

Responses to Rapid Environmental Change

T E Törnqvist, Tulane University, LA, USA

© 2007 Elsevier B.V. All rights reserved.

Introduction

The recognition of centennial to millennial scale environmental change, notably abrupt climate change, has sparked a great interest into how such rapidly changing boundary conditions influence landscape processes. Rivers are widely considered geomorphic entities that are highly sensitive to environmental change, but it is increasingly recognized that the fluvial response is extremely complex, with considerable spatiotemporal variability (Knox, 1983). This article provides an overview of the variety of fluvial responses to rapid environmental change and is intimately linked to the preceding article that focuses on longer-term (glacial–interglacial scale) fluvial responses (*see* Glacial-Interglacial Scale Fluvial Responses). The article will primarily discuss the effects of rapid climate change on fluvial systems in the alluvial reach (i.e., that portion of the fluvial system that is most likely to preserve – at least in a temporary fashion – a stratigraphic record); bed-rock rivers are discussed in more detail elsewhere (*see* Terrace Sequences). The first part consists of a discussion of general concepts and criteria for the recognition of fluvial responses, followed by a selection of case studies that provide examples of the different manifestations of late Quaternary fluvial responses to rapid environmental change.

General Concepts

It is usual to distinguish between climate change, base-level (commonly sea-level) change, and tectonism as the three categories of external (or allogenic) forcing of fluvial systems. In addition, distinction has been made between upstream and downstream controls. While climate change is typically an upstream control (i.e., the forcing propagates downstream through the drainage basin), sea-level change provides a distinct downstream control and can only affect the lowermost reaches of the fluvial system. Considerable debate has centered on the question of how far upstream sea-level control can propagate and it is likely that this varies greatly, depending on variables such as slope and sediment supply (Blum and Törnqvist, 2000). In principle, tectonism can affect any segment of the fluvial system. In addition,

the various allogenic controls commonly operate simultaneously.

Modes of Response to Allogenic Forcing

There are different mechanisms of fluvial response to allogenic forcing, including:

- 1) changes in the discharge regime;
- 2) changes in channel pattern (fluvial style); and
- 3) changes in the longitudinal profile by means of aggradation or degradation (incision).

Perhaps the most obvious and direct response to climate forcing is the change of discharge regime and associated changes in hydraulic geometry parameters, such as channel width, depth, and sinuosity. Such adjustments may in some cases lead to full transformations of fluvial style.

Changes in fluvial style have been the subject of research for a long time, commonly focusing on the time period around the Pleistocene–Holocene transition (Kozarski, 1983; and numerous others). Many of these investigations concern the transformation from braided to meandering channel patterns. While there is lively and ongoing debate about the boundary conditions that cause rivers to braid or meander (Van den Berg, 1995; Lewin and Brewer, 2001), it appears likely that braiding is favored by a high bed load and a high stream power (i.e., discharge and valley slope). In addition, several other factors have been mentioned in the literature (e.g., limited bank stability). Rapid climate change can modify boundary conditions that control fluvial style, but changes in fluvial style due to climate forcing can be spatially non-uniform.

Perhaps the most prolific response of the fluvial system to allogenic forcing is the adjustment of the longitudinal profile, either by aggradation or by degradation (incision). The concept of grade (Mackin, 1948) postulates that alluvial rivers strive to attain an equilibrium profile characterized by a more or less balanced sediment budget, typical of stable boundary conditions in terms of base level, discharge, and sediment supply (*see* Terrace Sequences). Disruptions of this delicate balance commonly occur by means of changes in the proportion between water discharge (Q_w) and sediment supply (Q_s). It is important to note that sediment supply in this context refers strictly to bed load, given the fact that rivers are virtually never saturated with respect to the transport of suspended load, while the supply of bed load at times exceeds sediment-transport capacity. Figure 1 shows how the balance between Q_w and Q_s dictates whether a fluvial reach will incise, aggrade, or maintain equilibrium. In this context, it is important to reiterate that disruptions in the Q_w/Q_s

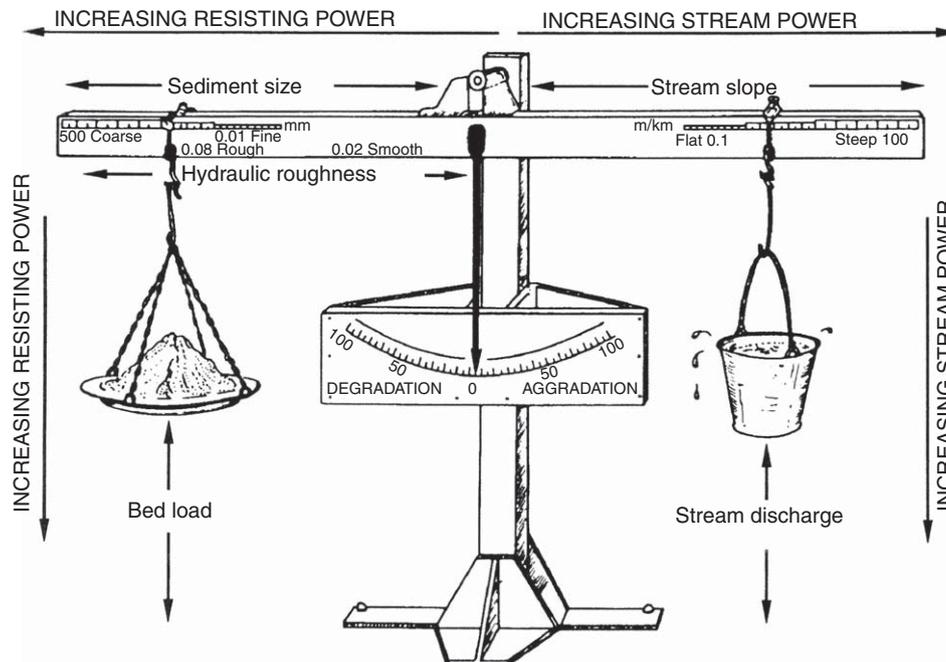


Figure 1 Balance model for aggradation and degradation (incision) in alluvial rivers, as dictated by the relative proportion of water discharge and sediment supply, referred to by Bull (1991) as the balance between stream power and resisting power. Channels aggrade when sediment supply (bed load: amount and grain size) exceeds sediment-transport capacity as determined primarily by discharge and slope, and incise when the reverse is the case. The role of base-level change can also be inferred from this conceptualization. Base-level rise tends to reduce the slope and therefore promote aggradation, whereas base-level fall may increase the slope leading to incision (also depending on the morphology of the surface that is exposed). Originated from an unpublished diagram by W. Borland; after Bull (1991). Reprinted by permission from Oxford University Press.

ratio may be accommodated by other adjustments (such as sinuosity), rather than by lowering or raising the longitudinal profile.

Recognizing Fluvial Incision

Fluvial aggradation and incision not only reflect changes in the sediment budget but also leave the most tangible imprint in the stratigraphic record. In fact, many studies of fluvial archives aim to identify fluvial unconformities resulting from phases of incision with regional significance that may be ascribed to allogenic forcing. However, the proper recognition of regional unconformities representing widespread incision has proven challenging for a number of reasons. This is due to the simple fact that river channels are erosional features by definition. Following Salter (1993) and Best and Ashworth (1997), it is therefore critical that distinction be made between fluvial scour, the autogenic (intrinsic) process that characterizes any alluvial channel (Fig. 2) versus allogenic incision. Best and Ashworth (1997), working in the vertically aggrading Ganges-Brahmaputra Delta, showed that channel scour can lead to reworking of the channel belt to depths as much as five times mean channel depth. They go on to show how the resulting stratigraphic phenomena can easily be mistaken for fluvial

incision with regional significance. In fact, numerous examples can be gleaned from the literature where channel scour in overall aggradational settings may have been misinterpreted as fluvial incision.

So how can fluvial incision and aggradation be recognized in the stratigraphic record? Given the discussion above, this is a critical, yet by no means a trivial question. Distinction should be made as to whether incision/aggradation is measured relative to the channel bed or the floodplain surface. Incision of the channel bed can be the result of base-level change, vertical crustal movements, or changes in Q_w relative to Q_s (Fig. 3A). However, changes in the discharge regime alone (i.e., the 'flashiness' of discharge) can cause floodplain aggradation or degradation, without vertical changes in the channel bed. Floodplains that are frequently inundated by deep overbank floods have the potential to aggrade to levels well above the channel bed (Fig. 3B). If lateral channel migration goes along with a reduction of the peak discharge (e.g., as a result of a decrease in the frequency of major storms) a new floodplain will, over time, be established at a lower level, leaving the previous floodplain behind as a terrace. These two mechanisms of fluvial terrace formation are shown schematically in Figures 4A and 4B, respectively, and

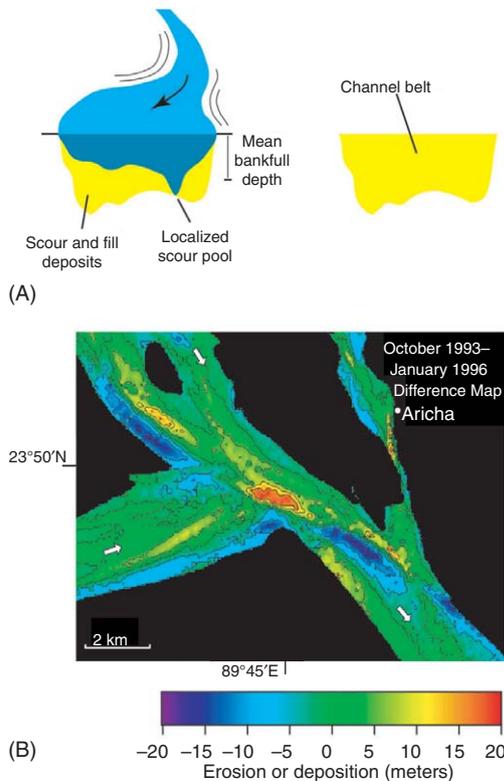


Figure 2 (A) Channel scour and fill in alluvial rivers leads to continuous reworking and deepening of the channel belt, exceeding mean bankfull channel depth (modified after Salter, 1993). (B) Repeated bathymetric surveys of the Ganges-Brahmaputra confluence show the dynamic nature of alluvial channels and their capability to form scour holes about five times the average channel depth that are likely to rework channel belts over annual to decadal timescales (after Best and Ashworth, 1997). Caution must be taken not to confuse such phenomena with fluvial incision and associated floodplain degradation. Reprinted by permission from Macmillan Publishers Ltd.

are further illustrated by means of animations available from the supplementary materials. Given these different mechanisms of terrace formation, a variety of combinations of processes are capable of producing – at least in theory – a plethora of stratigraphic results that may prove challenging to unravel (Blum and Törnqvist, 2000). For example, it cannot be ruled out that different allogenic forcings operate simultaneously and cause opposite stratigraphic results (Fig. 4C). In this hypothetical example, floodplain aggradation due to an increase in peak discharge would occur simultaneously with channel-bed incision, for instance due to a slight base-level drop, and vice versa. Finally, it should be stressed that incision as defined here is broadly defined so as to encompass floodplain degradation in the absence of channel-bed incision. Obviously, long-term incision over vertical intervals that substantially exceed mean channel depth cannot occur without channel-bed incision.



Figure 3 (A) The Sabarmati River, Gujarat, India, about 100 km upstream from Ahmadabad, bordered by a ~40-m-high terrace. The uppermost terrace deposits date to ~12 ka, whereas the bars are ~4.5 ka in age (Srivastava *et al.*, 2001), indicating spectacular incision that has been attributed to the early Holocene increase in monsoon activity that affected large sections of South Asia during this time (Tandon *et al.*, 2006). Photograph courtesy Martin Gibling. Reprinted by permission from SEPM (Society for Sedimentary Geology). (B) The Amite River in southeast Louisiana after a peak discharge event. Note the high-water mark recognizable by the mud-covered vegetation. The lower arrow shows the approximate thickness of fine-grained overbank deposits overlying sandy point-bar strata. The upper arrow indicates the minimal amount of continued floodplain aggradation that can be expected if the current discharge regime remains unaltered.

The overarching conclusion is that inferring fluvial incision and aggradation from the stratigraphic record can be most successfully done when data are available on both floodplain surfaces and channel bases. Unfortunately, this presents the problem that in the naturally incomplete stratigraphic record channel bases tend to have a much higher preservation potential than floodplain surfaces. Therefore, it is absolutely critical that the criteria for recognition of fluvial incision and aggradation be explicitly discussed. Unfortunately, often this is not the case, and the literature is riddled with examples of studies that infer longitudinal-profile adjustments while potentially misinterpreting autogenic scour phenomena as reflecting regional incision

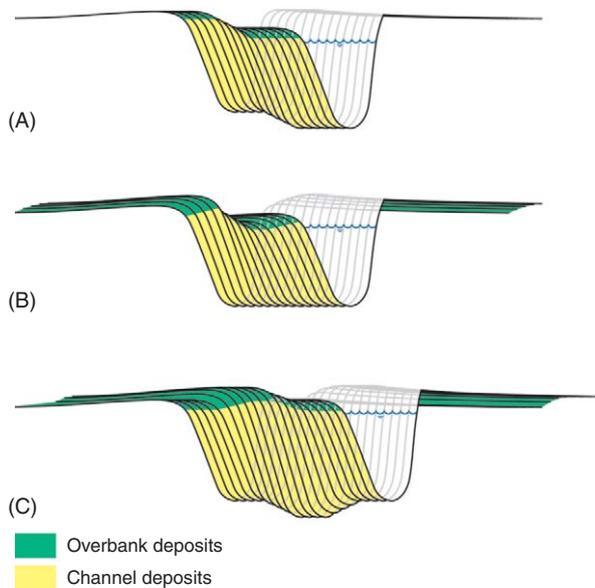


Figure 4 Hypothetical cross-sections illustrating contrasting mechanisms of fluvial incision, floodplain abandonment, and terrace formation (Blum and Törnqvist, 2000). (A) Equilibrium floodplain with lateral migration (from left to right) and minimal vertical aggradation, followed by a short phase of incision characterized by degradation of both the channel bed and the floodplain and a subsequent return to equilibrium conditions. This could be the result of either a reduction in bed load relative to discharge, a drop in base level, or tectonic uplift (or combinations thereof). (B) Fluvial system characterized by lateral migration and vertical aggradation of the floodplain due to frequent overbank flooding. A phase of floodplain degradation due to a reduction in peak discharge is followed by continued conditions of lateral migration and floodplain aggradation at a lower level. Note that the channel bed remains unchanged and that terrace formation is entirely the result of a drastic decrease in peak discharge and resulting floodplain degradation. (C) A combination of the processes operating in the previous two scenarios, where channel-bed degradation occurs simultaneously with floodplain aggradation due to increased overbank flooding. Subsequently, channel-bed aggradation coincides with reduced overbank flooding, resulting in the counterintuitive situation of simultaneous terrace formation and channel-bed aggradation. Animations of all three scenarios are available online as supplementary material.

(e.g., due to a focus exclusively on channel-belt bases rather than floodplain surfaces).

Complex Response and Response Time

A potentially large obstacle in the interpretation of fluvial stratigraphic records is the possibility of the occurrence of nonlinear responses. An experimental study by Schumm and Parker (1973) showed how a simple, rapid drop in base level can lead to alternating fluvial incision and aggradation. The concept of ‘complex response’ was subsequently discussed at length by Schumm (1977), who advocated that such nonlinearity can be caused by a variety of perturbations (sediment supply, tectonism), both upstream and downstream. The cyclic nature of the Schumm and

Parker (1973) experiment was later substantiated by mathematical modeling (Slingerland and Snow, 1988).

Regardless of the possibility of complex response, it has long been recognized that fluvial responses to environmental forcing exhibit time lags of variable duration. For example, Bull (1991) defines the geomorphic response time as the sum of the reaction time (time between the perturbation and the initial adjustment) and the relaxation time (time between the initial adjustment and renewed equilibrium). The spirit of these concepts is not unlike the theoretical work by Paola *et al.* (1992), who introduced the concept of equilibrium time (T_{eq}), defined as

$$T_{eq} = L^2/v$$

where L = basin (river) length (a proxy for the size of the drainage basin) and v = diffusivity (efficiency of sediment transport). It follows that small drainage basins that permit rapid sediment transfer are more likely to record abrupt, short-term climate changes than large fluvial systems. Recently, Castelltort and Van Den Driessche (2003) have applied this theory to 93 large rivers worldwide, suggesting that tens to hundreds of thousands of years are needed to fully accommodate changes in sediment supply and restore equilibrium conditions. In addition, these authors suggest that upstream forcing is in many cases accommodated in the fluvial transfer zone, implying that perturbations would not propagate to the river mouth. Nevertheless, as will be exemplified below, several cases have been documented of fairly rapid fluvial responses to environmental forcing, including examples from large drainage basins.

Case Studies

This article focuses on climate controls, because sea-level fluctuations that affect the downstream portions of the longitudinal profile commonly act over longer time intervals (*see* Glacial-Interglacial Scale Fluvial Responses). With the exception of episodic seismic events, tectonism also concerns longer timescales (*see* Terrace Sequences). The last glacial and its transition into the Holocene have witnessed numerous abrupt climate changes that have affected considerable parts of the globe. These changes manifest themselves as drastic fluctuations in temperature and precipitation, particularly well documented in the Greenland ice-core records (*see* Greenland Stable Isotopes). The Dansgaard-Oeschger events serve as some of the most prolific examples that were of specific importance in the North Atlantic region, but lower latitudes have experienced variations in monsoonal activity as well as higher frequency changes such as the

El Niño–Southern Oscillation. In addition, solar forcing has been proposed as another mechanism for short-term climate change.

In many respects, the Pleistocene–Holocene transition can be viewed as one of the most abrupt climate changes of the last glacial–interglacial cycle, in essence corresponding to Termination I. This is particularly the case in temperate regions of the Northern Hemisphere that were strongly influenced, either directly or indirectly, by glaciation. These are also the environments that have the longest tradition of studies of late Quaternary fluvial evolution, so the discussion below will open with a brief overview of some of those findings. The subsequent sections present selected examples of fluvial responses to climate forcing over different timescales, with a premier emphasis on longitudinal–profile adjustments. It should be noted that the subdivision of examples reflects interpretations of the stratigraphic record by the respective authors, based on a variety of observational data. The examples range from monsoonal fluctuations that operate over 10^3 – 10^4 year timescales, to Dansgaard–Oeschger style abrupt (10^2 – 10^3 years) climate changes that have been particularly prominent in the North Atlantic region, as well as higher frequency and lower amplitude (10^0 – 10^3 years) climate fluctuations with variable causes that characterize the Holocene. The examples provided here not only concern different timescales but also contrasting environmental settings, ranging from the tropics to temperate regions (with the latter predominantly subarctic during the last glacial).

Pleistocene–Holocene Transition

A long tradition exists of studies of fluvial channel-pattern changes across the last glacial to interglacial transition, particularly in temperate regions outside of the former centers of glaciation. Such investigations have been numerous in the northwest European lowlands that experienced an overall transformation from periglacial conditions with sparse vegetation cover to temperate, deciduous forests with climate conditions roughly comparable to those of the present. For example, detailed mapping by Berendsen and Stouthamer (2001) of the floodplains and adjacent terraces of the lower Rhine and Meuse Rivers near the Dutch–German border (Fig. 5) shows that braided channel patterns dominated during the last glacial, rapidly giving way to meandering planforms in the Holocene. Numerous investigators have argued that braiding was promoted by a high supply of bed load due to a lack of vegetation cover and active periglacial hillslope processes. In contrast, increased stabilization of soils and riverbanks by vegetation during the Holocene favored the transition to meandering patterns. These findings have been mostly substantiated by recent modeling (Bogaart *et al.*, 2003a).

It is interesting to note that strikingly similar changes in fluvial style have been mapped along the Rhine and Meuse (Fig. 5), despite the different character of these two rivers around the Pleistocene–Holocene transition, with the Rhine – unlike the Meuse – draining a substantially glaciated hinterland.

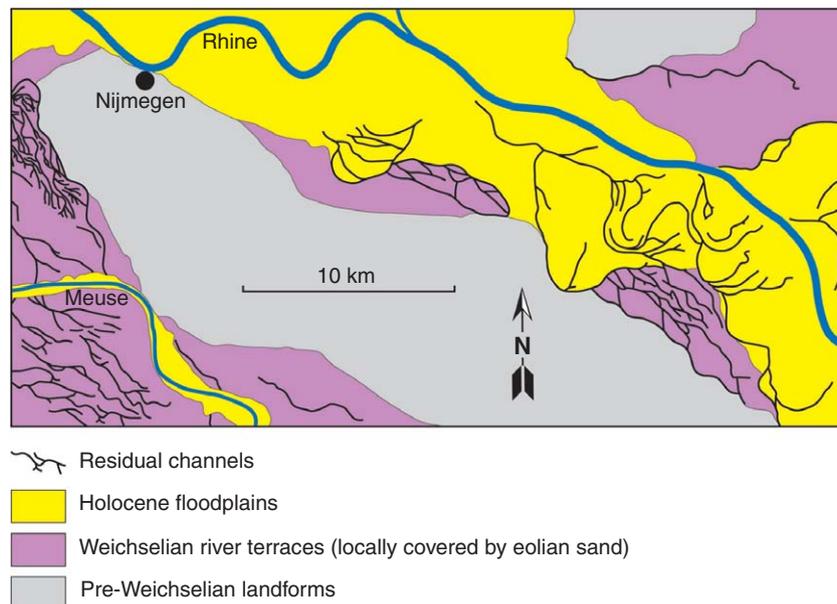


Figure 5 Channel patterns along the Rhine and Meuse Rivers during the late Pleistocene and Holocene near the Dutch–German border (after Berendsen and Stouthamer, 2001). Note the braided channel patterns on the Weichselian (late Pleistocene) terraces, as opposed to the meandering Holocene fluvial style.

Similar observations have been made in North America, with braided channel patterns dominating both glaciated drainage basins such as the Mississippi River (Fisk, 1944; Saucier, 1994) and ice-free settings along the Atlantic Coastal Plain (Leigh *et al.*, 2004) during the last glacial. As will be discussed in more detail below, higher frequency changes in fluvial style and longitudinal-profile adjustments occurred during the Pleistocene–Holocene transition in northwest Europe.

Monsoonal Forcing

Precession-dominated fluctuations in monsoonal activity in low-latitude regions are well documented. A number of recent studies highlight the associated dramatic responses of fluvial systems over millennial or slightly longer timescales, including extensive work in the Himalayan Foreland Basin. Tandon *et al.* (2006) present a large body of data from the drainage basin of the Ganges River, suggesting that widespread fluvial incision (commonly on the order of tens of meters), floodplain abandonment, and terrace formation was especially prominent during time intervals with a strengthened monsoon, particularly the period from about 15 to 5 ka. Similar processes operated farther west in India (Fig. 3A). The preceding period around the Last Glacial Maximum, when the southwestern monsoon was suppressed and discharge was substantially lower, was characterized predominantly by fluvial aggradation. Goodbred (2003) pointed out similar relationships and demonstrated the intimate connection between accelerated incision in the drainage basin of the Ganges River during the hypsithermal (notably the early Holocene) and accelerated sedimentation rates in the Ganges-Brahmaputra Delta (*see* Deltaic Environments). The significance of this finding is that this giant sediment-dispersal system was capable of transmitting a climate signal over a very short (millennial) timescale, from source to sink. Studies like the ones discussed here have been possible because of rapid advances in optically stimulated luminescence dating and its application to strata that previously lacked robust age control.

Dansgaard–Oeschger Style Forcing

The North Atlantic region could be viewed as the type area for abrupt climate change, particularly during the last glacial. The Dansgaard–Oeschger events, characterized by sudden warming that lasted for no more than a few thousand years before reversing back to glacial conditions, are likely to have caused major landscape changes. By far the best-documented Dansgaard–Oeschger event is the most recent one

(Bølling–Allerød–Younger Dryas), constituting the final episode of the last glacial. Numerous studies of northwest European rivers have revealed at least some commonality in changes of fluvial styles and terracing during this time interval. The Meuse River in The Netherlands has been particularly extensively studied (Huisink, 1997; Tebbens *et al.*, 1999). Although these two investigations use conflicting age models they share a number of findings, including a rapid (Tebbens *et al.*, 1999) or gradual (Huisink, 1997) transition from full-glacial braided channel patterns to a meandering fluvial style during the Allerød, reversing back to braiding during the Younger Dryas. In addition, several phases of incision and aggradation have been inferred, although some of these have been subsequently questioned by Bogaart *et al.* (2003b) who drew the attention to the same ‘scour versus incision’ problem as discussed above. Nevertheless, Bogaart *et al.* (2003b), using a novel modeling approach aimed explicitly at understanding centennial to millennial scale climatic forcing of fluvial systems, show the plausibility of short-lived incision associated with abrupt climate change, comparable to the pioneering work by Knox (1972) that is discussed below. This finding is consistent with floodplain degradation at the Allerød–Younger Dryas transition along the Meuse, as inferred by Huisink (1997).

One intriguing challenge in studies of fluvial evolution is the possible impact of the numerous earlier Dansgaard–Oeschger events of the last glacial. Studies of fluvial successions from this time interval in The Netherlands (Van Huissteden and Kasse, 2001) have suggested that prior to the last Dansgaard–Oeschger event discussed above, fluvial systems exhibited mostly autogenic behavior with only few episodes of more widespread erosion. They point out that the nature of fluvial responses is dependent on overall environmental boundary conditions, with a particularly prominent role for vegetation and permafrost. Only during the final episode of the last glacial an alternation between open shrub tundra and woodland allowed more dramatic fluvial responses due to the vegetational control on the hydrologic cycle. Nevertheless, there is ample room for more studies of fluvial records of the last glacial, especially in light of the current feasibility of better chronological frameworks.

Holocene Climate Forcing

The potentially nonlinear nature of fluvial response to abrupt environmental change was discussed by Knox (1972), who argued that high-order tributaries in southwest Wisconsin located near a major ecotone

responded in a highly sensitive way to Holocene shifts in atmospheric circulation. An abrupt transformation from prairie to hardwood forest $\sim 6,000$ ^{14}C years BP was associated with rapid alluviation along these streams. As shown in Figure 6, changes in fluvial activity are particularly concentrated in the relatively short interval following an abrupt shift in climate, largely due to the time lag in vegetational response. More specifically, a transition from arid to humid conditions provides a small time window with increased discharge and sparse vegetation cover, allowing accelerated hillslope erosion due to a limited infiltration capacity. This results in increased sediment yield and 'geomorphic work'. Knox (1972) raises the point that the exact nature of the fluvial response, in terms of incision versus aggradation, is highly dependent on location within the drainage network.

Somewhat different conditions prevailed in environments that are characterized by more flashy discharge regimes, with peak discharges as much as two or three orders of magnitude higher than mean annual discharge. This is illustrated by a number of rivers in central Texas, including the Colorado River

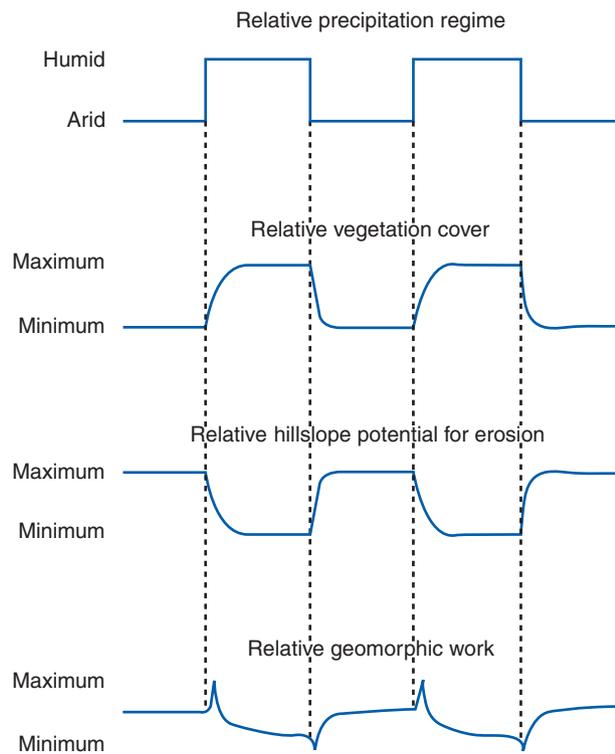


Figure 6 Conceptual model of nonlinear fluvial response to climate forcing (after Knox, 1972). Note that this model is intended to apply specifically to mid-latitude regions with an annual precipitation of 250–1,500 mm. Also note that 'geomorphic work' could refer to both incision and aggradation, depending on location within the drainage basin.

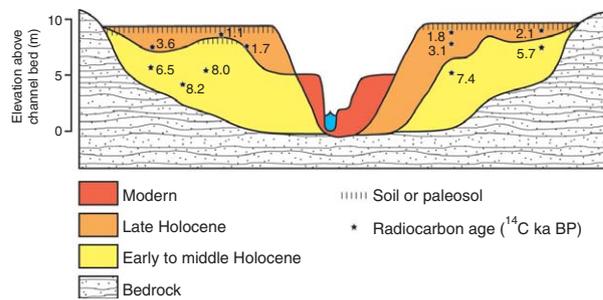


Figure 7 Three Holocene allostratigraphic units along the upper Colorado River, central Texas (after Blum *et al.*, 1994). For explanation see text.

(Blum *et al.*, 1994). Figure 7 shows a cross-section of this fluvial system featuring three Holocene allostratigraphic units (*see* Morphostratigraphy-Allostratigraphy). While the base of each unit is found at a roughly constant level, their surfaces vary widely, with the early Holocene unit entirely draped by younger strata. Blum *et al.* (1994) explain this by variations in the persistence of deep flooding, which was especially prolific during the relatively humid time period 2,500–1,000 ^{14}C years BP. In contrast, the past millennium was drier and led to the establishment of an inset floodplain at a lower level, along with pedogenesis and terrace formation.

Daniels and Knox (2005) provide an excellent example of a study of century-scale fluvial response, in their case with respect to the drought that characterized the interior of North America during the Medieval Warm Period. They show that tributaries in a small drainage basin in southwest Nebraska incised rapidly around 800–1,100 ^{14}C years BP, roughly synchronous to rivers elsewhere in Nebraska and Kansas. Drought in this semi-arid region is associated with dramatic reductions in vegetation cover and a more variable discharge regime with less frequent, yet more powerful floods. This would enable high erosion rates and the establishment of new floodplain levels several meters lower, within a time period of a few centuries or less. It appears that fluvial incision in this environment is correlated with drought, whereas in examples given above, such as the Meuse River, early Holocene incision was associated with an increase in discharge (Bogaart *et al.*, 2003b). This testifies again to the complexity of the fluvial response and its strong dependence on regionally specific boundary conditions.

Relatively rare are stratigraphic studies that focus on the response of the fluvial sediment transfer system to annual to decadal scale climate forcing. Naturally, it is most practical to study such relationships in the most recent sedimentary records, given the need for exceptionally high temporal resolution. Only a few environments remain that have been

essentially unaffected by human intervention over the past decades or century. Recent work in the pristine foreland basin of the Amazon drainage (Aalto *et al.*, 2003) suggests that floodplain aggradation is not a gradual process, but rather consists of rapid pulses of sedimentation separated by multi-year intervals of quiescence. These authors documented a strong correlation with the El Niño–Southern Oscillation, with rapid aggradation in the southern part of the Amazon Basin occurring during rainy La Niña intervals.

Summary

The interest in fluvial responses to rapidly changing climatic boundary conditions is here to stay, and will likely increase given the concerns about the impact of future global change. While there exists a rich literature of investigations of fluvial records for the past ~20 kyr, studies over shorter (decadal or centennial) timescales are less common (Blum and Törnqvist, 2000). One likely reason for this is the formidable task of developing high-resolution geochronological frameworks in fluvial successions, environments that commonly pose serious challenges for numerical dating.

The diverse collection of examples presented herein shows that there is a wide variety of fluvial responses to climate forcing. For example, the impact of increased aridity or humidity can be opposite in different geographic regions, to a large extent depending on initial boundary conditions. As a result, the scientific literature on the topic covered by this article is somewhat overwhelming and confusing, with numerous conflicting data and interpretations. To a considerable extent these conflicts are probably real, reflecting spatial variability, differences in sensitivity, and contrasting response times. However, it is likely that some of these conflicts simply stem from erroneous stratigraphic interpretations.

There are also discrepancies between field evidence and theory, given that large rivers may respond swiftly to environmental forcing, as so eloquently illustrated by the Ganges system. Thus major challenges lie ahead. The emergence of better and more rigorous concepts that are more strongly rooted in theory, as well as better analytical tools (notably dating methods), will likely offer new opportunities to tackle these important issues.

See also: Dating Techniques. Fluvial Environments: Sediments; Terrace Sequences; Deltaic Environments. Glacial-Interglacial Scale Fluvial Responses. Ice Core Records: Greenland Stable Isotopes. Luminescence Dating: Optically-Stimulated Luminescence. Paleoclimate

Reconstruction: Sub-Milankovitch (DO/Heinrich) Events; The Last Millennium. **Quaternary Stratigraphy:** Morphostratigraphy-Allostratigraphy.

References

- Aalto, R., Maurice-Bourgoin, L., Dunne, T., Montgomery, D. R., Nittrouer, C. A., and Guyot, J.-L. (2003). Episodic sediment accumulation on Amazonian flood plains influenced by El Niño/Southern Oscillation. *Nature* **425**, 493–497.
- Berendsen, H. J. A., and Stouthamer, E. (2001). *Palaeogeographic Development of the Rhine-Meuse Delta, The Netherlands*. Koninklijke Van Gorcum, Assen.
- Best, J. L., and Ashworth, P. J. (1997). Scour in large braided rivers and the recognition of sequence stratigraphic boundaries. *Nature* **387**, 275–277.
- Blum, M. D., and Törnqvist, T. E. (2000). Fluvial responses to climate and sea-level change: a review and look forward. *Sedimentology* **47**(Supplement 1) 2–48.
- Blum, M. D., Toomey, R. S., III, and Valastro, S., Jr. (1994). Fluvial response to Late Quaternary climatic and environmental change, Edwards Plateau, Texas. *Palaeogeography, Palaeoclimatology, Palaeoecology* **108**, 1–21.
- Bogaart, P. W., Van Balen, R. T., Kasse, C., and Vandenberghe, J. (2003a). Process-based modelling of fluvial system response to rapid climate change – I: model formulation and generic applications. *Quaternary Science Reviews* **22**, 2077–2095.
- Bogaart, P. W., Van Balen, R. T., Kasse, C., and Vandenberghe, J. (2003b). Process-based modelling of fluvial system response to rapid climate change II. Application to the River Maas (The Netherlands) during the Last Glacial–Interglacial Transition. *Quaternary Science Reviews* **22**, 2097–2110.
- Bull, W. B. (1991). *Geomorphic Responses to Climatic Change*. Oxford University Press, New York.
- Castelltort, S., and Van Den Driessche, J. (2003). How plausible are high-frequency sediment supply-driven cycles in the stratigraphic record? *Sedimentary Geology* **157**, 3–13.
- Daniels, J. M., and Knox, J. C. (2005). Alluvial stratigraphic evidence for channel incision during the Mediaeval Warm Period on the central Great Plains, USA. *The Holocene* **15**, 736–747.
- Fisk, H. N. (1944). *Geological Investigation of the Alluvial Valley of the Lower Mississippi River*. Mississippi River Commission, Vicksburg.
- Goodbred, S. L., Jr. (2003). Response of the Ganges dispersal system to climate change: a source-to-sink view since the last interstadial. *Sedimentary Geology* **162**, 83–104.
- Huisink, M. (1997). Late-glacial sedimentological and morphological changes in a lowland river in response to climatic change: the Maas, southern Netherlands. *Journal of Quaternary Science* **12**, 209–223.
- Knox, J. C. (1972). Valley alluviation in southwestern Wisconsin. *Annals of the Association of American Geographers* **62**, 401–410.
- Knox, J. C. (1983). Responses of river systems to Holocene climates. In *Late-Quaternary Environments of the United States* (H. E. Wright, Jr., Ed.), Volume 2. The Holocene, p. 26. University of Minnesota Press, Minneapolis.
- Kozarski, S. (1983). River channel adjustment to climatic change in west central Poland. In *Background to Palaeohydrology. A Perspective* (K. J. Gregory, Ed.), p. 355. John Wiley, Chichester.
- Leigh, D. S., Srivastava, P., and Brook, G. A. (2004). Late Pleistocene braided rivers of the Atlantic Coastal Plain, USA. *Quaternary Science Reviews* **23**, 65–84.
- Lewin, J., and Brewer, P. A. (2001). Predicting channel patterns. *Geomorphology* **40**, 329–339.

- Mackin, J. H. (1948). Concept of the graded river. *Geological Society of America Bulletin* 59, 463–511.
- Paola, C., Heller, P. L., and Angevine, C. L. (1992). The large-scale dynamics of grain-size variation in alluvial basins, 1: Theory. *Basin Research* 4, 73–90.
- Salter, T. (1993). Fluvial scour and incision: models for their influence on the development of realistic reservoir geometries. In *Characterization of Fluvial and Aeolian Reservoirs* (C. P. North and D. J. Prosser, Eds.), Vol. 73, pp. 33–51. Geological Society Special Publication.
- Saucier, R. T. (1994). *Geomorphology and Quaternary Geologic History of the Lower Mississippi Valley*. Mississippi River Commission, Vicksburg.
- Schumm, S. A. (1977). *The Fluvial System*. John Wiley, New York.
- Schumm, S. A., and Parker, R. S. (1973). Implications of complex response of drainage systems for Quaternary alluvial stratigraphy. *Nature Physical Science* 243, 99–100.
- Slingerland, R. L., and Snow, R. S. (1988). Stability analysis of a rejuvenated fluvial system. *Zeitschrift für Geomorphologie, Neue Folge, Supplementband* 67, 93–102.
- Srivastava, P., Juyal, N., Singhvi, A. K., Wasson, R. J., and Bateman, M. D. (2001). Luminescence chronology of river adjustment and incision of Quaternary sediments in the alluvial plain of the Sabarmati River, north Gujarat, India. *Geomorphology* 36, 217–229.
- Tandon, S. K., Gibling, M. R., Sinha, R., Singh, V., Ghazanfari, P., Dasgupta, A., Jain, M., and Jain, V. (2006). Alluvial valleys of the Ganga Plains, India: Timing and causes of incision. In *Incised-Valley Systems in Time and Space* (R. W. Dalrymple, D. Leckie and R. W. Tillman, Eds.), SEPM Spec. Pub. in press.
- Tebbens, L. A., Veldkamp, A., Westerhoff, W., and Kroonenberg, S. B. (1999). Fluvial incision and channel downcutting as a response to Late-glacial and Early Holocene climate change: the lower reach of the River Meuse (Maas), The Netherlands. *Journal of Quaternary Science* 14, 59–75.
- Van den Berg, J. H. (1995). Prediction of alluvial channel pattern of perennial rivers. *Geomorphology* 12, 259–279.
- Van Huissteden, J., and Kasse, C. (2001). Detection of rapid climate change in Last Glacial fluvial successions in The Netherlands. *Global and Planetary Change* 28, 319–339.

Terrace Sequences

D J Merritts, Franklin and Marshall College, PA, USA

© 2007 Elsevier B.V. All rights reserved.

Introduction

Fluvial terraces are important chronicles of (1) climatically driven changes in sediment supply, discharge, or base level that result in channel incision or aggradation, and (2) tectonically driven long-term uplift that results in channel incision and warping or faulting of terrace surfaces. A fluvial terrace, a relatively flat bench occurring along and above a river, is an abandoned floodplain surface that is separated from the modern floodplain (or a lower river terrace) by a steep slope, known as the terrace riser. River valleys often contain

flights of multiple terraces that reflect long periods of terrace formation, a history that can be unraveled through mapping, surveying, and dating of fluvial terraces. As such, terraces are useful in studies of Quaternary climate change and on the effects of climate change on landscape processes, such as increased upland erosion and consequent increased sediment supply. In tectonic studies, terraces are useful for assessing both the rate of rock uplift at a given reach and differential rates of deformation along river valleys.

We briefly summarize the causes and processes of terrace formation and then review case studies of terraces in Asia, New Zealand, and North America. As demonstrated by these examples, both climatic and tectonic processes have influenced the formation of fluvial terraces over time periods of thousands to hundreds of thousands of years during the Quaternary period (see Glacial-Interglacial Scale Fluvial Responses). The studies cited here used various methods of absolute and relative dating, including cosmogenic nuclide exposure dating, radiocarbon dating, correlation to dated tephra and loess stratigraphies, optically stimulated luminescence dating, and relative age dating from degree of soil development and thickness of weathering rinds on gravel clasts.

Types of Fluvial Terraces and Terrace Terminology

The two basic types of fluvial terraces are aggradational and degradational (Fig. 1) (see Responses to Rapid Environmental Change). Aggradation, or net deposition of sediment along a river channel and its floodplain over a prolonged period of time, leads to formation of an alluvial fill terrace. At the crossing of a geomorphic threshold from either deposition or stability (i.e., no net deposition) to net degradation, alluvium is incised and a fill terrace is both created and abandoned (Bull, 1991). Radiocarbon dating of organic matter in alluvium from an aggradational terrace along Cajon Creek, a stream that crosses the San Andreas fault in southern California, USA, reveals that it can take as long as 10 kyr for aggradation to form a fill terrace over a distance of ~10 km (Weldon, 1986). Furthermore, the time since the onset of filling, abandonment, and incision decreases upstream along Cajon Creek, indicating a time-transgressive terrace surface.

If incision of an aggradational terrace is punctuated by pauses that allow the stream to cut laterally rather than vertically, then cut terraces are carved into alluvial fill. Cut terraces (sometimes called cut-fill) have a distinctly different origin than the higher fill terrace into which they are carved. It is possible that a subsequent cycle of aggradation and degradation might