).

TABLE 1.2. *Projected globally averaged surface warming and sea level rise at the end of the twenty-first century*

Case	Temperature change (°C at 2090–2099 relative to 1980–1999)[a] Best estimate	Likely range	Sea level rise (m at 2090–2099 relative to 1980–1999) Model-based range excluding future rapid dynamical changes in ice flow
Constant Year 2000 concentrations[b]	0.6	0.3–0.9	NA
B1 scenario	1.8	1.1–2.9	0.18–0.38
A1T scenario	2.4	1.4–3.8	0.20–0.45
B2 scenario	2.4	1.4–3.8	0.20–0.43
A1B scenario	2.8	1.7–4.4	0.21–0.48
A2 scenario	3.4	2.0–5.4	0.23–0.51
A1FI scenario	4.0	2.4–6.4	0.26–0.59

[a] These estimates are assessed from a hierarchy of models that encompass a simple climate model, several Earth Models of Intermediate Complexity (EMICs) and a large number of Atmosphere–Ocean General Circulation Models (AOGCMs).
[b] Year 2000 constant composition is derived from AOGCMs only.

Source: From IPCC (2007a).

explaining half the observed global sea level rise since 1993 (Table 1.1), although with considerable decadal variability (IPCC, 2007a). Smaller component contributions are estimated to have come from glacier and ice cap shrinkage and, with less certainty, from the Greenland, and particularly, the Antarctic ice sheets. There is, however, no consensus on Antarctica. The balance of opinion appears to be for a shrinking West Antarctic ice sheet and a growing East Antarctic ice sheet, leading to a near-neutral effect (possibly perturbed by ice shelf losses on the Antarctic Peninsula). It should be noted, however, that the fit between estimated and actual sea level rise over the much longer period 1961–2003 is poor (Table 1.1).

This may partly be a function of the change in the measurement base after 1993, to satellite altimetry and away from tide gauge records. In the latter case, water level records are complicated by local vertical land movements, driven by glacial isostatic adjustments, neotectonics and/or subsurface fluid withdrawal, which need to be subtracted from the water level record. An additional uncertainty is that knowledge of changes in the storage of water on land (from extraction and increases in dams and reservoirs) remains poor. However, it is also not clear to what extent the sea level record reflects secular rise and to what extent it is a measure of regional inter-annual to inter-decadal climate variability from phenomena such as ENSO, the NAO and Pacific Decadal Oscillation (PDO) (Woodworth *et al.*, 2005) the effects of which are also strongly spatially variable (Church *et al.*, 2004). Thus, for example, elevated sea levels and anomalously high sea surface temperatures in the Pacific Ocean were closely correlated during the major 1997–1998 El Niño event (Allan and Komar, 2006). It appears likely that this variability also underpins the relations between coastal and global sea level rise, with faster coastal rise typical of the 1990s and around 1970 and faster ocean rise during the late 1970s and late 1980s (White *et al.*, 2005).

1.7.3 Future sea level rise

The average rate of sea level rise throughout the twenty-first century is likely to exceed the rate of 1.8 mm a^{-1} recorded over the period 1961–2003. For the period 2090–2099, the central estimate of the rate of sea level rise is predicted to be 3.8 mm a^{-1} under scenario A1B (Appendix 1.1) (the scenario spread is in any case small: Table 1.2), comparable to the observed rate of sea level rise 1993–2003, a period thought to contain strong positive

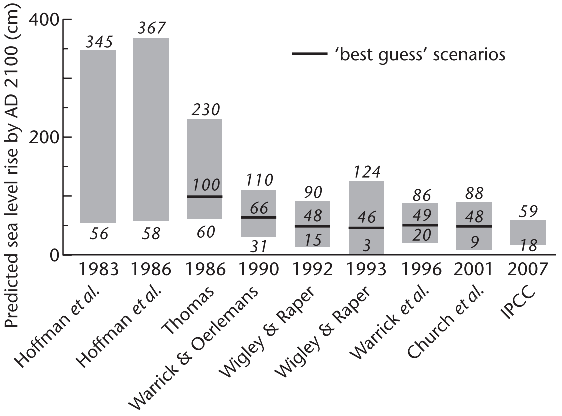

FIGURE 1.13. Changing estimates of the range of potential sea level rise to 2100 (predictions in the period 1983–2001) or 2099 (data from IPCC 2007a).

residuals within the long-term pattern of sea level variability. Under the A1B scenario, by the mid-2090s sea level rises by +0.22 to +0.44 m above 1990 levels, at a rate of 4 mm a^{-1}. The thermal expansion term accounts for 70–75% of the total rise, being equivalent to a sea level rise of 2.9 ± 1.4 mm a^{-1} in the period 2080–2100 (IPCC, 2007a).

In terms of the history of sea level rise projections, the IPCC Fourth Assessment predictions appear to suggest a further reduction in the expected rate of sea level rise (Fig. 1.13). However, these new projections do not allow for a contribution from ice flow from the Greenland and Antarctic ice sheets. Conservative estimates suggest that accelerated ice flow rates might add +0.1 to +0.2 m to the upper range of sea level rise (i.e. a sea level rise of up to 0.79 m under scenario A1FI: Appendix 1.1).

Non-model-based estimates of future sea level rise, based upon a semi-empirical relationship connecting temperature change and sea level rise through a proportionality constant of 3.4 mm a^{-1} per °C, suggest a potential rise at 2100 of 0.5 to 1.4 m (Rahmstorf, 2007), although this methodology has been highly contested.

1.8 Cumulative drivers of global environmental change (I): topographic relief

1.8.1 Introduction

By contrast with hydroclimate and sea level changes, relief and human activity (Section 1.9) are discontinuous both over space and through time. The implications of this simple fact are profound. Spatial discontinuities dictate that certain parts of the landscape are more sensitive to the drivers of change than others; temporal discontinuities mean that very old and very young landscape elements can exist side by side (Fig. 1.5). Global impact then becomes the net effect of change at a large number of disparate sites. A further implication is that the geomorphologist is best suited to identify those aspects of the landscape which are particularly sensitive to disturbance.

1.8.2 The sediment cascade

Continental-scale relief defines a pathway from the highest mountains to the ocean; local-scale relief, with associated sinks, defines a complex of pathways which can be best described by the term 'sediment cascade'. The type and rate of weathering, erosion and denudation are profoundly controlled by these pathways, which ultimately owe their variety to relief at a wide range of scales.

Weathering is the alteration by atmospheric and biological agents of rocks and minerals. The physical, mineralogical and chemical characteristics of the materials are modified so that these weathering products can be removed by either mechanical or biochemical erosion. Mechanical and biochemical erosion involves mobilisation, transport and export of rock and soil materials (Fig. 1.14a). Surface and subsurface water is critical to these processes. How much of these so-called 'clastic' sediments are broken up into their constituent chemical elements, the extent to which these elements have become combined with nutrients and the amount of comparatively unchanged rocks and minerals depends on the type and rate of weathering. The sediment which is exported is engaged to a greater or lesser extent in exchange processes between minerals, solutes and nutrients.

Primary sediment mobilisation can usefully be divided into 'normal regime' processes that are more or less pervasive and occur regularly, and episodic or 'catastrophic' events which occur less frequently. The former include soil creep, tree throw, surface disturbance by animals and surface erosion from exposed soils; the latter include rockfalls, rockslides, earthflows, landslides, debris avalanches and debris flows.

Sediment transport requires both a supply of transportable sediment and runoff competent to entrain the sediment. Sediments in suspension and bedload have the greatest influence on river channel form, whereas solutes, nutrients and pollutants are important indices of biogeochemical cycling processes.

The sediment cascade involves inputs and outputs with delays caused by: rates of rock breakdown, intermittent sediment mobilising events, the limited capacity of the flows to entrain sediment, and trapping points that occur downstream, so that sediment is intercepted and

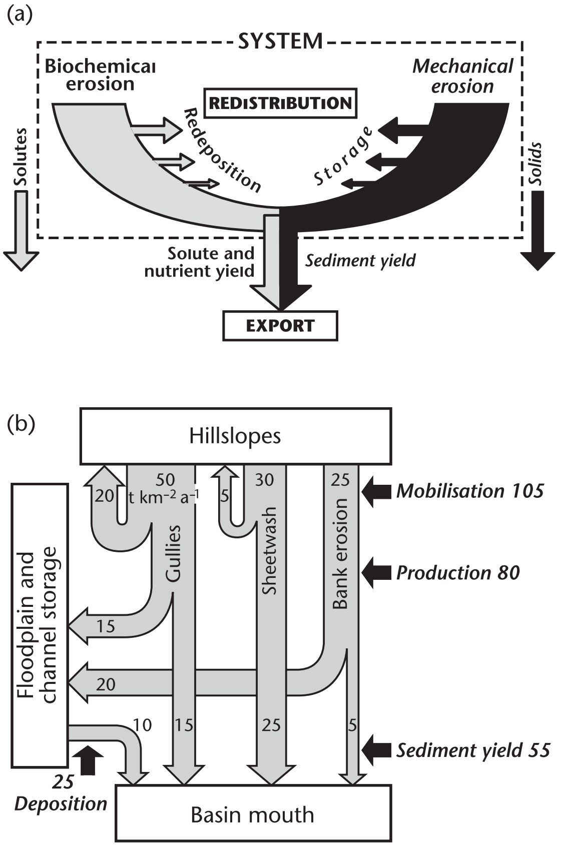

FIGURE 1.14. (a) The sediment cascade system from biochemical and mechanical weathering sources to export of sediment, solutes and nutrients. (b) Relations between sediment mobilisation, production, deposition and yield. Line widths are proportional to the amount of sediment transferred and values are shown in t km^{-2} a^{-1}. An average of 105 t km^{-2} a^{-1} is mobilised on hillslopes and only 55 t km^{-2} a^{-1} is exported from the basin (from Reid and Dunne, 1996).

remobilised at a later time. Sediment in a drainage system thus moves through a cascade of reservoirs (Fig. 1.14b).

This simple picture is distorted by the fact that sediment transport is also a sorting process. Mixtures of sedimentary particles of differing size and density segregate in the cascade into subpopulations with different transit times through the landscape. In the case of disturbance, there is a spatial complication in that the sediments have diffuse sources. The sedimentary signal originating in the uppermost part of the basin may move through a reach subject to similar disturbance and be reinforced. But at downstream points, if the disturbance is of varying intensity, the reinforcement will vary spatially. Sediment on its way from source to sink gets sidetracked in a number of ways, not only into channel and floodplain storage but also into other hillslope locations (Fig. 1.14b).

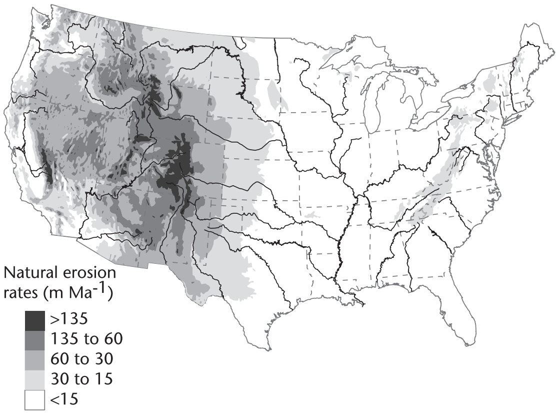

FIGURE 1.15. Estimates of average natural erosion (denudation) rates inferred from GTOPO30 area–elevation data and global fluvial erosion–elevation relations from Summerfield and Hulton (1994) (from Wilkinson and McElroy, 2007). Units are in metres of denudation per million years.

1.8.3 Topographic relief and denudation

In spite of the variety of ways in which sediment is delayed on its way to the ocean, there are extensive data sets that demonstrate a close relationship between topographic relief and rates of fluvial erosion. With the increasing availability of digital elevation models, it has also become possible to infer average natural erosion rates, as illustrated in Fig. 1.15 for the conterminous USA. The units used may be unfamiliar as they are given in metres of denudation per million years, but the main message of the map is that relief is a strong driver of landscape change (see Chapter 2 for an expansion of this theme and discussion of shortcomings of this generalisation).

1.8.4 The sediment budget

In order to account for the sources, pathways of movement and rates of delivery of sediments along coasts and through river basins, a method of budgeting of sediments has been developed. A river basin sediment budget is ‘an accounting of the sources and disposition of sediment as it travels from its point of origin to its eventual exit from a drainage basin’ (Reid and Dunne, 1996).

If the sediment budget is balanced, the residual will be zero. Thus the sediment budget can be expressed as

$$I - O = \Delta S \qquad (1.1)$$

where I is input, O is output and ΔS is change of storage over the time period of measurement. This equation will hold for any landform or landscape as long as the budget cell can be unambiguously defined. In the case of the river basin, the budget cell defines itself. But Cowell *et al.* (2003), for example, in working with the problem of determining an objective budget cell in coastal studies, have coined the term ‘coastal tract’. They define the coastal tract as the morphological composite comprising the lower shoreface, upper shoreface and back barrier. They use this framework in defining boundary conditions and internal dynamics to separate low-order from higher-order coastal behaviour (see Chapter 6 for further details).

The sediment budget is a mass-balance-based approach, which necessarily, in principle, includes a consideration of water, sediments, chemical elements and nutrients. This accounting of sources, sinks and redistribution pathways of sediments in a unit region over unit time is a complex exercise (Dietrich and Dunne, 1978). The primary application of sediment budgets to landscapes is in the accounting of clastic sediment transfers because clastic sediments provide the most direct indication of changing surface form. The US Corps of Engineers working on the coasts of southern California and New Jersey and geomorphologists working in the Swiss Alps and northern Scandinavia were the first to employ this methodology in coastal and river basin geomorphology in the 1950s.

Sediment budget studies have become a fundamental element of coastal, drainage basin and regional management, but only when somewhat simplified (Reid and Dunne, 1996). They can be formulated to aid in the design of a project, characterise sediment transport patterns and magnitudes and determine a project’s erosion or accretionary impacts on adjacent beaches and inlets (Komar, 1998). Although Trimble (1995) and Inman and Jenkins (1999) have developed flexible models to discriminate the effects of climate change and land use activities on sediment budgets, their application is at an early stage.

In conclusion, the growing interest in global environmental change has spurred interest in a variety of mass-balance calculations that permit quantitative comparisons from one region to another and from one time period to another, with appropriate scaling. The biggest challenge in the use of sediment budgets is in making the link between intensively studied smaller-scale systems to the global scale and in extrapolating from the short term to the longer term and future changes.

1.8.5 Limitations of the sediment budget approach in determining the role of relief

1. Summerfield and Hulton (1994) demonstrated that 60% (but no more) of the spatial variation of global sediment yield can be explained by relief and runoff.
2. The sediment budget approach often ignores the role of tectonics. This is unfortunate because the uplift of mountain ranges involves the input of new mass which directly influences the mass balance of the geosystem. When longer term studies of sediment flux are undertaken, it is essential to incorporate the style and rate of tectonic processes (see Chapter 15).
3. Global riverine changes such as chemical contamination, acidification, and eutrophication which are of great interest in global environmental change are rarely included in sediment budgets (see Chapter 3).
4. Order of magnitude effects produced by global-scale river damming (Nilsson *et al.*, 2005) and general decrease of river flow due to irrigation (Meybeck and Vörösmarty, 2005) scarcely require sediment budgeting (see Chapter 4).
5. Recent studies of the Ob and Yenisei rivers in Russia (Bobrovitskaya *et al.*, 2003) and of the Huanghe River in China (Wang *et al.*, 2007) suggest that the decline in sediment load delivered to the sea in recent years is caused primarily by soil conservation practices and reservoir construction; relief and runoff have relatively little influence.
6. These observations lead logically to an analysis of the critical role of human activity.

1.9 Cumulative drivers of global environmental change (II): human activity

Global population growth and the attendant land cover and land use changes pose serious challenges for management and planning in the face of global environmental change (Lambin and Geist, 2006). Wasson (1994) has emphasised the value of mapping past land use and land cover changes in attempting to interpret contemporary landscape change and degradation. De Moor *et al.* (2008) have demonstrated that in the past 2000 years, the impact of climate on river systems can be neglected when compared with the human impact. They link the considerable changes in hillslope processes induced by humans with equivalent sediment supply to the river valleys of the Netherlands. Factors that influence land cover and land use change can be divided into indirect and direct factors.

1.9.1 Indirect factors

Indirect factors include such broadly contextual factors as demographic change, socioeconomic, cultural and religious practices and global trade, which enhance the importance of governance *sensu lato*. The indirect drivers are of critical importance when we come to discuss scenario building (Appendix 1.1) in the sense that population level and density, socioeconomic context, societal values and the institutions available to implement change must all be incorporated into any forward-looking thinking.

Population growth

The history of humans as geomorphic agents is now becoming clear. Virtually all of Earth's biomes have been significantly transformed by human activity because of the enormous growth of the world's population during the second half of the twentieth century and the even more rapid growth in energy use (Turner *et al.*, 1990a). Some 80% of humankind lives in developing countries in Asia, Africa and South and Middle America and those countries account for more than 90% of the more than 100 million births each year. These populations are becoming increasingly urbanised; thus whilst only 3% of the population of less developed regions lived in cities larger than 100 000 inhabitants in 1920, this figure is set to rise to 56% by 2030. By 2015, Asia is predicted to have 1.02 billion people in urban centres of over 500 000 inhabitants. Many of these populations are being squeezed into narrow coastal and estuarine margins. Several of the fastest-growing cities, with rates of increase of up to +4% per year and all projected to have populations in excess of 15 million by 2015, have long histories of exposure to coastal hazards; they include Shanghai, Kolkata, Dhaka and Jakarta (United Nations Population Fund, 2007).

As a result, the biomes shown in Plate 3 are actually an abstract depiction of the climax vegetation in the absence of human intervention. Only in the areas unmodified by agriculture, forestry and urbanisation do these biomes correspond to the terrestrial ecosystems of today.

Socioeconomic context of soil degradation

If land loss continues at current rates, an additional 750 000–1.8 million km² will go out of production because of soil degradation between 2005 and 2020. There are 95 developing countries, each with less than 100 000 km² of arable land, for which the loss of their most vulnerable lands will mean either loss of economic growth potential or famine or both (Scherr, 1999). The development of long-term programmes to protect and enhance the quality of soils in these countries would seem to be a priority. Countries with large areas of high quality agricultural land (Brazil, China, India, Indonesia and Nigeria, for example) will probably focus on the more immediate economic effects of soil degradation. Because the poor are particularly dependent on agriculture, on annual crops and on common property lands, the poor tend to suffer more than the non-poor from soil degradation. Countries or sub-regions that depend upon agriculture as the engine of economic growth will probably suffer the most. Furthermore, as growing populations in the developing world become increasingly urbanised, the difficulties in maintaining food supply chains between cities and their rural hinterlands are likely to increase (Steel, 2008).

1.9.2 Direct factors

Direct factors include deliberate habitat change; physical modification of rivers, water withdrawal from rivers, pollution, urban growth and suburban sprawl (Goudie, 1997).

Cultivated systems

The most significant change in the structure of biomes has been the transformation of approximately one-quarter (24%) of Earth's terrestrial surface to cultivated systems. More land was converted to cropland in the 30 years after 1950 than in the 150 years between 1700 and 1850. There is a direct connection between soil erosion on the land (net loss of agriculturally usable soil to reservoirs) and coastal erosion resulting from a reduction in sediment delivery to the coast. It is estimated that human activity affects directly 8.7 million km² of land globally; about 3.2 million km² are potentially arable, of which a little less than a half is used to grow crops. Soil quality on three-quarters of the world's agricultural land has been relatively stable since the middle of the twentieth century, but the remaining 400 000 km² are highly degraded and the overall rate of degradation has been accelerating over the past 50 years. Almost 75% of Central America's agricultural land has been seriously degraded, as has 20% of Africa's and 11% of Asia's.

In the United States, cropland is being eroded at 30 times the rate of natural denudation (Figs. 1.15 and 1.16) and this is creating two problems in addition to the obvious loss of usable land *in situ*. First of all, there are large sediment sinks being created on land, where the sink consists mostly of clastic sediments and secondly, nutrient sinks are being created offshore. Trimble and Crosson (2000) have commented helpfully on the implications of the build-up of new sediment stores in low-order basins.

It has become increasingly difficult to assess the future impact of environmental changes on the sediment flux to the coastal zone because of the complex impacts of human activities (Walling, 2006). Globally, soil erosion is accelerating as a result of deforestation and some agricultural practices; but at the same time, sediment flux to the coastal zone is globally decelerating, because of dams and water diversion schemes. A summary statement by Syvitski *et al.* (2005) notes that human activities have simultaneously increased the sediment transport by global rivers through soil erosion

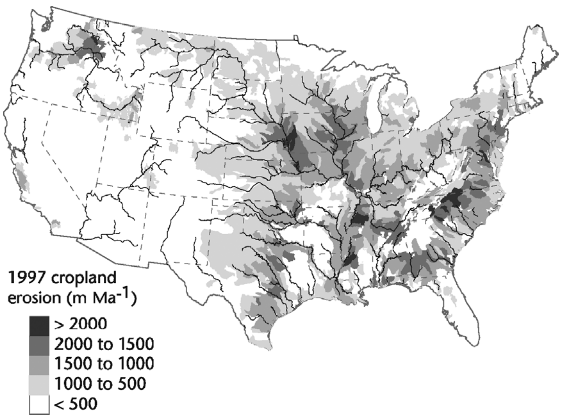

FIGURE 1.16. Rates of cropland erosion derived from estimates by the Natural Resources Conservation Service using the Universal Soil Loss Equation, and scaled to a farmland mean of 600 m Ma^{-1}. (from Wilkinson and McElroy, 2007).

by 2.3 ± 0.6 Gt a^{-1}, yet reduced the flux of sediment reaching the world's coasts by 1.4 ± Gt a^{-1} because of retention within reservoirs. Over 100 Gt of sediment and 1–3 Gt of carbon are now sequestered in reservoirs constructed largely within the last 50 years. Furthermore, the impact of dams on large rivers is likely to continue to reduce the global sediment load and will alter the patterns of sediment flux in many coastal zones (Dearing and Jones, 2003).

Reduced sediment loads delivered to the coastal zone result in accelerated coastal erosion and a decrease in habitat. The reduction of the seasonal flood wave also means that the sediment is dispersed over smaller areas of the continental margin. Although this is a correct aggregate picture, it should be borne in mind that tropical deforestation continues unabated while temperate forests are being enlarged. There are therefore numerous individual unregulated basins within the tropical world (e.g. Indonesia and Malaysia) where sedimentation at the coast continues to be considerable.

Milliman and Syvitski (1992) concluded that mountainous rivers, particularly in the island nations of Southeast Asia, contribute the largest proportion of global sediment flux. These regions have recent histories of severe deforestation and are dominated by low-order streams. It is therefore probable that the most rapid increase in future sediment flux to the ocean may well come from disturbed, small–medium-size basins feeding directly to the coast. This sediment is likely to contain enhanced loads of adsorbed nutrients and surface pollutants, a phenomenon which has already been documented in some detail from the west coast of India (Naqvi *et al*., 2000). The primary factor responsible for increased nitrous oxide production is the intensification of agriculture and the increasingly widespread application of anthropogenic nitrate and its subsequent denitrification. The western Indian continental shelf and the Gulf of Mexico immediately to the south and west of the Mississippi delta are well-documented hypoxic zones; that is, the concentration of oxygen in the water is less than 2 ppm. In the case of the Mississippi–Missouri drainage basin both phosphates (industrial) and nitrates (agricultural) constitute diffuse sediment sources which follow both surface and subsurface hydrological pathways (Fig. 1.17) (Goolsby, 2000; Alexander *et al*., 2008). The average extent of the hypoxic zone was 16 700 km² between 2000 and 2007. The goal of reducing the extent of the hypoxic zone to an average of 5000 km² by 2015 looks increasingly difficult as there has been no significant reduction in nutrient loading (Turner *et al*., 2008).

Desertification

Desertification is defined by the UN Convention to Combat Desertification as 'land degradation in arid, semi-arid and dry sub-humid areas resulting from various factors, including climatic variation and human activities'. Land degradation in turn is defined in that context as the reduction or loss of biological or economic productivity. From the perspective of the global hydrological cycle the role of vegetation in land surface response is critically important, especially through vegetation–albedo–evaporation feedbacks. Desertification is a global phenomenon in drylands, which occupy 41% of Earth's land area and are home to more than 2 billion people. Some 10–20% of drylands are already degraded. This estimate from the Desertification Synthesis of the Millennium Assessment is consistent with the 15% global estimate of soils permanently degraded. Excessive loss of soil, change in vegetation composition, reduction in vegetative cover, deterioration of water quality, reduction in available water quantity and changes in the regional climate system are implicated. Desertified areas are likely to increase and proactive land and water management policies are needed (Reynolds *et al*., 2007).

1.9.3 Conclusion

The fourth driver of global environmental change, namely human activity, is the most rapidly changing driver. Land use and land cover change, especially the transformation of forest and grasslands to logged forests, agricultural lands and urbanisation, have the most profound effect. The intensification of human activity in the temperate and tropical zones is especially effective in landscape change; by contrast, in polar latitudes, where population densities are low, climate in particular, but also relief and sea level, continue to be the more important drivers.

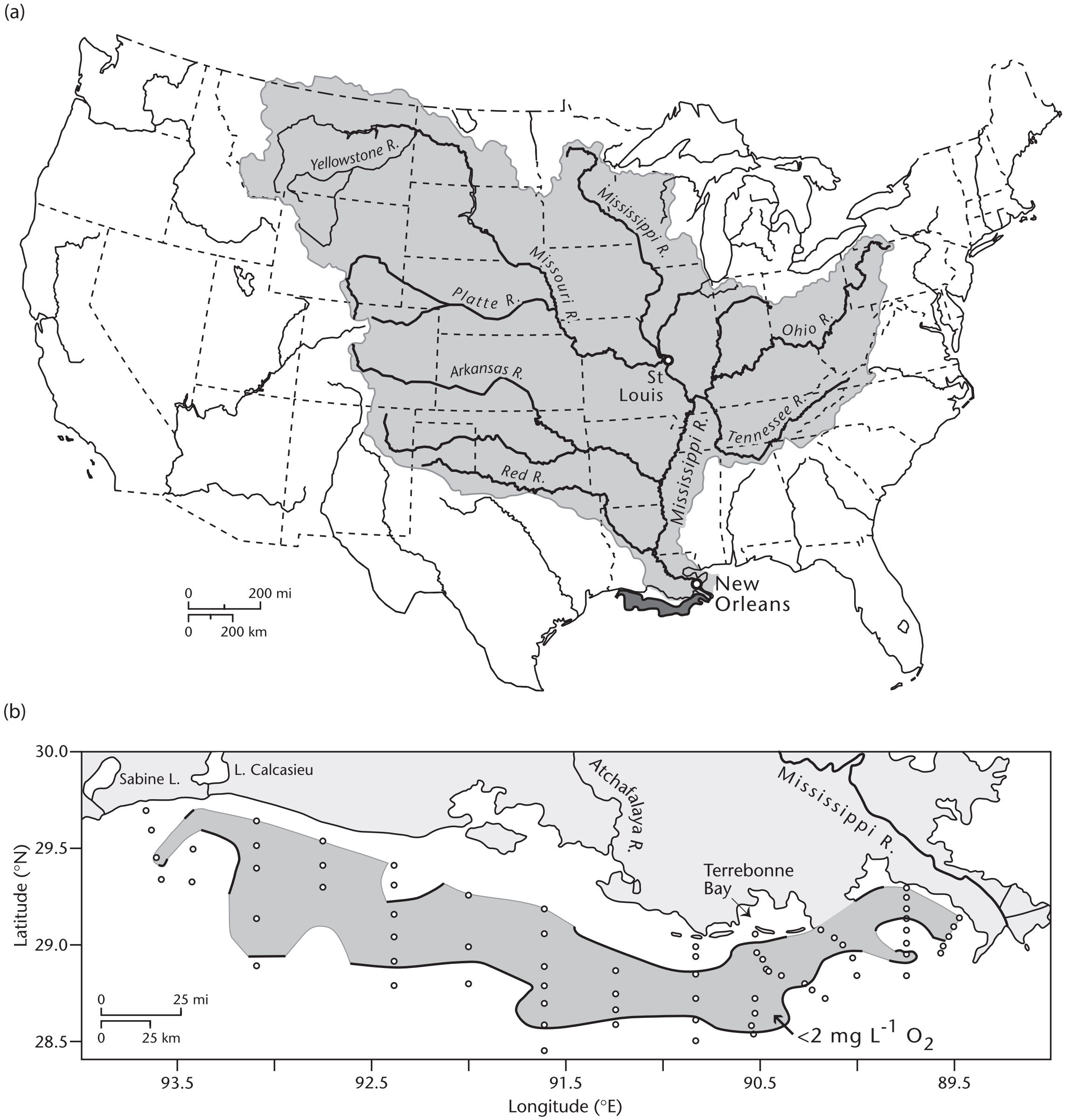

FIGURE 1.17. (a) Diffuse sediment sources of phosphates and nitrates from the Mississippi–Missouri drainage basin. (b) The resultant hypoxia in the Gulf of Mexico (modified from Goolsby, 2000).

1.10 Broader issues for geomorphology in the global environmental change debate

1.10.1 Putting the ‘geo’ into the ‘bio’ debates

Geodiversity is defined as a measure of the variety and uniqueness of landforms, landscapes and geological formations (Goudie, 1990) in geosystems at all scales; biodiversity is defined as the variation of life forms within a given ecosystem, biome or the entire Earth. There are thus strong parallels between the two concepts. The term natural heritage is more easily understood by the general public and sums up the totality of geodiversity and biodiversity. Geodiversity has its own intrinsic value, independent of any role in sustaining living things. The World Heritage Convention came into force in 1972 and after 35 years the World Heritage List now identifies, as of 2007, 851 sites of ‘outstanding universal value’ (http://whc.unesco.org/en/list/). Of these, 191 are

FIGURE 1.18. Bright Angel Canyon, Grand Canyon National Park: a landscape of 'outstanding universal value' (from Strahler and Strahler, 1994).

justified in terms of at least one component of geodiversity (Appendix 1.4). It is useful to note that biodiversity cannot exist without geodiversity, the natural diversity of our non-living environment. There is a tendency to think of biodiversity as being fragile, with geodiversity having greater robustness. However, this is not necessarily the case, but in those sites where geodiversity is relatively robust the loss of any one element of that diversity becomes doubly serious. Geomorphology has an important role to play in identifying physically sensitive landscapes that are highly responsive to environmental change. Geoconservation aims to preserve geodiversity (O'Halloran *et al*., 1994). This means protecting significant examples of landforms and soils, as well as a range of distinctive Earth surface processes. It is proposed that we have an ethical obligation to retain landforms and landscapes of unique natural beauty and diversity for future generations. There is a very good reason for active geoconservation management because, when a landform is lost, it can only be replaced over geological timescales. Glen Canyon in Colorado has disappeared and, in a significant sense, the Three Gorges of the Yangtze (Li-Jiang) River have disappeared. Although it is not anticipated that the Grand Canyon will disappear sometime soon, it is only through active geoconservation management that its pristine status can be maintained (Fig. 1.18).

But there are other reasons why biodiversity concerns cannot be divorced from geodiversity. There are linkages, for example, between above-sediment and sediment biota in freshwater ecosystems, which suggest that the monitoring of the bio- and the geodiversities should be collaborative (Lake *et al*., 2000). The standard view in ecology is that biodiversity confers stability and resilience and, to a more limited extent, natural floodplains conserve the resilience of landforms to changing environmental drivers.

Nevertheless, the analogy between biodiversity and geodiversity should not be overemphasised given the detailed functional differences between eco- and geosystems.

1.10.2 Geomorphology, natural hazards and risks

The dynamic nature of landscapes and landforms over space and through time has generated interest in defining geomorphological 'hotspots'. Biodiversity hotspots are defined as regions that contain at least 1500 species of vascular plants and which have lost at least 70% of their original habitat (Myers *et al*., 2000). In other words they are regions of special value and at the same time highly vulnerable to disturbance. By analogy, geomorphological hotspots are sites or regions of special value in terms of geodiversity and highly vulnerable to environmental change. 'Geoindicators' have been defined as one way of identifying such hotspots (Berger and Iams, 1996). They are measures of geomorphological processes and phenomena that vary significantly over periods of less than 100 years and are thus high-resolution measures of short-term changes in the landscape. Geoindicators have been designed as an aid to state-of-the-environment reporting and long-term ecological monitoring. They are also useful in the identification of potential natural hazards, where irreversible damage to property and loss of life occur. A wide range of slope failure, river, coastal and wind erosion related problems which have been exacerbated by human activity are recognised as natural hazards. Where the geoindicator detects unusual movement or instability, a geomorphological 'hotspot' is identified. If this instability is located close to human settlements or transport corridors, a geomorphological hazard

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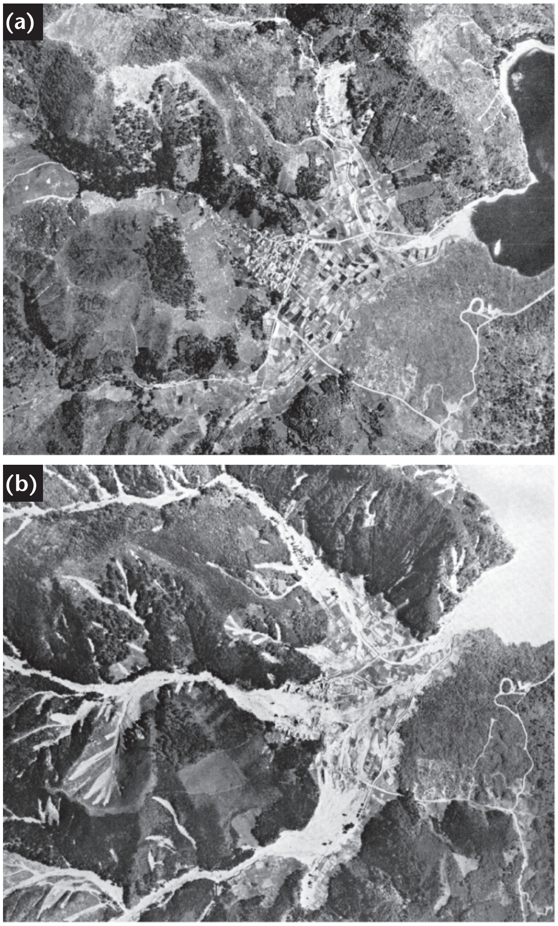

FIGURE 1.19. Debris flows as geomorphological hazard, illustrated from the results of an intense rainstorm in 1966 at Ashiwada in Yamanashi Prefecture, Japan. (a) Pre-1966; (b) post-typhoon 26, 1966 (from Akagi, 1973).

is declared and risk studies may be undertaken. It is the point of intersection of the human use system with the extreme geomorphological event which defines a geomorphological hazard (Glade, 2003).

Because of the high population density, the high-relief volcanic slopes, the intense rainstorms produced by multiple annual typhoons, the vulnerable coastline and the tendency to build settlements in the most vulnerable locations, there is a tragic history of loss of lives and infrastructure in the Japanese islands (Akagi, 1973). In the example illustrated (Fig. 1.19) a village, located on a debris flow fan on the western flanks of Mount Fujiyama, Japan is the human use system. The village was overwhelmed by debris flows (an extreme geomorphological event) following intense rainstorms accompanying Typhoon 26, in 1966. The unfortunate coincidence of a human use system interacting with a geomorphological event system (or sediment cascade) defines a geomorphological (or natural) hazard. Surrounding the question of natural hazards is the question of natural risk (Hufschmidt *et al*., 2005). Natural risk is a measure of the probability of adverse effects on health, property and society, resulting from the exposure to a natural hazard of a given type and magnitude within a certain time and area. If risk studies had been undertaken before the event shown in Fig. 1.19, it might have been possible to develop a plan for mitigation of the disaster and to save many lives and much property as a result.

1.10.3 Geomorphology and unsustainable development

The concept of sustainable development has infused the policy world since the publication of Gro Harlem Brundtland's *Our Common Future* (WCED, 1987). The concept of sustainability is highly contested in a field like geomorphology because the drivers of change are themselves constantly changing and landscapes and their soils are, over century timescales, frequently collapsing, due to overexploitation. While the value of sustainability has achieved wide currency in principle, the implementation has proved difficult. A distinction should be made between 'strong sustainability' in the case of a landscape and a 'weak sustainability' in the case of a society. Strong sustainability concerns preserving the structure and function of an ecosystem and its supporting geophysical substrate. Weak sustainability admits that landscapes may be changed by deliberate human agency so long as the total resource value is not devalued.

It would perhaps be more realistic in geomorphology, and in related sciences, to seek evidence of 'unsustainability' such that adaptation and/or mitigation can be planned well in advance of the system collapse. Four key concerns have been identified by the policy community and two promising approaches have emerged. Concerns are: the need to integrate natural and physical science with social science, health science and humanities research; a focus on the future; the need to involve stakeholders; and a sensitivity to the appropriate temporal and spatial scale of analysis required. The term 'back-casting' was coined by Robinson (2004) for an approach that involves working backward from a desired future end point to the present and finding the appropriate policy measures required to reach that point. Scenario building, discussed in Chapter 3, is one specific application of the back-casting approach. 'Integrated assessment' is another interdisciplinary process of 'combining, interpreting and communicating knowledge from diverse scientific disciplines in such a way that the whole set of cause–effect interactions of a problem can be evaluated from a synoptic perspective' (Rotmans and Dowlatabadi, 1998).

Whilst it must be admitted that these are promising policy approaches, especially with respect to their holistic emphasis, geomorphologists have to ask the question 'in what sense can landscapes be sustained over century or millennial timescales in the face of constantly changing human activities, sea level changes and climate change?'

Not only is there a problem of constant change and the possibility of achieving sustainability in the future, but many would claim that we have already exceeded the Earth's capacity to support our consuming lifestyle. Rapid increase in interest in the ecological footprint idea (Rees, 1992) confirms a move of public opinion towards greater concern about our degrading environment.

Ecological footprint analysis attempts to measure the human demand on nature and compares human consumption of natural resources with the Earth's ecological capacity to regenerate them (Plate 6). Ecological footprinting is now widely used as an indicator of environmental sustainability. The only prudent policy would seem to be the absolute minimisation of land cover change especially where urban sprawl impacts landforms of exceptional interest or soils whose optimal use is an agricultural one.

1.10.4 Geomorphology and the land ethic

Aldo Leopold's land ethic (Leopold, 1949) offered this general principle of land management: 'A thing is right when it tends to preserve the integrity, stability and beauty of the biotic community. It is wrong when it tends otherwise.' Land to Leopold had a broad meaning. It included soils, waters, plants and animals. The boundaries included people as members of nature. Leopold's lifelong land ethics journey led from a stewardship resource management mentality to stewardship entwined with ecological conscience.

Geomorphology provides certain constraints that limit how people should act towards the land and, at another level, it challenges the unspoken assumptions of an unwisely managed neoliberal society, which accepts uncritically the rule of the market. Only recently has the neoliberal view been willing to attempt proper valuation of environmental resources (e.g. Millennium Ecosystem Assessment (2005) and the Stern Review (2007) on the economics of climate change).

It is clear that the removal of soil cover will reduce livelihood options for people and agriculture. The careful management of land and its biogeochemical and aesthetic properties enhances long-term human security.

1.11 Landscape change models in geomorphology

1.11.1 Landscape change over long time periods

Brunsden (1980) has developed the idea of 'characteristic form time' (Fig. 1.20). This is a variant on the 'punctuated equilibrium' idea, but its importance is based on the fact that it is possible for a landscape to remain sufficiently unperturbed by environmental change such that it develops a form that is representative of the balance of resistance and driving forces, a balance which remains relatively unchanged over long periods of time. Whereas this was the prevailing assumption in geomorphology during pre-systems thinking, such has been the swing towards emphasis on change that some have questioned the possibility of a characteristic form ever being achieved. But Brunsden (1980) has pointed out that there is a need for the concept of characteristic form because the geological record gives evidence of past landscapes that appear to have retained constant characteristics over millions of years (e.g. much of the interior landscapes of Australia and the extremely low relief extensive erosion surfaces exposed in the stratigraphy of the Grand Canyon; Fig. 1.18).

The idea of the landscape as a palimpsest, with evidence preserved in layers which have simply to be unpeeled in

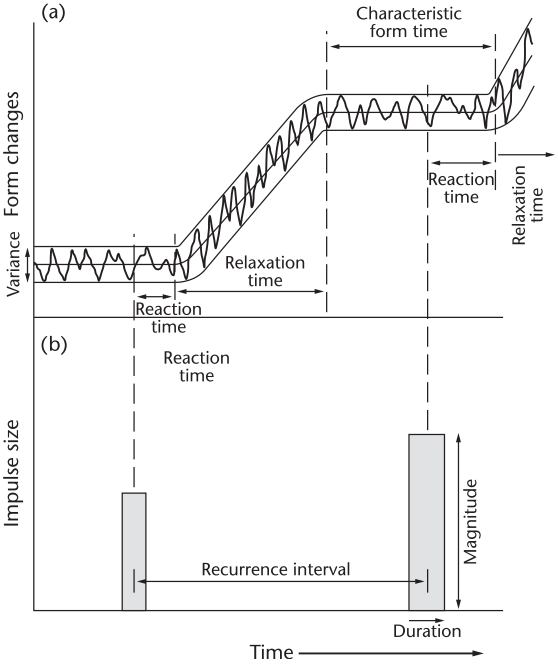

FIGURE 1.20. Definitions of geomorphological time, impulse recurrence, reaction, relaxation and characteristic form (modified from Brunsden, 1980).

order to discover the evidence of past landscape forming processes, is well enshrined in the literature (Wasson, 1994).

Frequency and magnitude of geomorphic events

However, in rapidly changing global environments, it is no longer possible to maintain the fiction of statistical stationarity in historical environmental data. Even in a landscape as quiescent as that of the UK, Higgitt and Lee (2001) demonstrated the difficulty of the concept of frequency and magnitude over the past 1000 years and Steffen *et al.* (2004), by invoking the 'no analogue' argument, have made it doubly difficult to sustain the traditional hydrological approach to the topic. It seems probable that the coupling of temporal and spatial dimensions through the analysis of lake and marine sediments (Dearing and Jones, 2003) and ice cores will provide the best estimates of changing frequencies and magnitudes of geomorphic events.

1.11.2 Thresholds and complex response

Individual slopes and river channels lie at variable distances from 'thresholds' (points at which major changes occur in response to perturbation) (Schumm, 1973; Brunsden and Thornes, 1979). A simple example of this effect is that a perturbation may generate a landslide or debris flow at a location in the headwaters of basin A; and the same perturbation may generate a similar slope failure close to the mouth of basin B. The response at the mouth of basin B will differ significantly from that at the mouth of basin A. In effect the communication of threshold exceedance through the river basin system is far more complex and has given rise to the complex response theory (Schumm, 1973).

Schumm (1973, 1977, 1985, 1991) has demonstrated the importance of discriminating between intrinsic and extrinsic variables in the evolution of landscapes. If we consider a river basin, we see a system which has its own organisation of river networks and slopes, adjusted to a greater or lesser extent to the prevailing internal properties of the basin, such as lithology, hydrology and biomass. These are intrinsic variables. At the same time, the system is subject to land use and land cover change and climate change. These are extrinsic variables. The point at issue is that the intrinsic and extrinsic variables operate independently and that systems with apparently identical intrinsic properties will respond differently to different extrinsic variables Even more subtly, side-by-side systems with apparently identical intrinsic properties may respond quite differently to apparently identical extrinsic variables. This is a result of the fact that the internal organisation of a geomorphic system contains historical elements that have not yet reached 'characteristic form' as defined above.

1.11.3 Landscapes of transition

Hewitt *et al.* (2002) have developed the idea of landscapes of transition. Nearly all landscapes bear the imprint of past conditions. Some of these past conditions no longer apply. Biomes have expanded and contracted geographically over large areas over geological timescales. There are at least two ways in which regional landscapes must be considered as transitional:

(a) some landforms reflect different past conditions. They are not merely relict forms; they operate as constraints upon present-day developments and
(b) there are also parts of landscapes and patterns of sedimentation that are in incomplete transition from past conditions.

The notion of temporal transition is intended to cover ways in which environmental changes are uniquely expressed. Although processes and landforms are driven by contemporary heat and moisture conditions, available relief and lithologies, they are not directly responding to them. They involve mechanisms or patterns of adjustment that are not readily obvious in climate change or tectonics. When geomorphic processes are modifying past landscapes, the adjustments do not travel directly from one equilibrium to another. There are combinations of intervening constraints, self-adjusting mechanisms or 'epicycles' peculiar to the earth surface processes affected.

In Canada, Church *et al.* (1999) have suggested that, at all scales above the order of 1 km², the landscape is still adjusting to the perturbation of continental glaciation. The fact that geomorphic systems have variable relaxation times following disturbance (i.e. time taken to return to the same conditions as those which prevailed prior to disturbance) has been well understood, but few careful quantitative studies have been available until recently.

The response of the cryosphere to global environmental change, which demonstrates high sensitivity to temperature change through the threshold 0 ºC, is a more obvious example than the response of such an extensive and resistant landscape as the whole of Canada.

There are radical differences in the role of geomorphology in global environmental change whether one takes the characteristic form approach or the transitional landscapes approach. At one level, it is a question of different punctuated equilibrium models of the landscape, where one is dominated by quiescence and the other by change. But it is not necessary to choose between the two approaches. There are elements of the landscape that have remained unchanged for long periods of time and others that are highly sensitive. The challenge and the opportunity of global environmental

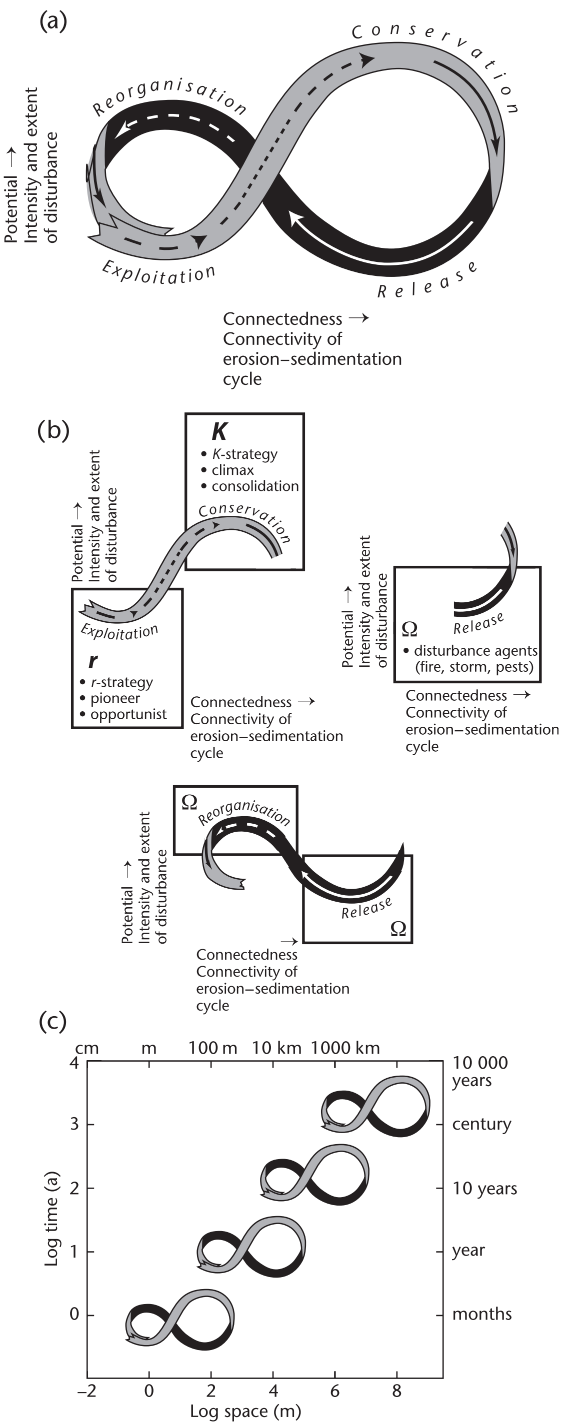

FIGURE 1.21. The panarchy framework (modified from Gunderson and Holling, 2002). (a) the adaptive cycle; (b) components of the adaptive cycle; and (c) panarchy in time and space.

change is to distinguish those parts of landscapes that are close to threshold and which, because of their vulnerability, deserve priority attention. The short-term challenge of global environmental change makes the transitional landscapes and complex response models more relevant; but this in no way invalidates the characteristic form time model for interpreting longer-timescale changes.

1.11.4 Adaptive systems

The transience of components of the landscape and the idea of transitional landscapes constantly undergoing change are interesting concepts that are directly relevant to contemporary global environmental change. If the IPCC definition of vulnerability is seriously engaged, then geomorphologists also have to investigate adaptive systems. Reliance on reactive, autonomous adaptation to the cumulative effects of environmental change is ecologically and socioeconomically costly. Planned and anticipatory adaptation strategies can provide multiple benefits. But there are limits on their implementation and effectiveness. Enhancement of adaptive capacity reduces the vulnerability of landscapes to environmental change, but adaptive capacity varies considerably among regions, cultures and socioeconomic groups.

It is possible to learn from ecology where recent models have placed environmental change and system collapse as central to an understanding of contemporary change and where there are similar complexity problems. Panarchy is a metaphor designed to describe systems of ecosystems at varying spatial and temporal scales. The terminology developed for panarchy (Holling, 2001) is entirely ecological and needs to be translated for the needs of geomorphology. Holling suggests that complex systems are driven through adaptive cycles which exist at a range of spatial scales. The term adaptive is self-evident in ecological systems; in geomorphic systems we often speak of self-regulating systems (Phillips, 2003). Adaptive cycles are defined as consisting of four phases, namely exploitation (the environmental disturbance regime), conservation (the response), collapse (threshold exceedance and unpredictable behaviour of the system) and reorganisation (recovery) (Fig. 1.21). A geomorphic analogue would be a glacial–interglacial cycle characterised by both orderly evolution and system collapse. The duration of these phases of adaptation in ecological systems depends on three factors: intrinsic wealth, connectivity and resilience of the system. A geomorphic analogue would be the intensity and extent of a glaciation (intrinsic wealth), the connectivity of the erosion–sedimentation cycles (connectivity) and the time required for the recovery of the system during interglacials (resilience).

The panarchy metaphor has a fascinating flexibility in dealing with complex systems and geomorphologists are working with this concept in an effort to introduce more flexible theory into the discussion of geomorphic complexity (Cammeraat, 2002). Although there are evident differences between geophysical systems and ecosystems, there are many parallels in the behaviour of self-organising systems which can assist in improving attempts to understand and manage the environment sensitively. The concepts and terminology of the panarchy model are consistent with geomorphic concepts such as complex response (Schumm, 1973), threshold exceedance, landscape sensitivity and barriers to change. Complex adaptive cycles throw new light on complex response in landscape systems. Resistances in the panarchy model of ecosystem behaviour perform a similar function to that of geomorphic barriers to change in geosystems.

In the context of rapid and accelerating global environmental change, geomorphologists are well placed to assess the potential for collapse and/or reorganisation of many of our desired landscapes. A scenario is a coherent, internally consistent and plausible description of a possible future state of the world (IPCC, 2007b.). Scenarios are not predictions or forecasts but are alternative images without ascribed likelihoods of how the future might unfold. The development of scenarios of landscape trajectories is a worthy aim. With such an approach, it may be possible to forestall the most serious negative outcomes and make wise use of the new opportunities created by global environmental change.

1.12 Organisation of the book

Following this introductory chapter, the volume is divided into two substantive sections, consisting respectively of six chapters (2–7) and seven chapters (8–14). The concluding Chapter 15 contains the highlights of conclusions from the substantive chapters, focussing on the identification of geomorphic hotspots, major uncertainties and matters of special concern that ought to be communicated to policy-makers, environmental managers and the scientifically literate public.

The two substantive sections of the book concern respectively azonal and zonal topics. In Chapters 2–7 (azonal topics) we attempt to follow the energy, mass and information cascade from mountain tops to the sea and focus attention on the ways in which environmental change is governed by a limited number of geophysical processes and their interactions with human activity. The hydrological cycle and the sediment budget constitute the central themes of this section and environmental change is discussed under the influence of this primarily geophysical framework. The chapters are sequenced along the topographic gradient: mountain environments; lake systems; river systems; estuaries, sedimentary coasts and coastal wetlands; beaches, cliffs and deltas; and coral reefs.

In Chapters 8–14 (zonal topics) we have attempted to identify the critical landscapes thought to be the most sensitive to potential environmental change although it is accepted that this list may not be exhaustive. The biome is used as the unit of zonality as vegetation is a good integrator of average climate conditions. The biomes selected for treatment in depth are: tropical rainforest; tropical wet and dry savanna; deserts; Mediterranean landscapes; mid-latitude temperate forest and rangelands (with particular reference to landslides and other slope processes in this biome); tundra and permafrost-dominated taiga; and ice sheets and ice caps. In some cases the whole zone is composed of critical landscapes (e.g. savanna and permafrost-dominated taiga), but in other cases the hotspots are located around the boundaries of the zone (zones of transition).

The mid-latitude temperate forest lands of Europe have been deliberately excluded for two reasons: firstly because the biome has been so intensively modified by human activity that climate change will probably produce only marginal geomorphological change and secondly because the azonal chapters include good coverage of this biome.

The final Chapter 15 sums up the key conclusions on landscape change trajectories, both positive and negative; provides warnings about special concerns; lists opportunities for landscape enhancement; and, where appropriate, makes recommendations for action by policy-makers and concerned citizens. It also considers the relation between this book and the IPCC Fourth Assessment Reports and recommends a closer integration of future landscape change discussions with the anticipated IPCC Fifth Assessment.

APPENDIX 1.1
The IPCC scenarios

Assumptions contained within the IPCC scenarios (Table 1.3) are as follows:

A1. The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three

TABLE 1.3. *Description of SRES emissions scenarios*

Scenario	Description
A1	Globally integrated world with rapid economic growth A1FI – Continued dependence on fossil fuels A1B – Balance of fossil and renewable energy sources A1T – Shift to renewable energy sources
A2	A world of independently operating self-reliant nations
B1	Globally integrated but with ecologically friendly growth
B2	Emphasis on local solutions to environmental problems

Source: After IPCC (1996b).

groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B) (where balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end use technologies).

A2. The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change more fragmented and slower than other storylines.

B1. The B1 storyline and scenario family describes a convergent world with the same global population, that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives.

B2. The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social and environmental sustainability. It is a world with continuously increasing global population, at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented towards environmental protection and social equity, it focusses on local and regional levels.

How the IPCC process deals with uncertainty

The question of uncertainty in prediction is discussed explicitly in each of the IPCC reports (IPCC, 2001b, Box 1–1, p. 79) and is reported in two different ways:

(a) a five-point confidence scale is used to assign confidence levels to many of the conclusions. The confidence levels are stated as probabilities, meaning that they represent the degree of belief among the authors of the report in the validity of a conclusion, based on their collective expert judgement of all observational evidence, modelling results and theory currently available. The confidence levels are: very high (>95%); high (67–95%); medium (33–67%); low (5–33%); and very low (<5%).
(b) Qualitative 'state of knowledge' descriptors, labelled: well-established; established but incomplete; competing explanations; speculative descriptors are used when a quantitative scale seems inappropriate.

All the following initiatives (Appendices 1.2–1.5) have started with the same 'storylines' by envisaging six different future world contexts as identified in Appendix 1.1.

APPENDIX 1.2
Global Environmental Outlook scenarios to 2032 (GEO-3: see UNEP, 2002) and the fourth Global Environmental Outlook: environment for development (GEO-4)

The Global Environmental Outlook process has over the past 10 years (1997–2007) produced a series of global integrated environmental assessment reports aimed at providing comprehensive, reliable, scientifically credible and policy relevant assessments on the interaction between environment and society. GEO-1 (1997), GEO-2 (1999), GEO-3 (2002) were UNEP's three previous global assessments and GEO-4 appeared in 2007. Special attention is paid to the role and impact of the environment on human well-being and vulnerability. There are five themes:

(a) Present global and regional issues in the context of the development of international environmental governance;
(b) State and trends of the global environment analysing human drivers and the impact of natural phenomena on

http://dx.doi.org/10.1017/CBO9780511627057.002

the environment, the consequences of environmental change for ecosystem services and human well-being;

(c) Interlinkages between major environmental challenges and their consequences for policy and technology response options;

(d) Cross-cutting issues on how environment can contribute to sustainable development goals and how environmental degradation impedes progress; and

(e) Global and sub-global outlooks, including short-term (to 2015) and medium-term (up to 2050) scenarios for the major environmental issues.

APPENDIX 1.3

The Millennium Ecosystem Assessment scenarios to 2100

The Millennium Ecosystem Assessment (2005) was carried out between 2002 and 2005 to assess the consequences of ecosystem change for human well-being and to establish the scientific basis for actions needed to enhance the conservation and sustainable use of ecosystems and their contributions to human well-being. The Assessment responds to government requests for information received through four global conventions: the Convention on Biological Diversity, the UN Convention to Combat Desertification, the Ramsar Convention on Wetlands and the Convention on Migratory Species.

The underlying assumption of this Assessment is that everyone in the world depends completely on Earth's ecosystems and the services they provide, such as food, water, disease management, climate regulation, spiritual fulfilment and aesthetic enjoyment. Over the past 50 years, humans have changed these ecosystems more rapidly and extensively than in any comparable period of time in human history, largely to meet rapidly growing demands for food, fresh water, timber, fibre and fuel. This transformation of the planet has contributed substantial net gains in human well-being and economic development. But not all regions have benefited from this process. In fact, most have been harmed or at least rendered more vulnerable to further change and to reduction in material productivity. Moreover, the full costs associated with these gains are only now becoming apparent.

The Assessment focusses on the linkages between ecosystems and human well-being and in particular on 'ecosystem services'. Ecosystem services are the benefits people obtain from ecosystems. In sum, these services are quite similar to those provided by geomorphology as discussed in the previous section. In showing how ecosystems influence human well-being, human well-being is defined to include basic material for a good life, such as: secure and adequate livelihoods, enough food at all times, shelter, clothing and access to goods; health, clean air and access to clean water; good social relations; security, including secure access to natural and other resources; and freedom of choice and action, including the opportunity to achieve what an individual values doing and being.

Five overarching questions guided the issues that were assessed: What are the current condition and trends of ecosystems, ecosystem services and human well-being? What are future plausible changes in ecosystems and their ecosystem services and the consequent changes in human well-being? What can be done to enhance well-being and conserve ecosystems? What are the strengths and weaknesses of response options that can be considered to realise or avoid specific futures? What are the key uncertainties that hinder effective decision-making concerning ecosystems? What tools and methodologies developed and used in the Assessment can strengthen capacity to assess ecosystems, the services they provide, their impacts on human well-being and the strengths and weaknesses of response options?

APPENDIX 1.4

The Land Use and Land Cover Change (LUCC)Project

Land use and land cover change is an important component of global environmental change. The International Geosphere–Biosphere Programme (IGBP) and the International Human Dimensions Programme on Global Environmental Change (IHDP) commissioned a Core Project Planning Committee/Research Programme Planning Committee for Land Use and Land Cover Change (CPPC/RPPC/LUCC), working from 2000 to 2005.

The main topics covered areas of deforestation or forest degradation over the last 20 years (1980–2000); the main areas of land degradation in the drylands and hyper-arid zones (1980–2000); the main areas of change in cropland extent (1980–90); the main areas of change in urban extent (1990–2000); and the fire events with long-term impact on land cover. There were three research foci: land use dynamics; land cover dynamics; and regional and global models.

In response to the question 'How has land cover been changed by human use over the last 300 years?' it was noted that human activities have transformed Earth's landscapes for a long time. The pace and intensity of land cover change increased rapidly over the last three centuries and accelerated over the last three decades. Rapid land cover changes are clustered on forest edges and along transportation networks, mostly in humid forests. Decreases in croplands in temperate regions and expansion of forest lands display opposite trends from those seen in the tropics, where croplands are expanding and deforestation is marked. Land cover change data sets are inadequate for many parts of the world, but dryland degradation, soil degradation in croplands, wetland drainage and urban expansion are some of the most common changes.

In response to the question 'What are the major human causes of land cover change?' the most important finding was that the mix of driving forces of land use change varies in time and space, according to specific human–environment conditions. A distinction is made between decadal timescales, influenced by individual and social responses to changing economic conditions, mediated by institutions and a centennial timescale, dominated by demographic trends.

In response to the question 'How will changes in land use affect land cover in the next 50–100 years?' a number of predictive models were developed and tested against past land use patterns, but on the whole a regional approach was preferred to global modelling. Urbanisation was seen to be the dominant factor in future land use patterns.

In response to the question 'How do human and biophysical dynamics affect the coupled human–environment system?' attention was directed to historical and contemporary examples of land use transitions associated with societal and biophysical changes. Finally, in response to the question 'How might changes in climate and biogeochemistry affect both land cover and land use and vice versa?' it was noted that slow land cover conversion takes place against a background of high-frequency regional-scale fluctuations in land cover conditions caused by harvest cycles and climatic variability. Abrupt short-term ecosystem changes are often caused by the interaction of climatic and land use factors.

APPENDIX 1.5

World Heritage Sites, the World Conservation Union (IUCN) and UNEP's Global Programme of Action

Global Scenarios Group (GSG) Scenarios to 2050 (Raskin *et al.*, 2002) have incorporated ecological and land use variables. World Heritage sites have been established under the Convention concerning natural and cultural sites (1972). Roughly 20% of the 851 World Heritage Sites have been selected on the basis of 'natural' criteria. From a world landscapes perspective, the most interesting part of this process is the identification of 'natural sites' that are threatened or are particularly unique and worthy of preservation (Fig. 1.18).

The IUCN, operating within the Convention on Biodiversity, has established a Red List of threatened species and ecosystems. As always, improved governance mechanisms, capacity-building and awareness raising and improved financing are the broad policy recommendations. But within those broad parameters, basin-wide pollution treatment and basin management of land use and better allocation of resources, with particular focus on the effects on coastal areas are emphasised (in cooperation with UNEP's Global Programme of Action). In summary, the most critical factors that influence land and land use change can be divided into indirect and direct drivers.

Indirect drivers include such broadly contextual factors as:

(a) demographic change;
(b) economic, sociopolitical, cultural and religious drivers;
(c) science and technology;
(d) global trade which magnifies the importance of governance and management practices; and
(e) urban growth, and more particularly suburban sprawl.

Direct drivers include:

(a) deliberate habitat change resulting from land use change;
(b) physical modification of rivers;
(c) water withdrawal from rivers;
(d) pollution;
(e) sea level change; and
(f) climate change.

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