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Global warming and fluvial geomorphology

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Abstract

Future global warming has a number of implications for fluvial geomorphology because of changes in such phenomena as rates of evapotranspiration, precipitation characteristics, plant distributions, plant stomatal closure, sea levels, glacier and permafrost melting, and human responses. Potential changes in rivers are outlined in this review in the context of changes in the intensity of rainfall, the activity of tropical cyclones, runoff response (including that of Europe, dry lands and high latitude environments), and geomorphological reactions, including rates of soil erosion. In general, however, much work remains to be done to establish the full range of geomorphological responses that may take place in fluvial systems.

Keywords: Global warming; Fluvial geomorphology; Runoff; Snow pack; Deltas

1. Introduction

Over past millennia, humans have had a plethora of impacts on fluvial systems, directly (as, for example, by the construction of dams and embankments) or indirectly (as, for example, by changes in land cover) (Goudie, 2006). Now, however, it is likely that we are entering a new era of anthropogenic influence on rivers (Table 1) because of climatic changes associated with the greenhouse effect and global warming (Jones et al., 1996; Arnell, 1996; Meteorological Office, 2005). Many climatological, hydrological and vegetational scenarios have been developed for future decades, but these have not been matched for the most part by the development of scenarios of future geomorphological change in fluvial systems.

In themselves increases in temperatures, estimated by the Intergovernmental Panel on Climate Change (IPCC, 2001) to be between 1.5 and 6 °C on a global basis by 2100, will tend to melt snow and ice and promote greater loss of soil moisture through increased evapotranspiration. A few restricted areas might suffer modest cooling, but the overall picture is one of rising temperatures. In addition, changes will occur in the amount, intensity, duration, type and timing of precipitation, which will affect river flows and groundwater recharge. On a global basis it is possible that runoff will increase in a warmer world because of a global increase in precipitation (Douville et al., 2002) and historical discharge records indicate that global runoff increases by ca. 4% for each 1 °C rise in temperature (Labat et al., 2004). Major regional differences, however, will occur. For example, in the subtropics an enhanced Hadley Circulation and associated accentuation of subsiding air may have a drying impact. In some parts of the world increasing intensities of tropical storms may create more

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Table 1
Some key changes in the hydrological system associated with elevated levels of the atmospheric greenhouse

1) Changes in precipitation amount and seasonal distribution
2) Possibly increased intensity of precipitation
3) Change in balance between snow and rain
4) Increased evapotranspiration and loss of soil moisture
5) Changes in vegetation cover brought about by temperature and precipitation change
6) Consequential changes in human land management
7) Change in balance between snow and rain
8) Melting of glacier ice and of permafrost
9) Change in fire risk
10) Impact of sea level rise on coastal deltas
11) Effects of elevated levels of carbon dioxide on plant physiology, transpiration and water use

extensive flooding, whereas in others stream flows will be greatly reduced as a result of increasing droughts. Furthermore, vegetation cover will respond to temperature and precipitation changes and to fire frequency, with concomitant changes in sediment yields and the operation of erosional processes. Climate change will also promote further human interventions in river basins, with, for example, greater use of irrigation in areas subjected to an increased risk of drought (Conway et al., 1996). Higher atmospheric CO_2 levels may stimulate plant growth and lead to changes in the efficiency of water use by plants and, thus, to transpiration and runoff (Eckhardt and Ulbrich, 2003; Morgan et al., 2004). Finally, changes in sea level may have profound implications for large river deltas depending on the balance between deltaic aggradation and increasing marine inundation.

The nature of the changes caused by climatic changes, as opposed to changes brought about by other human activities, is going to be to a certain extent dependent on scale. Ashmore and Church (2001) have argued that future effects of land-use change will tend to dominate in smaller drainage basins, where a large proportion of the basin area may be affected. On the other hand, in larger drainage basins, where land-use change is seldom sufficiently widespread to affect the entire basin, climatic effects will tend to dominate.

The complexity of future changes in the environment makes effective prediction and modeling extremely difficult (Blum and Törnqvist, 2000). As Bogaart et al. (2003) have pointed out, landscape response to climate change is highly non-linear, and characterized by numerous feedbacks between different variables and by lead–lag phenomena. The example they give is of an increase in precipitation in an initially semi-arid area. This would by itself increase hillslope erosion and the capacity to transport sediment. Over time, soil and vegetation conditions, however, would adjust to the new environmental conditions, resulting in a better soil structure and more vegetation. As a result, after a lag of time, hillslope erosion and sediment yield might decrease. The extensive literature on valley alluviation and *arroyo* trenching in the American southwest is probably relevant in such debates, if only because it demonstrates the complexity and speed of response to such trends as drought, increased rainfall intensity, and human interference with land cover (see, for example, Waters and Haynes, 2001).

This paper will review the current state of knowledge with respect to (i) some key changes in precipitation characteristics (rainfall intensity and the role of cyclones), (ii) predicted runoff responses, (iii) geomorphological responses in some key environments — dry regions, cold regions, the UK and Europe, and river deltas, and (iv) some general geomorphological consequences of hydrological change. What may become clear from this review, is just how little work has been done by geomorphologists, using available climatological and hydrological scenarios, to develop scenarios of future geomorphological change.

2. 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). During recent warm decades, some evidence exists that rainfall events in a number of countries have become more intense. Examples are known from the United States (Karl and Knight, 1998; Kunkel, 2003), 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 United Kingdom an upward trend has occurred in the largest winter rainfall events (Osborn et al., 2000).

Various reasons exist to expect increases in extreme precipitation if and when significant warming occurs. More moisture will occur in the atmosphere, and greater thermodynamic instability is likely (Kunkel, 2003).

Under increased concentrations of greenhouse gases, some GCMs exhibit enhanced intensities of mid-latitude and global precipitation 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; Christensen and Christensen, 2004). 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 although the increases had only occurred in certain decades and in certain places, in general terms the frequency of great floods had increased substantially during the twentieth century, particularly during its warmer later decades. Their model suggested that this trend will continue in coming decades. Probabilistic analysis of General Circulation Models (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 for extreme summer precipitation for the latter. Increased monsoonal rainfall would have potentially grave implications for flooding in countries like Bangladesh.

3. Tropical cyclones

Were an increase in hurricane intensity and frequency to occur in a warmer world, numerous geomorphological consequences would result in low latitudes, including accentuated river flooding and coastal surges, the triggering of landslides, and accelerated land erosion and siltation (DeSylva, 1986).

Whether such an increase will occur is far from clear. The IPCC (2001: 606) stresses that considerable debate continues as to whether or not the frequency, distribution, tracking and intensity of tropical cyclones (hurricanes) will change in a warmer world. Evidence suggests that peak intensity may increase by 5–10% and that precipitation rates may increase by 20–30%. Walsh (2004) has reiterated that currently no detectable changes appear in the observed characteristics of tropical cyclones that can genuinely be ascribed to global warming. In the future, no significant change in regions of formation is likely, and little evidence of substantial changes exists in the poleward extent of active tropical cyclones, once they leave the tropical regions of formation. Moreover, as Goldenberg et al. (2001) have pointed out, although the sea surface temperatures in the North Atlantic have exhibited a warming trend over the last 100 years and cyclone activity was high in the last years of the twentieth century, Atlantic hurricanes have not exhibited trend like variability over the last century, but rather distinct multidecadal cycles. In other words, factors other than or additional to sea surface temperature play a role. Trenberth (2005) has argued that these factors include an amplified high-pressure ridge in the upper troposphere across the eastern and central North Atlantic and reduced vertical wind shear over the central North Atlantic (which tends to inhibit vortex formation).

Emanuel (1987), however, used a GCM which predicted that with a doubling of present atmospheric concentrations of CO_2 an increase of 40–50% in the intensity of hurricanes will occur. 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/s wind speed, an increase of 5–12%. Similarly, Emanuel (2005) has suggested that tropical cyclones have become increasingly destructive over the last 30 years and that this can be related to warmer temperatures at the sea surface. Henderson-Sellers and Blong (1989) argued that under greenhouse conditions on the margins of the Great Sandy Desert near Port Hedland, in NW Australia, the number of cyclones crossing the coast will approximately triple from around 4 per decade to 12 per decade.

Some scientists (*e.g.* Trenberth and Hoar, 1997) have suggested that ENSO (El Niño Southern Oscillation) events will be altered under global warming conditions, and that the ENSO phenomenon is also related both to hurricanes and generation of rainfall (Viles and Goudie, 2003). 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 causes increases in tropical cyclone formation (*e.g.* the South Pacific and the North Pacific between 140°W and 160°E), while in others it tends to bring decreases (*e.g.* the North Atlantic, the Northwest Pacific and the Australian region). La Niña phases typically bring opposite conditions.

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 United States is 28% during El Niño years, 48% during neutral years and 66% during La Niña years. Very large differences can occur in hurricane landfalls from decade to decade. In Florida, over the period 1851–1996, the number of landfalls by hurricanes ranged from 3 per decade (1860s and 1980s) to 17 per decade (1940s) (Elsner and Kara, 1999).

Severe El Niños, like that of 1997/1998, can have a remarkable effect on hurricanes and also on the amount of rainfall. This was shown with particular clarity in the context of Peru (Bendix et al., 2000), where normally hyper-arid locations suffered huge storms so that major floods resulted (Magilligan and Goldstein, 2001). At Paita (mean annual rainfall 15 mm), 3803 mm was recorded in 1998.

4. Runoff response

The modeling capability in this area is still highly imperfect and different models indicate differing degrees of sensitivity to climatic change (Nash and Gleick, 1991;

Nijssen et al., 2001). Studies of the response of runoff to climate changes have tended to indicate that the volume of annual runoff 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, 1999b: Najjar, 1999) with arid catchments showing a greater sensitivity than humid climates (Gordon and Famiglietti, 2004). 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.

Another key aspect of the runoff response to climate change is that, as historical records show, higher than average annual precipitation leads to higher stream flow and 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.

Attempts to map future trends of runoff on a global basis have been made by Douville et al. (2002), Arnell (2002) and Wetherald and Manabe (2002). Wetherald and Manabe (2002) suggest that given predicted changes in evapotranspiration and rainfall, runoff will increase globally by about 7.3% by mid-century. What is striking about this work, however, is the large range of responses in different regions. Some areas will become very markedly prone to greatly reduced annual runoff (*e.g.* New England (Huntington, 2003)), while others will see an enhancement of flows, including extreme events (*e.g.* Sierra Nevada, California (Kim, 2005)). The degree of change will vary substantially according to the levels of CO_2 in the atmosphere and the consequent amount of temperature change. The patterning at a global scale, however, indicates that by the 2080s, high latitudes in the Northern Hemisphere, together with parts of Central Africa and Central Asia, will have higher levels of annual runoff, whereas Australia, southern Africa, north west India, the Middle East and the Mediterranean basin will show reduced levels of runoff. Some tendency exists, to which the Taklamakan of Central Asia appears to be an exception, for some major deserts (*e.g.* Namib, Kalahari, Australian, Thar, Arabian, Patagonian and North Sahara) to become even drier. Also, shifts will occur in the seasonality of flow, and so, for example, models suggest that California will experience decreases in summer flows, increases in winter flows, and a shift of flow to earlier in the year (Maurer and Duffy, 2005).

5. Dry regions

Some dry regions will suffer particularly large diminutions in the levels of soil moisture (Wetherald and Manabe, 2002) and annual runoff (sometimes 60% or more). Drylands appear to be more vulnerable than humid regions (Guo et al., 2002). The sensitivity of runoff to changes in precipitation is complex, but in some environments quite small changes in rainfall can cause proportionally larger changes in runoff. As rainfall amounts decrease, the proportion that is lost to stream flow through evapotranspiration increases.

The sensitivity of dryland catchments has been indicated for two areas of southern Australia by Chiew et al. (1996: 341):

> In the southwest coast and the South Australian Gulf about 70% of the annual rainfall of 500 to 1000 mm occurs in the winter-half of the year. The streams in these regions generally flow for only 50% of the time, and on average less than 10% of the annual rainfall becomes runoff. It is also common for the total annual runoff to come from only one or two significant flow events during winter. The simulations indicate that the average annual runoff increases at a much faster rate than the corresponding increase in rainfall. A rainfall increase of 10% enhances runoff by 50%, an increase of 20% more than doubles runoff and an increase of 40% results in runoff being almost four times greater. A decrease in rainfall has a potentially more serious consequence as the amount of stream flow drops very quickly. A decrease in rainfall by 20% reduces runoff by one third while a decrease of 40% reduces runoff by 90%.

Highly significant runoff changes and rates of aquifer recharge (Rosenberg et al., 1999) may also be anticipated for the semi-arid environments of the southwest United States (Thomson et al., 2005). The early model of Revelle and Waggoner (1983) suggests that the effects of increased losses of evapotranspiration, as a result of a 2 °C rise in temperature, would be particularly serious in those regions where the mean annual precipitation is less than about 400 mm. Projected summer dryness in such areas may be accentuated by a positive feedback process involving decreases in cloud cover and associated increases in radiation absorption on the ground consequent upon a reduction in soil moisture levels (Manabe and Wetherald, 1986). Shiklomanov (1999) has suggested that in arid and semi-arid areas, as a whole, an increase in mean annual temperature by 1° to 2° and a 10% decrease in precipitation could reduce annual runoff in rivers by up to 40–70%.

Channels in arid regions are particularly sensitive to changes in the characteristics of precipitation and runoff (Nanson and Tooth, 1999). They can display rapid changes between incision and aggradation over short time periods in response to quite modest changes in climate. This is particularly true in the case of the arroyos of the American southwest (Balling and Wells, 1990), which have undergone major changes in form since the 1880s. Considerable debate addresses the causes of phases of trenching, and it is far from easy to disentangle anthropogenic from climatic causes, but in many cases fluctuations in either the amount or intensity of rainfall have been the controlling factor (Hereford, 1984; Graf et al., 1991). Thus, the sort of changes in precipitation and runoff discussed in this paper could have a profound influence on channel characteristics.

6. Cold regions

Many factors are to be considered in an analysis of the response of cold region hydrological systems to climate change (Table 2) and good reviews are provided by Woo (1996) and Rouse et al. (1997). In the Arctic, the overall amount of moisture in the atmosphere is expected to increase as the atmosphere warms, leading to a general increase precipitation and in river discharges. Peterson et al. (2002) have analyzed discharge records for the six largest Eurasian rivers that flow into the Arctic Ocean and have shown that as surface air temperatures have increased so has the average annual discharge of freshwater. It grew by 7% from 1936 to 1999. They suggest that increased levels of warming (1.5 to 5.8° by 2100) there would represent an 18 to 70% augmentation in Eurasian Arctic river discharge over present conditions. Wetherald and Manabe (2002) suggest that by the middle of this century the runoff from such major rivers, as the Mackenzie and Ob, could be increased by more than 20%. This analysis is largely confirmed by Wu et al. (2005) and McClelland et al. (2004), who believe that the main driver of the larger river discharge in the area is the increasing northward transport of moisture as a result of global warming. Prowse and Beltaos (2002) and Beltaos and Burrell (2003) explore the effects that climate change could have on ice jams and, thus, on the size and seasonality of floods and low flows, with the occurrence of ice break-up occurring earlier in the year. This appears to have been the case in the last several decades (Yoo and D'Odorico, 2002).

The amount of snow pack accumulation is another major control on hydrological conditions in cold regions (Nijssen et al., 2001; Barnett et al., 2005). Winter snow accumulation in alpine watersheds provides most of the runoff to streams in western North America and similar regions of the world. Following a global analysis of future hydrological trends, Nijsssen et al. (2001) suggested that the largest changes in the hydrological cycle are predicted for the snow-dominated basins of mid to higher latitudes, and in particular marked changes are likely in the amplitude and phase of the annual water cycle (Arora and Boer, 2001). Lapp et al. (2005) have modeled the likely response of snow pack accumulation to global warming in the Canadian Rockies, and have suggested that (a) a substantial decline will occur in the over-winter snow accumulation in most years, and (b) that the spring volume of runoff may substantially decrease with the decline in snow packs. This is confirmed by the work of Mote et al. (2005), who provide an historical analysis of changes in the conditions of snow packs in recent warming decades. They indicate that the losses in snow pack to date will continue and even accelerate, with faster losses in milder climates like the Cascades and the slowest losses in the high peaks of the Rockies and southern Sierra.

The predicted fast retreat of glaciers, particularly in tropical regions, can have a series of geomorphological effects that could be costly to society. Increased rates of melting for a period of years may cause a greater incidence of summer melt water floods, but when the glaciers have disappeared, the volume of river flow may be drastically reduced (Braun et al., 2000). This is of great concern, for many great rivers depend on a glacial contribution to the flow. Melting glaciers, for example, account for 70% of the summer flow in the Ganges. As Barnett et al., 2005, p. 306) have remarked, 'It appears that some areas of the most populated region on Earth are likely to 'run out of water' during the dry season if the current warming and glacial melting trends continue for several more decades'. Moreover, lakes in areas such as the Himalayas of Nepal and Bhutan are rapidly expanding because they are fed by increasing amounts of melt water and may become more hazardous if the

Table 2
Some factors involved in the response of river systems to global change in cold regions

1) Increasing high latitude precipitation
2) Higher than global average temperature increases
3) Change in balance between snow and rain
4) Earlier melt of snow pack
5) Release of water from melting ice caps and glaciers
6) Changes in timing and extent of ice jams
7) Development of increased depression storage as a result of thermokarst formation
8) Promotion of river bank erosion as a result of permafrost decay
9) Increased sediment delivery from debris flows as thickness of active layer on slope increases
10) Enhanced transport of subsurface water through unfrozen soils

natural dams are breached or overtopped (Vilímek et al., 2005). Likewise, as slopes over steepened by previous glacial erosion are deprived of the buttressing effects of glaciers, they can become unstable and generate a risk of increased landsliding and debris avalanches (Kirkbride and Warren, 1999; Holm et al., 2004). Haerberli and Burn (2002) have shown the association between glacier retreat, since the Little Ice Age, and processes of slope movements, such as gravitational deformations of rock slope, rock avalanches, debris flows, and debris slides.

Regions underlain by permafrost may be especially prone to the effects of global climate change. First of all, the permafrost itself is by its very nature and definition susceptible to the effects of warming. Secondly, the amount of temperature increase predicted for high latitude environments is greater than the global mean. Thirdly, permafrost itself is an especially important control of a wide range of hydrological and geomorphological processes and phenomena, including slope stability, groundwater flow and recharge, rates of river bank erosion, ground subsidence (thermokarst formation) and surface runoff. Fourthly, the nature (*e.g.* rain rather than snow) and amount of precipitation may also change substantially. Fifthly, the northern limits of some very important vegetation zones, including boreal forest, shrub–tundra and tundra may shift latitudinally by some hundreds of kilometers. Changes in snow cover and vegetation may also have a considerable impact on the state of permafrost because of their role in insulating the ground surface. For example, if spring temperatures were to increase and early spring snowfall became rain, the duration of snow cover would decrease, surface albedo would also decrease, leading to an increase in air temperatures, and the snow might provide less insulation. This could cause relatively rapid permafrost degradation (Ling and Zhang, 2003). Conversely, if the warming were to occur in rather more severe periglacial climates, where temperatures are predicted to remain below or at freezing, the winters could become warmer, and wetter, producing an increase in the longevity and depth of the snow pack. This could lead to more insulation (retarding the penetration of the winter cold wave) and a reduction of warming because of an increase in surface albedo. A good general review of the likely environmental consequences of climate change in the tundra of Canada is provided by Smith (1993).

A particularly interesting analysis of recent trends of temperature and stream flows in the permafrost region of Northeast China is provided by Liu et al. (2003). Warming has changed the depth of the active layer, enabling enhanced transport of subsurface water through unfrozen soils and a greater contribution of this flow to winter base flow. Stream flow data for the period 1958 to 1998, indicated significantly greater runoff, with flow during February and March in the 1990s increasing by 80–100% over prior values.

7. The UK and Europe

Some of the main tendencies in runoff that are likely to occur in Europe are listed in Table 3. Arnell (1996) has studied the likely hydrological changes that will occur in the UK. With higher winter rainfalls and lower summer rainfalls (particularly in the southeast) he forecasts for the 2050s:

i) An increase in average annual runoff in the north of Britain of between 5 and 15%.
ii) A decrease in the south of between 5 and 15%, but up to 25% in the southeast.
iii) An increased seasonal variation in flow, with proportionately more of the total runoff occurring during winter.
iv) High flows increased in northern catchments and decreased in the south.

In southern England, lower summer rainfall, coupled with increased evaporation, means that stream flows will probably decrease during summer, whereas in the catchments in northern Britain, stream flow will increase in winter, but change little in summer.

Werritty (2002) has looked specifically at Scottish catchments and has noted that GCM scenarios suggest 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 inundation of the valley floors. A study of the history of valley floors in upland Scotland, however, suggests that they are relatively robust, many of them being armored by coarse sediments, so that although they may become subject to extensive reworking, they are unlikely to undergo large-scale destabilization (Werritty and Lees, 2001).

Table 3
Some major tendencies affecting fluvial systems in Western and Central Europe in a warmer world

1) Increased winter precipitation and decreased summer precipitation
2) General intensification of precipitation
3) Increased moisture loss through increased evapotranspiration
4) Less winter snow pack
5) Earlier melting of snow pack
6) Smaller glacial contribution to summer flow

In mainland Europe, vulnerability to flooding seems to be increasing because of such factors as the occupation of floodplains by more people and the engineering structures, and unusually severe floods affected much of the continent during the 1990s and early 2000s (Mitchell, 2003). Therefore, a major question is the extent to which future flooding may be exacerbated by climate change. Planton et al. (2005) have suggested that extreme events of winter precipitation may become more common. More generally, Arnell (1999a) has modeled potential changes in hydrological regimes for mainland Europe, using four different GCM-based climate scenarios. While differences exist 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 Menzell and Burger's (2002) work in Germany, for they also suggest that peak flows will be very substantially reduced. A model by Eckhardt and Ulbrich (2003) for the Rhenish Massif in Germany found that in summer mean monthly groundwater recharge and stream flow may be reduced by up to 50%.

Rising temperatures will affect snowfall and snowmelt (Seidel et al., 1998). Under relatively mild conditions, even a modest temperature rise might mean that snow becomes virtually unknown, being replaced by rain, so that the spring peak attributed to snowmelt would be eliminated. It would be replaced by higher flows during the winter. Under more extreme climatic 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.

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

8. River deltas

The coastal deltas of many rivers are likely to be impacted by higher sea levels associated with global warming (Broadus et al., 1986). They are also zones of subsidence because of crustal depression by sediments (Milliman and Haq, 1996). The degree to which they will suffer from inundation, however, depends to a substantial degree on the rate at which compensating sediment accretion occurs (Milliman et al., 1989; Warrick and Ahmad, 1996). That in turn may be affected by changes in land cover upstream, by sedimentation behind dams, by embankment construction, and by sediment retention in irrigation channels (Stanley, 1996). A common problem in deltas, like those of the Nile and the Mississippi, is that they are being substantially undernourished with sediment because of these factors (El-Raey, 1997). Such deltas may be especially prone to the effects of sea level rise and isostatic subsidence. Another factor that will influence the morphology of river deltas will be vegetation changes caused by changing salinity levels and by migration of species such as mangroves (Day et al., 2005). Moreover, the changing activity of cyclones and associated storm surges may be hugely effective in moulding the morphology. Upstream changes in soil erosion, slope instability, and discharge may also be significant in delta morphology (Sánchez-Arcilla and Jiménez, 1997).

9. Geomorphological consequences of hydrological change

Changes in river flow will likely cause changes in river morphology, particularly in sensitive systems, which include fine-grained alluvial streams. Bedrock channels and armored stream beds, however, 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, 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.

Geomorphologists are starting to model changes in soil erosion and sediment yield that may occur as a consequence of changes in the amounts and intensities of rainfall (Nearing, 2001; Yang et al., 2003; Nearing et al., 2005) though it is difficult to determine the likely effects of climate change compared to future land use management practices (Wilby et al., 1997). If farmers react to climate change by implementing different crops and land use, erosion and deposition patterns will also be changed. For example, row crops, such as vines and maize, may become much more prevalent in southern Britain as temperatures rise, and this could be at the expense of some present land uses (such as grasslands for dairy herding) and this could lead to accelerated runoff and erosion. It is also necessary to consider the indirect effects that climate change has on rates of erosion through its modification of land cover and biomass. Rates of erosion are also highly affected by fires, and evidence exists that fire frequencies will respond to changes in climate, especially to increasing drought, windiness, and the frequency of lightning strikes. An analysis by Flannigan et al. (2000) suggests that the severity of future fires could increase over much of North America. They anticipate increases in the area burned in the USA of 25–50% by the middle of the twenty-first century, with most of the increases occurring in Alaska and the southeast USA.

Sun et al. (2002) calculated the erosivity changes from runoff for China using the Revised Universal Soil Loss Equation (RUSLE) of Renard and Freid (1994), though it needs to be remembered that this is a field scale model rather than a continental scale model. They adopted the UKMO Hadley Centre climate scenario for their China study and produced a map of rainfall erosivity for 2061–2099. They suggested that for China as a whole, assuming current land cover and land management conditions, that the rates of soil erosion will increase by 37–93% 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 yield of sediment in their areas 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 impacted upon rates of erosion directly, and also through the effects on rates of crop growth and on soil properties. Nonetheless, they showed that rates of erosion were likely to rise, particularly in wet years. In the USA, after analyzing a range of different models, Nearing et al. (2005, p. 151) remarked:

> If rainfall amounts during the erosive times of the year were to increase roughly as they did during the last century in the United States, the increase in rainfall would be on the order of 10%, with greater than 50% of that increase due to increase in storm intensity. If these numbers are correct, and if no changes in land cover occurred, erosion could increase by something on the order of 25–55% over the next century.… Both storm water runoff and soil erosion are likely to increase significantly under climate change unless offsetting amelioration measures are taken.

10. Conclusions

River systems will respond to global warming in some very significant ways, notably in cold, tropical and arid regions, but also more generally. Some areas will experience overall increases in runoff, while others will experience decreases. More intense rainfall may cause more widespread flooding in some catchments. The annual flow regimes will be modified by changes in such phenomena as snow packs. While bedrock and armored channels may be robust, alluvial channels may be substantially more sensitive to discharge changes, as the history of the arroyos of the American Southwest has so clearly shown. Rates of erosion and sediment yields will also change in response to precipitation changes, fire frequencies and land cover changes. Modeling studies from a range of different environments suggest that the increases in rates of erosion could be on the order of 25–50%. Coastal deltas will respond to the combined effects of sea level rise, local subsidence, and the speed of sediment accretion.

Therefore, while geomorphologists, following the lead of George Perkins Marsh, have historically tended to examine the effects of a range of anthropogenic processes on river systems, such as land use change, dam construction, water abstraction and inter-basin water transfers, we are now entering an era when such processes, while continuing to operate, will be joined by the many changes that will be caused by climate warming. Geomorphologists have yet to devote to this theme the same amount of attention that has been expended by, for example, life scientists and hydrologists. Remarkably few scenarios for future geomorphological changes have been developed. This is a major research priority.

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