10 THE FUTURE: HYDROLOGIC IMPACTS

Introduction

Global warming will affect hydrologic systems and fluvial geomorphology in a whole range of ways (Arnell, 1996; Jones et al., 1996). Increasing temperatures will tend to melt snow and ice and promote greater evapotranspirational losses. There will be changes in the amount, intensity, duration, and timing of precipitation, which will affect river flows and groundwater recharge. Vegetation cover will respond to temperature and precipitation changes, as will land use. Higher CO_2 levels may lead to changes in plant growth and physiology, which can lead to changes in transpiration. Global warming may also affect soil properties (such as organic matter content) which could alter runoff generation processes. Climate change will also lead to human interventions in the hydrologic system with, for example, greater use of irrigation in areas subject to increased drought risk, and the continued spread of engineering controls on flooding and erosion.

The nature of the changes that will take place in fluvial systems depends to a certain extent on scale. As Ashmore and Church (2001: 5) explained:

> The nature of the changes caused by climatic change depends to some extent on the size of the drainage basin in question. Drainage basin size also affects the relative impact of widespread climate change compared to local land-use change. The effects of land-use change are expected to dominate in smaller basins where a large proportion of the basin area may be affected, leading to substantial changes in runoff and erosion throughout the basin. In larger drainage basins, land use change is seldom sufficiently widespread to affect the entire basin and climatic effects will dominate. The impacts of climatic change will also vary with basin size. Thus, small basins will be affected by changes in local, high-intensity storms, whereas larger basins will show a greater response to cyclonic events or basin-wide snowmelt effects.

Equally, as Ashmore and Church (2001: 5) maintain, there are many ways in which river systems may change:

> Potential consequences of climatic change for river processes include changes to the magnitude of flood flows; modification of river channel dimensions and form; changes to bank stability, bank erosion rates, and channel migration;

modification of in-channel erosion and deposition; on-set of long term aggradation or degradation of river channels; changes to intensity and frequency of overbank flooding and ice-jams; and changes to the stability of valley sides. These changes in channel processes present a significant risk to structures both in and near streams including dams, bridges, water intakes, and outfalls. Structures on or near floodplains or valley margins are also at risk. Other environmental, scenic and economic attributes of streams will also be affected, especially in stream and riparian habitat.

Rainfall intensity

Rainfall intensity is a major factor in controlling such phenomena as flooding, rates of soil erosion, and mass movements (Sidle and Dhakal, 2002). Under increased greenhouse gas concentrations some GCMs exhibit enhanced mid-latitude and global precipitation intensity and shortened return periods of extreme events (Hennessy et al., 1997; Zwiers and Kharin, 1998; McGuffie et al., 1999; Osborn et al., 2000; Jones and Reid, 2001; New et al., 2001).

There is some evidence of increased rainfall events in various countries over recent warming decades, which lends some support to this notion. Examples are known from the USA (Karl and Knight, 1998), Canada (Francis and Hengeveld, 1998), Australia (Suppiah and Hennessy, 1998), Japan (Iwashima and Yamamoto, 1993), South Africa (Mason et al., 1999), and Europe (Forland et al., 1998). In the UK there has been an upward trend in the heaviest winter rainfall events (Osborn et al., 2000).

Probabilistic analysis of GCMs by Palmer and Räisänen (2002), applied to western Europe and the Asian Monsoon region, shows under global warming a clear increase in extreme winter precipitation for the former and in extreme summer precipitation for the latter. Increased monsoonal rainfall events would have potentially grave implications for flooding in Bangladesh.

In their analysis of flood records for 29 river basins from high and low latitudes with areas greater than 200,000 km^2, Milly et al. (2002) found that the frequency of great floods had increased substantially during the twentieth century, particularly during its warmer later decades. Their model suggested that this trend would continue.

Changes in tropical cyclones

Tropical cyclones (hurricanes) are highly important geomorphologic agents, in addition to being notable natural hazards, and are closely related in their places of origin to sea-temperature conditions. They only develop where sea-surface temperatures (SSTs) are in excess of 26.5°C. Moreover, their frequency over the past century has changed in response to changes in temperature, and there is even evidence that their frequency was reduced during the Little Ice Age (see Spencer and Douglas, 1985). It is, therefore, possible that as the oceans warm up, so the geographic spread and frequency of hurricanes will increase (Figure 10.1). Furthermore, it is also likely that the intensity of these storms will be magnified (Figure 10.2). Emanuel (1987) used a GCM which predicted that with a doubling of present atmospheric concentrations of CO_2 there will be an increase of 40–50% in the destructive potential of hurricanes. More recently Knutson et al. (1998) and Knutson and Tuleya (1999) simulated hurricane activity for a sea-surface temperature warming of 2.2°C and found that this yielded hurricanes that were more intense by 3–7 m per second for wind speed, an increase of 5–12%.

An increase in hurricane intensity and frequency would have numerous geomorphologic consequences in low latitudes, including accentuated river flooding and coastal surges, severe coast erosion, accelerated land erosion and siltation, and the killing of corals (because of freshwater and siltation effects) (De Sylva, 1986).

Figure 10.1 indicates one scenario of the likely latitudinal change in the extent of warm, cyclone-generating seawater in the Australian region, using as a working threshold for cyclone genesis a summer (February) sea-surface temperature of 27°C. Although cyclones do occur to the south of this line, they are considerably more frequent to the north of it. Under greenhouse conditions it is probable that on the margins of the Great Sandy Desert near Port Hedland the number of cyclones crossing the coast will approximately triple from around four per decade to twelve per decade (Henderson-Sellers and Blong, 1989).

However, it needs to be pointed out that the Intergovernmental Panel on Climate Change (Houghton et al., 1990: 25) was somewhat equivocal on the question

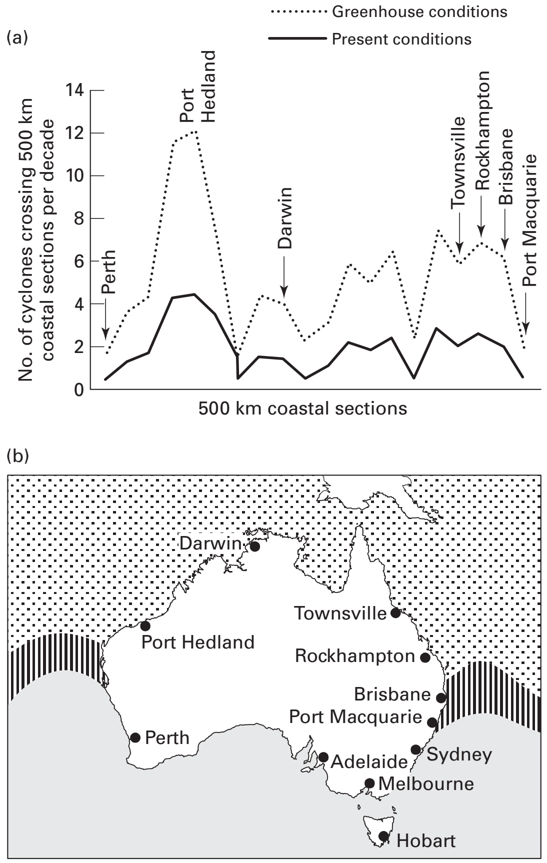

Figure 10.1 (a) The present frequency of cyclones crossing 500-km-long sections of the Australian coast, and an estimate of the frequency under conditions with a 2°C rise in temperature. (b) The area where February sea-surface temperatures around Australia are currently greater than 27°C (stippled) and the additional area with such temperatures with a 2°C rise in temperature (hatched) (modified after Henderson-Sellers and Blong, 1989, figures 4.12 and 4.14).

of the extent to which warming would stimulate cyclone activity, stating:

> Although the areas of sea having temperatures over this critical value (26.5°C) will increase as the globe warms, the critical temperature itself may increase in a warmer world. Although the theoretical maximum intensity is expected to increase with temperature, climate models give no consistent indication whether tropical storms will increase or decrease in frequency or intensity as climate changes; neither is there any evidence that this has occurred over the past few decades.

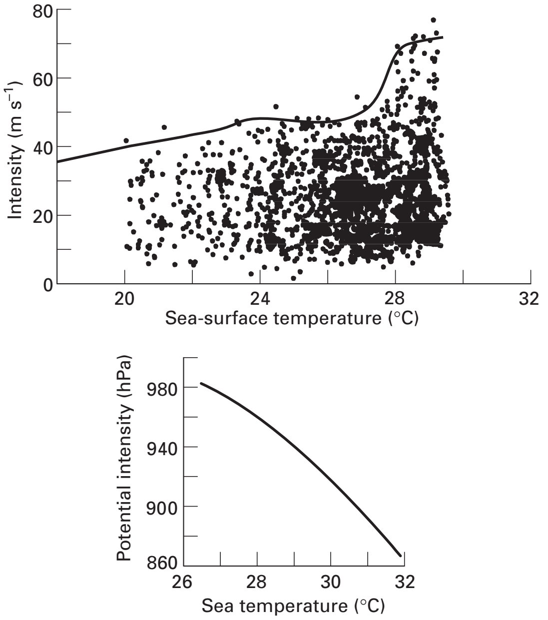

Figure 10.2 (a) Scatter diagram of monthly mean sea-surface temperature and best-track maximum wind speeds (after removing storm motion) for a sample of North Atlantic tropical cyclones. The line indicates the 99th percentile and provides an empirical upper bound on intensity as a function of ocean temperature. (b) The derived relationship between sea-surface temperature and potential intensity of tropical cyclones. (Source: Holland et al., 1988, figures 5 and 6.)

Such caution is also evident in the recent review by Walsh and Pittock (1998), and Gray (1993) discusses some of the reasons why increased SSTs may not lead to changes in hurricane activity:

> Changes in the atmospheric circulation associated with future SST increases may not be the same as the historical variations on which the estimates of hurricane frequency are based. Since these changes modify the tropical storms environment, they could prevent the storms from reaching the potential increased strength estimated from thermodynamic considerations. For example, an increase in vertical shear of the zonal wind over the tropical Atlantic would tend to decrease the frequency of tropical storm formation, thereby moderating an increase in frequency from higher SSTs, while a decrease in vertical shear would tend to have the opposite effect.

Hurricane activity is linked to the ENSO phenomenon, so that if this were to be changed by global warming then so might the frequency, distribution, and intensity of hurricanes.

Severe El Niños, such as that of 1997–1998, can have a remarkable effect on rainfall amounts. This was shown with particular clarity in the context of Peru (Bendix et al., 2000), where normally dry locations suffered huge storms. At Paita (mean annual rainfall 15 mm) there was 1845 mm of rainfall, while at Chulucanas (mean annual rainfall 310 mm) there was 3803 mm. Major floods resulted (Magilligan and Goldstein, 2001). The ENSO phenomenon also affects tropical cyclone activity. As Landsea (2000: 149) remarked, 'Perhaps the most dramatic effect that El Niño has upon the climate system is changing tropical cyclone characteristics around the world.' In some regions, an El Niño phase brings increases in tropical cyclone formation (e.g., the South Pacific and the North Pacific between 140°W and 160°E), while others tend to see decreases (e.g., the North Atlantic, the Northwest Pacific, and the Australian region). La Niña phases typically bring opposite conditions. Landsea sees a variety of reasons why ENSO should relate to cyclone activity: modulation of the intensity of the local monsoon trough, repositioning of the location of the monsoon trough, and alteration of the tropospheric vertical shear.

The differences in cyclone frequency between El Niño and La Niña years are considerable (Bove et al., 1998). For example, the probability of at least two hurricanes striking the USA is 28% during El Niño years, 48% during neutral years and 66% during La Niña years. There can be very large differences in hurricane landfalls from decade to decade. In Florida, for instance, over the period 1851–1996, the number of hurricane landfalls ranged from three per decade (1860s and 1980s) to 17 per decade (1940s) (Elsner and Kara, 1999). Given the importance of hurricanes for slope, channel, and coastal processes, changes of this type of magnitude have considerable geomorphologic significance. Mangroves, for example, are highly susceptible to hurricanes, being damaged by high winds and surges (Doyle and Girod, 1997).

The IPCC report (2001: 606) concludes thus on tropical cyclones:

> There is some evidence that regional frequencies of tropical cyclones may change but none that their locations may change. There is also evidence that peak intensity may increase by 5% to 10% and precipitation rates may increase by 20% to 30%. There is a need for much more work in this area to provide more robust results.

Runoff response

Studies of the sensitivity of runoff to climate changes have tended to indicate that annual runoff volume is more sensitive to changes in precipitation than to changes in potential evapotranspiration and that a given percentage change in precipitation results in a greater percentage change in runoff (Arnell, 1996: 99; Najjar, 1999), with arid catchments showing a greater sensitivity than humid climates. As Table 10.1 shows, an increase in annual precipitation of 10% is enough to offset the higher evaporation associated with a 2°C rise in temperature. The effects of increasing or decreasing precipitation are greatly amplified in those catchments with the lowest runoff coefficients (Pease, Nzoia, and Saskatchewan).

Another key aspect of the runoff response to climate change is that, as historical records show, higher average annual precipitation leads not only to higher streamflow but also to higher flood discharges. In Canada, for example, Ashmore and Church (2001) found that in the Southern Prairies and the Atlantic coast the magnitude of large floods (with a 10 year recurrence interval) increases by up to 50–100% for only 5–15% increases in annual precipitation. Flood discharges increase proportionately much more than mean flows.

An attempt to map future runoff trends on a global basis has been made by Arnell (2002). What is striking in this work is the large range there is in responses. Some areas will become very markedly prone to greatly reduced annual runoff, while others will see an enhancement of flows. The degree of change will vary substantially according to the levels of CO_2 in the atmosphere and the consequent amount of temperature change. However, the patterning at a global scale indicates that by the 2080s high latitudes in the Northern Hemisphere, together with parts of Central Africa and Central Asia, will have higher annual runoff levels, whereas Australia, southern Africa, northwest India, the Middle East and the Mediterranean basin will show reduced runoff levels. There is some tendency, to which the Taklemakan of Central Asia appears to be a major exception, for some of the major deserts (e.g., Namib,

Table 10.1 Percentage change in annual runoff with different changes in annual precipitation and an increase in temperature of 2°C. Source: From various sources in Arnell (1996, table 5.1)

River	*Location*	*Percentage change in precipitation*				
		–20	*–10*	*0*	*10*	*20*
White	Colorado basin, USA	–23	–14	–4	7	19
East	Colorado basin, USA	–28	–19	–9	1	12
Animas	Colorado basin, USA	–26	–17	–7	3	14
Upper Colorado	Colorado basin, USA		–23	–12	1	
Lower Delaware	USA	–23		–5		–12
Saskatchewan	Canada	–51	–28	–15	11	40
Pease	Texas, USA	–76	–47	–12	40	100
Leaf	Mississippi, USA	–50	–30	–8	–16	40
Nzoia	Kenya	–65	–44	–13	17	70
Mesohora	Greece	–32	–18	–2	11	25
Pyli	Greece	–25	–13	–1	13	25
Jardine	Northeast Australia	–32	–17	–1	11	28
Corang	Southeast Australia	–38	–21	–3	16	33

Kalahari, Australian, Thar, Arabian, Patagonian, and North Sahara) to become even drier.

Cold regions

In the Arctic, overall the transport of moisture is expected to increase as the atmosphere warms, leading to a general increase in river discharges. Peterson et al. (2002) have analyzed discharge records for the six largest Eurasian rivers that discharge into the Arctic Ocean and have shown that as surface air temperatures have increased so has the average annual discharge of freshwater. It increased by 7% from 1936 to 1999. They suggest that with increased levels of warming (1.5 to 5.8°C by 2100) there would be an 18 to 70% increase in Eurasian Arctic river discharge over present conditions.

However, there are many factors to be considered in an analysis of the response of cold region hydrologic systems to climate change (Table 10.2), and good reviews are provided by Woo (1996) and Rouse et al. (1997). Prowse and Beltaos (2002) review the effects that climate change could have on ice jams and thus on floods and low flows.

The peatlands of cold temperate regions are another landscape type that may be impacted by global change, although uncertainties exist about how they will respond (Moore, 2002). On the one hand, higher temperatures will tend to enhance plant productivity and organic matter accumulation but, on the other, will also lead to faster decomposition rates. Equally any decrease in water availability in the summer could cause peat loss and bog contraction.

Table 10.2 Potential hydrologic changes in permafrost regions. Source: from information in Woo (1996)

Increased precipitation
Reduced proportion of snow, increased proportion of rain
Earlier melting of snow packs
More groundwater storage in deeper active layers
Increased summer evaporative losses due to higher temperatures or replacement of lichens and mosses by transpiring plants
Less overland flow across impermeable permafrost
Degradation of permafrost will add water during the transient phase of climatic change
Changes in timing, extent and duration of ice jams
Increase in surface ponding due to thermokarst development
Subterranean flow conduits may reopen

Changes in runoff in the UK

Arnell (1996) has studied the likely changes that will occur in the UK as a result of global warming. With higher winter rainfalls and lower summer rainfalls (particularly in the southeast) he forecasts for the 2050s:

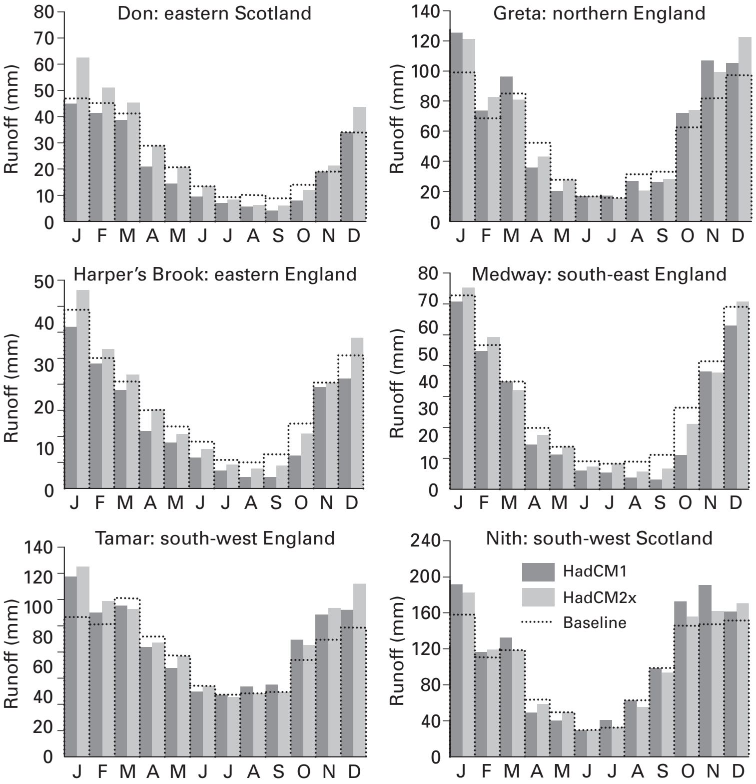

Figure 10.3 Monthly runoff by the 2050s under two scenarios for six British catchments (modified from Arnell and Reynard, 2000, figure 7.19).

1 an increase in average annual runoff in the north of Britain of between 5 and 15%;
2 a decrease in the south of between 5 and 15%, but up to 25% in the southeast;
3 an increased seasonal variation in flow, with proportionately more of the total runoff occurring during winter;
4 high flows increased in northern catchments and decreased in the south.

Figure 10.3 shows the change in monthly streamflow under two climatic scenarios for six British catchments. As can be seen, in southern England, lower summer rainfall, coupled with increased evaporation, means that streamflows decrease during summer, whereas in the catchments in northern Britain, streamflow increases in winter, but changes little in summer.

Werritty (2002) has looked specifically at Scottish catchments and has noted a particularly marked increase in precipitation in the north and west in the winter half of the year. He predicts that by the 2050s Scotland as a whole will become wetter than at present, and that average river flows will increase, notably in the autumn and winter months. He believes that high flows could become more frequent, increasing the likelihood of valley floor inundation. However, a study of the history of valley floors in upland Scotland suggests that they are relatively robust, so that although they may become subject to extensive reworking they are unlikely to undergo large-scale destabilization (Werritty and Lees, 2001).

Europe

Arnell (1999b) has modeled potential changes in hydrologic regimes for Europe, using four different GCM-based climate scenarios. While there are differences between the four scenarios, each indicates a general reduction in annual runoff in Europe south of around 50°N and an increase polewards of that. The decreases could be as great as 50% and the increases up to 25%. The proposed decrease in annual runoff in southern Europe is also confirmed by Menzel and Burger's (2002) work in Germany, who also suggest that peak flows will be reduced very substantially.

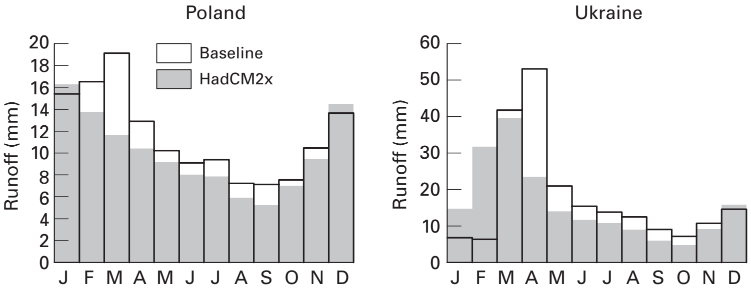

Figure 10.4 Effect of a climate change scenario on streamflow in two European snow-affected catchments by the 2050s (modified from Arnell, 2002, figure 7.20).

Rising temperatures will affect snowfall and when it melts (Seidel et al., 1998). Under relatively mild conditions, even a modest temperature rise might mean that snow becomes virtually unknown, so that the spring snowmelt peak would be eliminated. It would be replaced by higher flows during the winter. Under more extreme conditions, all winter precipitation would still fall as snow, even with a rise in temperature. As a consequence, the snowmelt peak would still occur, although it might occur earlier in the year. In Figure 10.4, for instance, in the Polish example the snowmelt peak is eliminated by the 2050s, whereas in the Ukraine example it is brought forward.

One of the most important rivers in Europe is the Rhine. It stretches from the Swiss Alps to the Dutch coast and its catchment covers 185,000 km^2 (Shabalova et al., 2003). Models suggest that the Rhine's discharge will become markedly more seasonal, with mean discharge decreases of about 30% in summer and increases by about 30% in winter, by the end of the century. The increase in winter discharge will be caused by a combination of increased precipitation, reduced snow storage, and increased early melt. The decrease in the summer discharge is related mainly to a predicted decrease in precipitation combined with increases in evapotranspiration. Glacier melting in the Alps also contributes to the flow of the Rhine. Once these glaciers have wasted away, this contribution will diminish sharply.

Other examples

Zambezi

A study of the Zambezi River in central Africa, using different GCMs and projecting conditions for 2080, indicates that river flow may decline substantially. Simulations indicate that for three scenarios the annual flow levels at Victoria Falls (Figure 10.5) reduce between 10 and 35.5% (Harrison and Whittington, 2002).

Figure 10.5 The Zambezi River at Victoria Falls.

Susquehanna, eastern USA

The Susquehanna, which flows into Chesapeake Bay, the largest estuary in the USA, is an example of a river system that will enjoy larger annual flows because of increased precipitation over its catchment (Najjar, 1999). For a 17.5% increase in annual precipitation, and a temperature increase of 2.5°C, the total predicated increase in annual streamflow is 24%.

California

One of the most pronounced features of some recent GCMs (Hadley Centre and Canadian) is that they show a projected increase in precipitation for California and the southwest. This would be the result of a warmer

Table 10.3 Predicted change in climate variables for different GCM scenarios
(a) Climate change scenarios for the 2080s (relative to 1961–1990 mean)

	HadCM2	*HadCM2-S*	*ECHAM4*
Precipitation change (%)	–12.5	–17.6	–1.6
Temperature change (°C)	+5.3	+4.4	+5.0

(b) Seasonal changes in runoff under GCM scenarios

GCM scenario	*Runoff change (%)*		
	Annual	*Wet season (January–July)*	*Dry season (August–December)*
ECHAM4	–10.0	–9.5	–12.1
HadCM2	–28.3	–28.2	–28.9
HadCM2-S	–35.5	–36.1	–32.6

(c) Estimated change in runoff in California (from Smith et al. 2001, table 1) using Canadian and Hadley GCMs*

Historical runoff (mm yr^{-1}), 1961–90	*Change in annual runoff (mm yr^{-1}), 2025–2034*		*Change in annual runoff (mm yr^{-1}), 2090–2099*	
	Canadian	*Hadley*	*Canadian*	*Hadley*
232	60	63	320	273

*The Hadley model for California proposes for the 2090s a 4.9°C increase in winter temperatures and a 4.6°C increase in summer temperatures. Annual precipitation will increase by 30%. The Canadian model equivalents are 7.1°C and 4.3°C and *c.* 70%.

Pacific Ocean causing an increase mainly in wintertime precipitation (MacCracken et al., 2001). Smith et al. (2001), using the Hadley and Canadian models, estimate that California runoff will increase by the 2030s by about three-fifths and double by the 2090s (Table 10.3).

Pacific northwest of USA

Wigmosta and Leung (2002) modeled the response of the American River in the Pacific northwest of the USA. More winter precipitation falling as rain rather than snow, and also leading to more rain-on-snow events, produced a future with greater winter flooding. However, the reduced snowpack caused fewer flows in the spring and reduced flows in summer.

Bangladesh

In a warmer world it is probable that there will be a general increase in precipitation, caused by enhancement in summer monsoon activity. This could be a cause of increased flood risk in areas such as Bangladesh.

In Table 10.4, from the work of Mirza (2002), four GCM scenarios are presented for changes in temperature and precipitation for three major catchments that create floods in Bangladesh. In addition, predicted mean peak discharges for those scenarios are presented. The current peak discharges (cubic meters per second) are 54,000 for the Ganges, 67,000 for the Brahmaputra and 14,000 for the Meghna. The four GCMs display some differences, as do predicted peak discharge values. However, overall the discharge values show a range from a modest decline to a substantial increase.

Geomorphologic consequences of hydrologic change

It is likely that changes in river flow will cause changes in river morphology, particularly in sensitive systems, which include fine-grained alluvial streams. Bedrock streams will probably be less sensitive. Ashmore and Church (2001: 41) summarize some of the potential effects:

> The potential impacts of increased discharge include channel enlargement and incision, a tendency toward either higher sinuosity single channels or braided patterns, increased bank erosion, and more rapid channel migration. Increased magnitude of large floods will result in sudden changes to channel characteristics that may trigger greater long-term instability of rivers. Increased frequency of large floods will tend to keep rivers in the modified and unstable state. Decreased discharge often results in channel shrinkage, vegetation encroachment into the channel, sedimentation in side channels, and channel pattern change toward more stable, single-channel patterns. In entrenched or confined valleys there may be reductions in the stability of the valley walls

Table 10.4 Changes in precipitation under various warming scenarios and corresponding mean peak discharge for three south Asian rivers. Source: Mirza (2002), with modifications

GCM	*ΔT (°C)*	*Ganges*			*Brahmaputra*			*Meghna*		
		ΔP (%)	*Mean peak discharge ($m^3 s^{-1}$)*	*	*ΔP (%)*	*Mean peak discharge ($m^3 s^{-1}$)*	*	*ΔP (%)*	*Mean peak discharge ($m^3 s^{-1}$)*	*
CSIRO9	2	8.5	57,790	107	–0.5	64,853	97	4.5	15,171	108
	4	17.0	62,900	116	–1.0	64,840	97	9.0	16,267	116
	6	25.5	68,010	126	–1.5	64,827	97	13.5	17,378	124
HadCM2	2	–2.8	50,963	94	7.2	70,308	105	9.7	16,017	114
	4	–5.6	49,240	91	14.4	75,757	113	19.4	17,971	128
	6	–8.4	47,523	88	21.6	81,199	121	29.1	19,927	142
GFDL	2	4.6	55,419	103	7.2	67,487	101	11.3	16,844	120
	4	9.2	58,159	108	14.4	70,107	105	22.6	19,614	140
	6	13.8	60,898	113	21.6	72,728	109	33.9	22,412	160
LLNL	2	0.5	52,996	98	1.4	65,385	98	7.7	15,958	114
	4	1.0	53,312	99	2.8	65,904	98	15.4	17,842	127
	6	1.5	53,628	99	4.2	66,423	99	23.1	19,740	141

* = Percentage of present peak discharge value.

and, hence, increases in the rate of erosion caused by a greater tendency for streams to erode the valley walls. Increased valley-side erosion will increase sediment delivery to the streams with consequences for stream morphology.

In the southeast of England, Collison et al. (2000) have also sought to model the impact of climate change on the Lower Greensand escarpment of Kent. Using the Hadley Centre GCM (HadCM2), combined with downscaling and a GIS-based combined slope hydrology/stability model, they found that because increases in rainfall would largely be matched by increases in evapotranspiration the frequency of large landslides would be unchanged over the next 80 years. They argued that other factors, such as land-use change and human activity, would be likely to have a greater impact than climate change.

Mass movements on slopes will also be impacted upon by changes in hydrologic conditions. In particular, slope stability and landslide activity are greatly influenced by groundwater levels and pore-water pressure fluctuation in slopes.

Various attempts have been made to model potential slope responses. For example, in the Italian Dolomites, Dehn et al. (2000) suggested that future landslide activity would be reduced because there would be less storage of precipitation as snow. Therefore, the release of meltwater, which under present conditions contributes to high groundwater levels and strong landslide displacement in early spring, would be significantly diminished. However, because of the differences between GCMs and problems of downscaling, there are still great problems in modeling future landslide activity, and Dehn and Buma (1999) found that the use of three different GCM experiments for the assessment of the activity of a small landslide in southeast France did not show a consistent picture of future landslide frequencies.

Geomorphologists are starting to model changes in soil erosion that may occur as a consequence of changes in rainfall (Yang et al., 2003), although it is difficult to determine the likely effects of climate change compared with future land-use management practices (Wilby et al., 1997). For example, Sun et al. (2002) calculated runoff erosivity changes for China and Nearing (2001) for the USA using the Revised Soil Loss Equation (RSLE) of Renard and Freid (1994). They adopted the UKMO Hadley climate scenario for their China study and produced a map of rainfall erosivity for 2061–2099 and suggested that for China as a whole, assuming current land cover and land management conditions, the soil erosion rates will increase by 37–93%

Table 10.5 Possible consequences of future climate change for building stone decay in the UK. Source: Viles (2002, table 3)

Region (climate change)	*Dominant building stone type*	*Process responses*	*Other threats*	*Overall response*
Northwest (warmer, wetter winters)	Siliceous sandstones and granites	Increased chemical weathering. Less freeze–thaw weathering. More organic growths contributing to soiling	Increased storm activity may cause episodic damage. Increased wave heights may encourage faster weathering in coastal areas. Increased flooding may encourage decay	Enhanced chemical decay processes and biological soiling, reduced physical decay processes
Southeast (warmer, drier summers)	Limestones	Less freeze–thaw weathering. Reduced chemical weathering as a result of less available water. Increased salt crystallization in summer. More deteriorating organic growths	Increased drying of soils (especially clay-rich soils) will encourage subsidence and building damage. Low-lying coastal areas will be particularly prone to marine encroachment. Increased drought frequency may encourage decay	Enhanced physical and biological weathering, more dust for soiling, reduced chemical weathering

across China. For Brazil, Favis-Mortlock and Guerra (1999) used the Hadley Centre HadCM2 GCM and erosion model (WEPP – Water Erosion Predictions Project). They found that by 2050 the increase in mean annual sediment yield in their area in the Mato Grosso would be 27%. For the southeast of the UK, where winter rainfall is predicted to increase, albeit modestly, Favis-Mortlock and Boardman (1995) recognized that changes in rainfall not only impacted upon erosion rates directly but also indirectly, through their effects on rates of crop growth and on soil properties. Nonetheless, they showed that erosion rates were likely to rise, particularly in wet years.

Weathering

Remarkably little work has been done on how weathering rates of rock will change with changes in climate. Two attempts, however, deserve mention. The first of these is the study by Viles (2002) on stone deterioration in the UK. There she contrasted the likely impacts of climate change on building stones between the northwest and the southeast of the country (Table 10.5). She argued that in the northwest, which would have warmer and wetter winters, chemical weathering's importance might be increased, whereas in the southeast, which would have warmer, drier summers, processes such as salt weathering might become more important. Viles (2003) has also tried to model the impacts of climate change on limestone weathering and karstic processes in the UK (Figure 10.6), but the model has wider significance and could be applied to karst areas

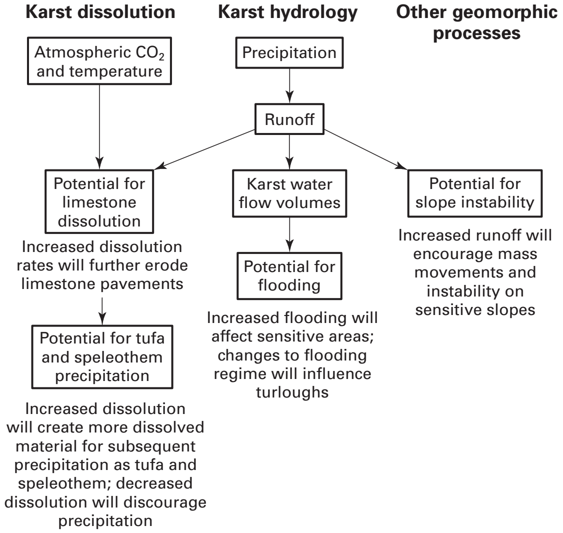

Figure 10.6 Conceptual model of the impacts of effective precipitation, air temperature, and atmospheric CO_2 concentration on karst dissolution, hydrology, and other geomorphic processes. (Source: Viles, 2003, figure 1.)

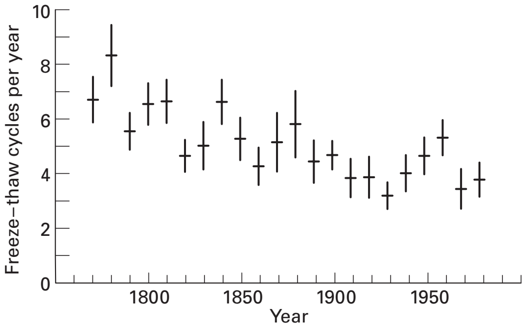

Figure 10.7 Decadal means of the freeze–thaw cycles in central England. (Source: Brimblecombe and Camuffo, 2003, figure 3.)

worldwide. Finally, as the climate warms, the number of freeze–thaw cycles to produce frost weathering in areas such as central England are likely to decrease, as they did during the warming of the nineteenth and twentieth centuries (Figure 10.7) (Brimblecombe and Camuffo, 2003).

Points for review

Will rainfall amounts and intensities change in a warming world? Where may these be greatest?
What are the likely ways in which rivers in (a) periglacial and (b) arid environments respond to global warming?
To what extent may rates of soil erosion, mass movements, and rock weathering change in coming decades?

Guide to reading

Arnell, N. W., 2002, *Hydrology and global environmental change.* Harlow: Prentice Hall. A discussion of the responses of river systems to climate change.

Sidle, R. C. (ed.), 2002, *Environmental change and geomorphic hazards in forests.* Wallingford: CABI. A consideration of the ways in which mass movements and other hazards may change in the future.