9.37 Impacts of Land-Use and Land-Cover Change on River Systems

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Abstract

Human land-use activities have fundamentally changed the hydrogeomorphology of rivers. Since the late Holocene, anthropogenic changes to alluvial stratigraphy and channel morphology have often been greater than those left by climate change. This chapter reviews four general topics related to land use: (1) landscape sensitivity and scale; (2) changes to processes of flood generation, soil erosion, sediment sequestration, and sediment yields; (3) how accelerated water, erosion, and sediment deliveries transform fluvial systems; and (4) the long-term history of land-use change impacts following the Neolithic advent of agriculture and its spread. In covering these topics, the chapter introduces the newly emerging field of land-change science.

9.37.1 Introduction

The extent to which humans have modified fluvial systems through changes in land use is difficult to overestimate. Changes in land use have impacted the delivery of water, sediment, nutrients, and other materials downstream, and can alter water quality, aquatic habitat, and channel and floodplain morphology over short to intermediate timescales (10^{-1}–10^{3} yr). To some extent, this was known to Greek philosophers (Glacken, 1967), and it has been known to modern science since George Perkins Marsh (1864) described the decreased permeability of the Earth and the erosive effectiveness of runoff:

> The face of the earth is no longer a sponge, but a dust heap, and the floods which the waters of the sky pour over it hurry swiftly along its slopes, carrying in suspension vast quantities of earthy particles which increase the abrading power and mechanical force of the current, and, augmented by the sand and gravel of falling banks, fill the beds of the streams, divert them into new channels and obstruct their outlets.
>
> (Marsh, 1864: 215)

These topics have also been covered by several books (Turner et al., 1990; Goudie, 2005; Anderson et al., 2007) and symposia (Thomas, 1956; Brierley and Stankoviansky, 2002, 2003;

James, L.A., Lecce, S.A., 2013. Impacts of land-use and land-cover change on river systems. In: Shroder, J. (Editors in chief), Wohl, E. (Ed.), Treatise on Geomorphology. Academic Press, San Diego, CA, vol. 9, Fluvial Geomorphology, pp. 768–793.

 http://dx.doi.org/10.1016/B978-0-12-374739-6.00264-5

James and Marcus, 2006). Where land use increases runoff or sediment supplies, flooding and sedimentation can increase and stream habitats can be severely altered (Jacobson et al., 2001). Where past land uses have generated a large sediment pulse, the storage of sediment in the system may explain modern patterns of sediment remobilization (Fryirs and Brierley, 1999; Brierley, 2010). Legacy-sediment deposits associated with human activities can also contain nutrients or toxic pollutants. Modern and historical land uses in watersheds should be understood to develop a spatially distributed watershed perspective of the river and a sense of the temporal dynamics of the system. These are important considerations for river rehabilitation and management.

Land use generally refers to the Earth's terrestrial surface as modified by human activities, whereas land cover may refer to natural biophysical attributes of the Earth's surface. This chapter addresses the indirect impacts of upland and floodplain land use on fluvial systems, but not direct alterations within river channels. Human impacts on rivers have been classified as 'direct changes' within channels or to riparian vegetation versus 'indirect changes' to land use, such as vegetation changes, agriculture, urbanization, and mining (Brookes, 1994; Brierley and Fryirs, 2005). A broad view is taken here by considering changes in land use and land cover (LU/LC) that may be driven by either human alterations or natural processes such as spatial and temporal variability in climate. Although the emphasis is on the effects of human activities, isolating those effects from natural processes of land-cover change is commonly not feasible. In many ways, watershed responses to anthropogenic and climate changes are similar, and evaluations of changes in LU/LC are logically covered in tandem.

Separating the effects of anthropogenic change from those of climatic variability or change on complex landscapes can be extremely difficult and results vary with spatial and temporal scales. For instance, Foster et al. (2003) concluded that sediment production rates in a small watershed in France were dominated by land use over the late Holocene but that climate change and meteorological events become more important at shorter timescales. Moreover, the question of 'What is natural?' arises with attempts to isolate purely human influences (Graf, 1996; Wohl, 2001; Newson and Large, 2006; Wohl and Merritts, 2007; Montgomery, 2008; Fryirs and Brierley, 2009). If the relatively subtle effects of Paleolithic hominids are considered to be a part of natural processes, then when do human impacts cease to be natural? Furthermore, accelerated human activity coincides largely with substantial mid- to late-Holocene climatic adjustments, so it is difficult to identify watersheds where either human activities or climate change did not occur, which are needed as controls for testing. These topics are explored in Volume 13 of this treatise, which focuses on human impacts and climate change. This chapter examines how rivers are influenced by changes in human LU/LC.

Anthropogenic transformations of the land not only have repercussions on fluvial systems but also have impacts on many other systems. Land-use changes exacerbate climate change (Houghton, 1995; Bonan, 1997), cause species extinctions (Pimm and Raven, 2000), introduce toxic pollutants to the environment, and increase the production and delivery of runoff, sediment, nutrients, and other pollutants to rivers. Land-use change poses a growing challenge for the coming millennium with consequences that may exceed those of climate change (Sala et al., 2000; Vörösmarty et al., 2000; DeFries and Eshleman, 2004). Unfortunately, the impacts of anthropogenic land-use change on hydrologic systems have received far less attention than the impacts of climate change (Lambin et al., 2002), but a growing movement in land-change science is emerging (Turner et al., 2003; DeFries and Eshleman, 2004).

Factors driving global environmental change in the modern epoch can be divided into four categories: hydroclimatic, sea-level rise, topographic relief, and human activity (Slaymaker et al., 2009). Such a categorization is appropriate for this chapter because it isolates human agency, which, outside of high-latitude regions, is the most effective and most rapidly varying cause of change. In Europe, the magnitude of human impacts over the past 2000 years has exceeded those of climate change (de Moor et al., 2008), and similarly over the past 200 years in many locations including the United Kingdom (Walling et al., 2003) and the upper Midwest of the USA (Knox, 2006).

This chapter begins with a discussion of landscape sensitivity, that is, what landscapes are sensitive to change, their resilience, differences between upland changes that propagate downstream to rivers, and sensitivity to change by rivers themselves. It also addresses how spatial and temporal scales are linked in such a way that broad global-scale studies may require a historical perspective. The effects of LU/LC change on watershed hydrology are briefly examined. Section 9.37.4 focuses on downstream responses of fluvial systems to the hydrological changes upstream. Rivers may respond to changes in upland water and sediment production by experiencing channel and floodplain metamorphosis through a variety of forms, at gradual or punctuated rates. River response depends on the nature of change to inputs and the character of the fluvial conveyance system. The emphasis of this chapter is on upland land uses and the responses of channels and floodplains downstream. Changes in floodplain land uses, such as vegetation clearance, are covered only peripherally. In-channel and floodplain changes, such as weirs, bypasses, channelization, levees, bank protection, riparian vegetation clearance, ditching, leveling, wetland drainage, and chemical applications, are not covered. Dams and flow regulation are covered elsewhere in this volume (*see* Chapter 9.38). Section 9.37.5 presents an overview of the history of human activities with an emphasis on the advent and spread of agriculture during the Neolithic, the diffusion and intensification of agricultural technology into Northern and Western Europe, its relatively rapid introduction into the Americas and Australia, resultant alluvial episodes, and the present state of legacy sediment stored in affected watersheds. In some cases, contrary to common assumptions, pre-Columbian agriculture was geomorphically effective, but this remains to be tested by stratigraphic evidence throughout the Americas and Oceania. Similarly, episodic soil erosion and sedimentation following European colonization were not universal, and the hypothesis of rapid postcolonial alluviation should also be tested.

9.37.2 Landscape Sensitivity and Scale

Two interrelated concepts should be addressed before considering the specific processes and consequences of land-use change. The sensitivity of systems to change strongly influences responses, and the spatial and temporal scales under study have a great bearing on the patterns that emerge. Recognizing these factors is essential to a full understanding of interactions between land use and responses of fluvial systems.

9.37.2.1 Landscape Sensitivity

The likelihood that LU/LC changes will generate substantial responses in runoff or sediment production varies greatly between watersheds and through time depending on a variety of factors. A given change in one watershed may promulgate substantial responses in water and sediment production, whereas the same changes in another watershed may have no effect. Moreover, the effectiveness of changes in water and sediment loadings in generating geomorphic responses downstream in rivers and floodplains may also vary greatly within and between basins (Fryirs et al., 2009). Many geomorphologists have used the concept of landscape sensitivity to express variability in geomorphic response to change. The concept of landscape sensitivity can improve explanations and predictions of the potential magnitude and frequency of responses to external influences, including both natural and human perturbations, as well as resistance to change (Allison and Thomas, 1993). Definitions vary, so sensitivity should be explicitly defined when the concept is used. This chapter adopts the definition expressed by Brunsden and Thornes (1979) as the likelihood that changes in controls of a system will produce a 'sensible, recognizable and persistent response' (cf. Brunsden, 2001). They described sensitivity as reliant upon the resisting elements of the landscape (barriers) and disturbing forces, both of which have strong spatial and temporal variabilities (cf. Brunsden, 1993). The concept includes at least three definitions (Allison and Thomas, 1993):

1. spatial variation in the ability of landforms to change (Brunsden, 1990),
2. susceptibility to disturbance or fragility (Huggett, 1988), and
3. ability of landforms to resist change (Brunsden and Thornes, 1979).

The third definition may be regarded as a type of landscape resilience that has an opposite or inverse connotation (insensitivity). Resilience may also include recovery from change. Sensitivity implies an element of instability in the system that may result in rapid, irreversible change (Thomas, 2001). It varies with scale and is complicated by an intimate dependency on thresholds of geomorphic stability that require consideration of the magnitude and frequency of events (Thomas, 2001). Sensitivity is generally taken to mean susceptibility to frequent, moderate-magnitude events, but geomorphic changes to insensitive landscapes may be extensive and enduring in response to large infrequent events (Evans, 1993).

Sensitivity of channels and floodplains is highly variable and depends not only on geomorphic and structural elements but also on their interactions and spatial patterns (Fryirs and Brierley, 2009). Antecedent conditions may also be important to river sensitivity and have been characterized in terms of geologic, climatic, and anthropogenic memories that influence landscape processes (Brierley, 2010). Although most studies of river metamorphosis have focused on areas of dramatic change, those reaches may be atypical. In the upper Hunters watershed of southeastern Australia, Fryirs et al. (2009) found that less than 20% of the channel length had experienced metamorphosis and documented gradients between stable and changed reaches.

Many studies of landscape sensitivity have been concerned with perturbations to uplands or soil erosion (Boardman, 1993; Evans, 1993; Quine and Walling, 1993). The concept of landscape sensitivity extends beyond the sensitivity of the landscape that is hydrologically contributing (the watershed), however, to also include the sensitivity of geomorphic systems in receiving areas such as channels, fans, deltas, and floodplains. This is in keeping with definitions based on the likelihood that changes will produce a sensible, recognizable, and persistent response. Several applications of the concept have been made to fluvial systems (Downs and Gregory, 1993) and to interactions between upland systems and fluvial systems. For example, Knox (2001) concluded that the introduction of agriculture in the upper Mississippi Valley during European colonization increased landscape sensitivity through reductions in infiltration, increased runoff generation and flood magnitudes, and resulted in tributary channel enlargement.

9.37.2.2 Scales of Space and Time

Careful evaluations of river responses to land-use change inevitably bring up questions of scale. Responses to LU/LC change vary with spatial scale. Small perturbations that are effective locally may be imperceptible or missing in larger systems at a broader scale. For example, human impacts in the Rhine Basin were substantial in small watersheds but negligible in larger rivers until the nineteenth century (Lang et al., 2003). Temporal scales are also important. Although the traditional focus of landscape sensitivity has been on catastrophic (rapid) responses, the concept extends to protracted but gradual changes (Allison and Thomas, 1993). For example, periods of accelerated erosion and sedimentation may appear in the geologic record as a sudden episode. Thus, major late-Holocene sedimentation events preserved in the stratigraphic record represent substantial responses of landscapes that were sensitive to the changes imposed.

In a general sense, scale is a governing factor in many of the Earth sciences. Relationships that are recognized at one scale may not hold at another scale, imposing a scale dependency recognized in many fields (Goodchild and Quattrochi, 1997). In geomorphology, spatially extensive approaches are needed to address global-scale concerns or to assess the implications of broad land-use changes. Schumm (1991) argued that the dimensions of time and space are linked. As the geographic extent of events increases, the average rates of effective change decrease and the time span to be considered increases; that is, as spatial scales of land-use change increase, more information is needed from historic (or prehistoric) reconstructions (**Figure 1**):

> As the size and age of a landform increases, fewer of its properties can be explained by present conditions and more must be inferred about the past.
>
> (Schumm, 1991: 52)

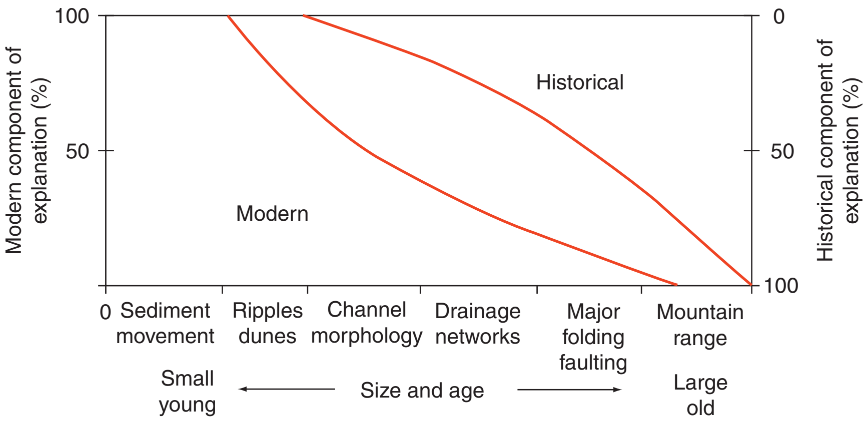

Figure 1 Schematic diagram illustrating relevant timescales required to explain geomorphic processes at increasing spatial scales. To understand geomorphic systems at spatial scales relevant to global change studies, processes will need to be understood at historical timescales. Adapted with permission from Schumm, S.A., 1991. To Interpret the Earth: Ten Ways to be Wrong. Cambridge University Press, New York, NY, 131 pp.

Thus, the geomorphic dimension of global change must include historical perspectives of geomorphic science.

Geomorphology has a strong geologic-science component, and, therefore, concepts of time and history have been an essential part of understanding geomorphic features and processes (Thornes and Brunsden, 1977; Albritton, 1980). Depending on the purpose of an investigation, hillslope and river systems may need to be understood at a variety of timescales including Cenozoic (10^6–10^7 yr), Holocene (10^3), historical (10^2–10^3), or steady time (10^0–10^1). The practices of geomorphology and engineering tend to part over the concept of time, which can be historic or evolutionary to geomorphologists but tend to be steady time to the engineer (James, 1999). In fact, geomorphologists recognize the potential for causality to shift on the basis of the timescale considered (Schumm and Lichty, 1965); that is, a dependent variable at short timescales (e.g., erosion depends on slope) may become an independent variable over geologic time (erosion determines slope). Geomorphologists have an arsenal of intellectual and analytical methods to deal with geologic time such as 'ergodic' reasoning (Paine, 1985), geomorphic equilibrium (Gilbert, 1877; Thorn and Welford, 1994), effective discharge (Wolman and Miller, 1960), and thresholds of stability (Schumm, 1979).

9.37.3 Hydrogeomorphic Changes Caused by Land Use

Upland land use affects watershed processes that govern the production, transport, and storage of water, sediment, nutrients, metals, and other pollutants. Human activities that disrupt vegetation and destabilize soils have the potential to decrease soil infiltration, suppress groundwater recharge, and amplify runoff generation and flood magnitudes. The altered flow pathways often increase flood frequencies, erosion, and sediment production, and sedimentation, while degrading water quality and aquatic ecology. Increases in runoff produced by land clearance are most effective in small watersheds but can be subtle in watersheds larger than 5 km in area (Potter, 1991; Jones and Grant, 1996; Jacobson et al., 2001). The hydrologic processes that can be changed, such as infiltration capacities and hillslope pathways of runoff, can occur over a wide range of spatial and temporal timescales and are covered in other chapters of this treatise (*see* Chapters 9.3 and 13.3).

9.37.3.1 Changes to Flood Regimes

Changes to runoff caused by land use generally generate changes in streamflow downstream that can be measured with hydrographs. The shape of storm hydrographs may change with hydrologic responses to land use. The area under a hydrograph represents the volume or yield of water. For a given yield, the shape can vary from a system characterized by gradually varying flows to a flashy system with high peaks and low base flows. Increased runoff generation contributes to larger storm flows and flood peaks downstream. As infiltration decreases with land clearance, surface runoff increases and hydrologic response becomes flashier with higher peak flows, short lag times, and low base flows (**Figure 2**).

Many studies have documented increases in water yield with deforestation using controlled experiments in paired watershed studies (Bosch and Hewlett, 1982; Brown et al., 2005). Less is known about the relationships between deforestation and extreme floods. Such an analysis should stratify events by magnitudes of storms and floods, watersheds by size, and land-use change by type and extent. During extreme rainfall intensities and durations, at some point when the infiltration capacity of forest soils is exceeded, saturated forested areas ultimately should produce as much runoff as their deforested counterparts. Nevertheless, particularly for moderate-magnitude floods, infiltration and reduced runoff deliveries from forests will tend to reduce flooding. In a study of 56 developing nations, Bradshaw et al. (2007) found a positive correlation between flood frequencies and area of forest removal and a negative correlation between flood frequencies and area of forest remaining. Other studies have

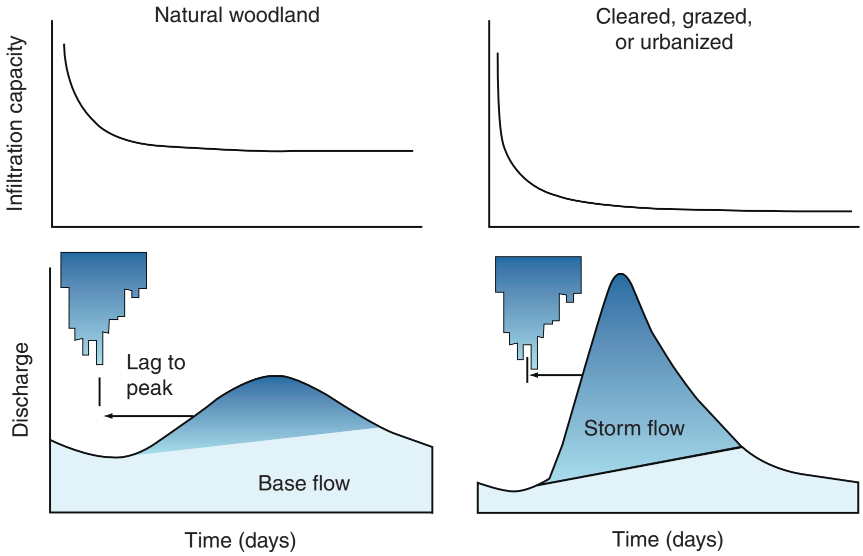

Figure 2 Idealized infiltration curves and storm hydrographs for two contrasting small watersheds. Natural woodland (left) has high infiltration rates and generates hydrographs with low peak discharge, long lag-to-peak, and high base flows. An urban watershed (right) has low infiltration rates and generates Hortonian flows that will cause flashy hydrographs with high peak discharges, short lag-to-peak, and low base flows.

found that the effects of land-use change on floods are most pronounced in small watersheds with moderate-magnitude events (Tollan, 2002; Eisenbies et al., 2007). With regard to agricultural land uses, some crop types generate substantially more runoff than others. Examination of more than 45 years of runoff from a small watershed in the southeastern USA under changing land use indicates that row crops generated more runoff and higher peak discharges than kudzu, rescue grass, or Bermuda grass (Endale et al., 2006).

The timing and magnitude of flood peaks are not simply affected by local hillslope processes such as decreased infiltration and increased runoff. As the size of watersheds increases, floodwater storage and conveyance increase in importance. The factors that influence flood timing and magnitude include storage in ponds, lakes, reservoirs, wetlands, floodplains, and broad valley bottoms. In large rivers, hydrographs are determined by the arrival times of individual flood peaks from various tributary sources, each of which is influenced by local runoff generation and storage elements. At this scale, processes can be greatly influenced by valley-bottom land-use practices that may alter floodwater storage. For example, wetland drainage, channelization, and levee construction decrease flood storage, accelerate down-valley conveyance, and shift downstream hydrographs toward a flashier response with high flood peaks (Opperman et al., 2009). Conversely, construction of dams or other storage reservoirs increases storage, decreases down-valley conveyance, and attenuates hydrographs. In spite of these complexities, increased flood volumes from hillslopes and small watersheds generally produce higher flood peaks downstream. As larger floods are generated, the frequency of occurrence of a given size flood increases and its recurrence interval decreases. Thus, intensified land use in forested areas tends to involve deforestation that increases both the magnitude and frequency of flooding. Conversely, decreased intensity of agricultural land use is often associated with reforestation, the recovery of forests by planting (afforestation) or natural succession, which may reverse the changes in flood magnitudes and frequencies. The magnitude of these changes, however, depends on both the size of the watershed and the magnitude of the flood; large watersheds and large floods tend to be less affected (Benson, 1964; Knox, 1977; Pitlick, 1997; Wohl, 2000; Lecce and Kotecki, 2008).

The impoundment of streams by dams has a considerable effect on the flow regimes of large rivers through the storage and gradual release of peak flows (Williams and Wolman, 1984; Graf, 1999). This topic is covered elsewhere in this volume (*see* Chapter 9.38). The hydrologic effect of numerous small impoundments on headwater streams is far less well documented. The large number of farm ponds and other impoundments in the USA (Smith et al., 2002) plays a substantial role in reducing flood discharges when flood storage is increased in many small tributaries. The influence of small impoundments on sediment and nutrient deliveries in small watersheds is discussed at the end of Section 9.37.3.3.

9.37.3.2 Soil Erosion

In addition to increased flood magnitudes downstream, reduced infiltration capacities may cause a shift toward Hortonian flows that can be highly erosive on uplands. The same land-use changes that decrease infiltration rates and magnify runoff are commonly associated with vegetation clearance that leaves soils vulnerable to severe erosion. Vegetation removal, agriculture, overgrazing, mining, road building, and construction tend to accelerate erosion by sheet flow, rills, and gullies. Rills and gullies not only represent volumes of eroded sediment but also increase drainage densities by extending channel networks that concentrate flows and deliver water and sediment more efficiently downstream. Thus, changes in LU/LC may initiate severe episodes of soil erosion on uplands and sedimentation downstream. Historically, extensive land-use changes associated with colonization and deforestation have generated periods of accelerated erosion, sediment deliveries, and channel filling, followed by decreased upland erosion, reduced sediment deliveries, and channel incision. This sequence can be described as an aggradation–degradation episode (ADE) (James, 2010). Several ADEs and the legacy sediment left behind are described below in Section 9.37.5.

Erosion by water results where forces applied by the fluid exceed the forces resisting erosion. The dominant applied fluvial forces are exerted by raindrop impacts and flows in sheets or channels. In modern terminology, especially in agricultural settings, raindrop splash and sheet erosion are often referred to as 'interrill erosion' (Nearing et al., 1989). Although classic hydrologic theory emphasized sheetflow as the primary process in soil erosion (Horton, 1933), the importance of raindrop splash and the kinetic energy of precipitation was recognized later (Wischmeier and Smith, 1965, 1978). Raindrop splash dominates on interrill areas where it causes soil detachment and transport in all directions but with net movement downslope (Muchler and Young, 1975; Meyer, 1981). Raindrop splash and sheetwash erosion may work together, but their relative importance shifts with increasing depths of overland flow. The translation of raindrop energy into soil particles is greatest in the absence of sheet flows, although transport of dislodged particles is facilitated by sheet flows. As the depth of sheet flow increases, erosion induced by raindrop splash may increase as dislodged particles are removed by sheet flow. As sheet-flow depths increase further, however, less energy from the raindrops reaches the soil surface and erosion by sheet flow begins to dominate. Raindrop splash is also minimized at a critical ponding depth (Gao et al., 2003). The effectiveness of raindrop splash and sheet flow to entrain and transport particles depends on the raindrop size, depth and velocity of sheet flows, vegetation cover, slope, grain size, grain cohesion, and organic matter. Land-use changes may substantially decrease resistance to erosion by removing vegetation, compromising root mats, and reducing organic matter. They may increase the applied forces by increasing runoff generation and concentrating flows into channels.

A first approximation of the magnitude of increased soil erosion owing to land use can be made based on parameters of Universal Soil Loss Equation (USLE). This approach indicates that conversion of LU/LC from natural woodland to bare soil could result in three orders-of-magnitude increase in erosion for some soils (**Figure 3**). Most of the sediment produced from such accelerated erosion is likely to remain near the site but it may reside in unstable deposits on oversteepened slopes from where it may be remobilized and conveyed further downslope by subsequent erosional events.

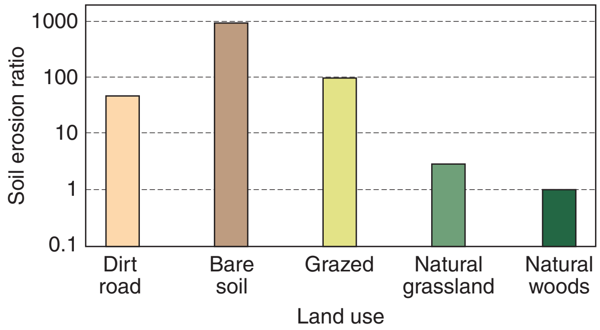

Figure 3 Soil erosion can increase up to three orders of magnitude when land use is converted from natural woodland to more erodible land uses. Values are based on changing parameters in the Universal Soil Loss Equation. Adapted from Jacobson, R.B., Femmer, S.R., McKenney, R.A., 2001. Land-use changes and the physical habitat of streams: a review with emphasis on studies within the US Geological Survey Federal-State Cooperative Program/USGS Circular No. 1175, with permission from USGS.

9.37.3.3 Sediment Yields and Delivery Ratios

Some proportion of sediment produced on hillslopes reaches fluvial systems. The processes associated with suspended sediment and bedload transport are covered in detail elsewhere in this treatise (*see* Chapters 9.8 and 9.9). The emphasis here is on sedimentation generated by changes in land use. Only a small proportion of sediment produced by soil erosion reaches large river systems downstream (Walling, 1983), and much of the eroded soil is trapped behind dams (Walling, 2006). The difference between sediment production and sediment yield (amount leaving the watershed) is expressed as the 'sediment delivery ratio' (SDR):

$$\mathrm{SDR} = S_\mathrm{Y}/S_\mathrm{P} \qquad [1]$$

where S_Y is the sediment yield measured at the outlet of a basin and S_P is the sediment production, usually computed from soil erosion estimates and not including fluvial erosion of channels and floodplains. Thus, the SDR reflects how much of the eroded soil from uplands reaches the outlet of a watershed. This ratio is usually much less than unity, indicating that sediment storage is considerable, although this is highly variable depending on factors controlling sediment transport and accommodation space. The SDR is strongly scale dependent, varying from $>50\%$ in small watersheds less than 1 km^2 in area to 10% or less in watersheds greater than 100 km^2 (**Figure 4**). The large proportion of sediment stored in small watersheds carries several implications:

1. Sediment yield is scale dependant, so computations must account for position in the watershed and conveyance capacities of the fluvial system. The sediment-conveyance system includes both channels and floodplains and factors controlling conveyance are idiosyncratic and highly variable. Connectivity is described in Section 9.37.4.1.
2. Many estimates of anthropogenic sediment generation have been low because they were based primarily on sediment yield measurements at stream gauges on large rivers. Large sediment repositories that continue to be reworked often remain along rivers and streams.
3. A disequilibrium exists between hillslopes and fluvial systems. Values of SDR <1 reveal a shifting of sediment from hillslopes to adjacent lowlands that would ultimately reduce local relief and gradients to zero over geologic time.
4. Low SDRs may represent local storage of anthropogenically produced sediment. This may be a relatively recent, transient condition in response to intensified land use during

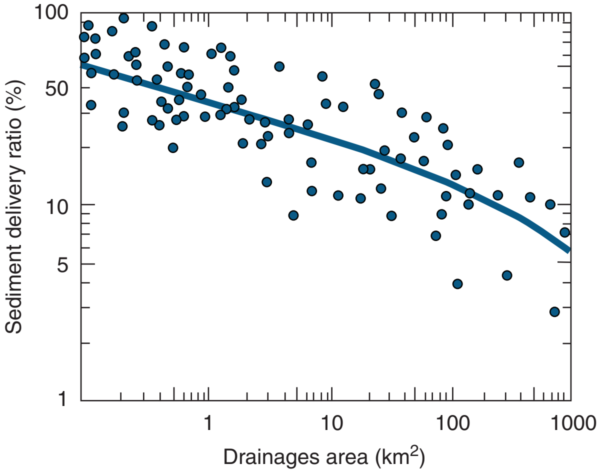

Figure 4 Sediment delivery ratios as a function of drainage area. Most sediment produced in uplands does not leave small watersheds. Adapted from Novotny and Chester (1989); cf. Vanoni (1975).

the postcolonial period. If so, increasing SDRs might be anticipated as conservation practices and reforestation reduce sediment production, and channels increasingly exploit the reservoirs of stored sediment on valley bottoms.

Computations of sediment yields and sediment budgets require an estimate of the amount of sediment stored that varies greatly between locations in a watershed. As sediment storage potential is not well understood, this is an area in need of research. The importance of geologic controls on accommodation space (e.g., valley width) is one important factor (Magilligan, 1985; Lecce, 1997; Brierley, 2010). Although the SDR, in conjunction with soil erosion estimates, can be used to compute sediment yields by rearranging eqn [1] (Renfro, 1975), and charts such as **Figure 4** provide guidance as to the values of SDR, this is an imprecise practice that provides, at best, a first approximation. In this method, the SDR is essentially a monotonic black-box model that must account for all of the sediment storage and conveyance variability throughout the watershed. The importance of local sediment storage presents a great deal of uncertainty in sediment yield estimates and requires a greater appreciation for sediment storage potential on valley bottoms. This firmly weds watershed hydrology to floodplain geomorphology. Recognizing spatial variations in storage and differentiating temporary storage sites from sediment sinks are essential to river management (Fryirs and Brierley, 2001).

The second implication arising from the dominance of sediment storage in small watersheds is that anthropogenic sediment production was much greater than that has been estimated. A central thesis of this chapter is that the impacts of land use on fluvial systems during colonization and industrialization involved major increases in runoff and sediment production. Understanding these impacts over a variety of spatial and temporal scales requires a sophisticated appreciation for sediment storage. Early recognition of the importance of human impacts on sediment production was based largely on suspended sediment data (Douglas, 1967; Meade, 1969). These computations tended to compensate for large dams but they did not adequately compensate for storage in small watersheds (Trimble, 1977). Thus, initial estimates of human-induced sediment production may have been grossly underestimated.

The third implication of low SDRs is tied to geomorphic theory. If most sediment production is stored in nearby small watersheds, then this indicates a state of disequilibrium between hillslopes and the fluvial systems to which they are coupled (Trimble, 1977; Walling, 1983). An equilibrium was commonly assumed in early long-term denudation sediment studies that assumed present sediment yields could be used to hindcast rates over geologic time (Judson, 1968). If SDRs were continuously low over geologic time, however, upland erosion and valley filling ultimately would have reduced local slopes and relief to zero. Apparently, low SDRs are a geologically recent phenomenon.

The fourth implication is that local storage of anthropogenically accelerated sediment production may explain much of the current disequilibrium indicated by low SDRs. This follows from the third implication that low SDRs are probably a geologically recent and transient condition. Land-use changes, generally in conjunction with late-Holocene climate change, introduced vast amounts of sediment that have not yet worked through fluvial systems. Several examples of Holocene sedimentation are documented later in this chapter. If this is a viable explanation for low SDRs, a shift toward increasing SDRs might be anticipated as conservation practices and reforestation reduce sediment production and channels increasingly exploit the reservoirs of stored sediment on valley bottoms. Fryirs and Brierley (2001) described a case in the Bega catchment, New South Wales, Australia, where SDRs to the lowlands are relatively high (almost 70%), yet most of the sediment remains stored there and has not made it through the estuary to the ocean. The importance of long-term storage suggests that forecasts of sedimentation rates, reservoir infilling, water quality, and other sediment-related phenomena should anticipate spatially and temporally complex processes that govern the gradual release and downstream arrival of sediment.

Spatially distributed simulations of land-use effects on erosion and sediment deliveries in moderately large watersheds (500–2000 km^2) can be made with models that permit allowances for sediment storage and are operable with large available data sets. The SWAT model (Soil Water Assessment Tool, SWAT) was developed in the USA by the US Department of Agriculture Agricultural Research Service for use at this scale with broad-based data sets. The SWAT model was developed to predict impacts of land management on water, sediment, fertilizer, and pesticide yields in large ungauged basins (Arnold et al., 1998). It can use State Soil Geographic Database (STATSGO) (1:250 000 scale) or Soil Survey Geographic Database (SSURGO) (1:250 000 scale) soil data from the USDA Natural Resources Conservation Service (NRCS) with land-use data from the USDA National Agricultural Statistics Service (NASS) or from the US Geological Survey (USGS) National Gap Analysis Program (GAP). It uses the Soil Conservation Service (SCS) curve number method to estimate runoff from daily precipitation, and simulates infiltration, evapotranspiration, channel routing, and groundwater flows. The model is spatially distributed to the sub-basin scale (hydrologic response units; cf. Leavesley et al. (1983)), but lumped within sub-basins. At broad scales of study, the quality of land-use and soil data is not ideal, and much of the uncertainty associated with runoff modeling at this scale arises from estimates of input parameters derived from soil and land-use data (Heathman et al., 2009).

With the proper use of isotope concentrations, sediment provenance, pathways, depositional histories, and budgets can be reconstructed. Relative and absolute dating of sedimentary deposits can be used to constrain past rates of soil erosion. Over the long term (10^3–10^5 yr), methods include cosmogenic nuclides such as ^{10}Be and ^{26}Al (McKean et al., 1993; Small et al., 1999; Heimsath et al., 1999, 2005), optically stimulated luminescence (Wallinga, 2002), and traditional dating tools such as ^{14}C and correlations with cultural artifacts. For erosion and sedimentation rates over historical time periods, fallout radionuclides can be used (Quine and Walling, 1993; He and Walling, 2003). The use of ^{137}Cs isotope concentrations in erosion studies can identify stable surfaces as well as distinguish and partition surface soil from subsoil as sediment sources in young deposits (Ritchie et al., 1974; Walling and Woodward, 1992; Wallbrink and Murray, 1993). This method may allow historical reconstructions of the onset and cessation of gullying in a watershed during the historic period (Olley and Wasson, 2003). Radionuclides may also be used to identify sediment sources. Wilson et al. (2008) used a mixing model based on ^{7}Be and ^{210}Pb radionuclides in small watersheds to determine the relative contributions of upland versus channel sources in suspended sediment. They found that sediment from surface soil erosion was prevalent early in runoff events, but, later in storm events, channel contributions became dominant. Hillslope sediment production can be quantified under various land uses, along with rates of storage in colluvial deposits along valley margins, in alluvial deposits on floodplains, and within channels (Vandenberghe and Vanacker, 2008).

Dams may have a tremendous effect on downstream sediment deliveries in fluvial systems by storing sediment and, in some cases, negating the effects of accelerated anthropogenic erosion (Syvitski, 2003; Syvitski et al., 2005; Walling, 2006). The effects of large dams on river sedimentation are discussed in Chapter 9.38. From an upland land-use perspective, the proliferation of small ponds can have an extreme effect on runoff and sediment and nutrient deliveries (Smith et al., 2002; Renwick et al., 2006; Verstraeten and Prosser, 2008). Whereas previous studies concluded that colluvial and alluvial deposits are the primary sinks for sediment eroded from uplands, there is some evidence that small farm ponds are a major sediment sink. For example, Renwick et al. (2005) showed that small impoundments are important components of sediment budgets, capturing an estimated 25% of sheet and rill erosion.

9.37.3.4 Impacts of Urbanization

Urbanization is a particularly pervasive type of land-use change that represents a suite of alterations that are associated with industrial, commercial, and residential development. This form of land-use change may increase runoff and sediment production and generate substantial responses in flooding, sedimentation, and channel morphology downstream. Urbanization tends to decrease infiltration capacities, increase Hortonian overland flow, and concentrate flows in storm drains and channels. A common measure of the degree of urbanization used by hydrologists is percent impervious or impermeable area, which is related to population density (Stankowski, 1972; Reilly et al., 2004). When the percent impervious surface area exceeds 10% impacts on riparian ecology begin to appear, and at percentages greater than 30% these ecological impacts are acute (Arnold and Gibbons, 1996; Goetz et al., 2003). Increases in impervious area generate the greatest hydrologic change in small watersheds that have highly permeable surfaces, so that conversion to impervious surfaces results in the greatest decrease in infiltration (Bledsoe and Watson, 2001). In addition to the percent area covered, the connectivity of impervious surfaces to drainage systems is also important. Connectivity can be quantified using the 'effective impervious area' (EIA), the impermeable area directly connected to storm drain systems (USEPA, 2000). The style of urbanization can also determine the magnitude of runoff increase. For example, Brander et al. (2004) found that urban cluster development of residential subdivisions generated a lower volumetric increase in runoff than that in curvilinear, coving, or new urbanism styles of suburban development owing to a greater area of natural permeable surfaces retained in neighborhood design.

Remote-sensing methods, such as digital processing of multispectral imagery, facilitate accurate land-use classifications and mapping of impervious surfaces (Fankhauser, 1999). Several types of remote-sensing imagery have been utilized for this purpose, and methods can be improved by combining multisensor or multi-image analyses (Carlson and Arthur, 2000; Wu and Murray, 2003). For example, the combination of aerial photography and Light Detection and Ranging (LiDAR) data greatly improved impervious mapping, especially with the addition of vegetation cover-height derived from LiDAR (Hodgson et al., 2003). In addition to directly mapping impermeable surfaces such as rooftops and roads, surrogate parameters that influence impervious surfaces in residential areas can be measured, such as lot size, residential capacity, street width, and intersection density (Stone, 2004).

New stormwater management methods and technologies are available that can greatly reduce the hydrologic impact of urban land use. These practices, known as 'low impact development' (LID), include the use of permeable paving materials and the diversion, detention, or retention of storm water to permeable areas. Permeable materials can reduce surface runoff to almost zero (Brattebo and Booth, 2003). Impervious areas may also be reduced by the use of vegetated (green) rooftops, landscaping with 'rain gardens', and other on-site collection methods that detain stormwater and encourage infiltration. Conventional urban development conveys runoff away from the site, whereas LID projects integrate landscaping and green space to mimic natural infiltration processes onsite. By encouraging infiltration and groundwater recharge, LID can mitigate the harmful effects of urban runoff generation. LID methods may also cost less than conventional development by reducing the need for storm sewers and culverts. Simulating the effects of urban development on runoff with spatially distributed models may require special adjustments for diversions of runoff from impervious surfaces to rain gardens or detention structures (Moglen, 2000; Holman-Dodds et al., 2003). The brief coverage of urban land use here is not proportional to its importance, but reflects the fact that the topic is covered in another chapter of this volume (*see* Chapter 9.39).

9.37.3.5 Impacts of Climate Change

Regional climates have rarely been static over centennial or millennial timescales, so evaluations of the effects of land use on fluvial systems should consider that past and future climates might be quite different from the present. Global temperatures are predicted to rise 2–5 °C during the coming century (IPCC, 2007). Many studies are being conducted on potential watershed responses to the combined effects of global environmental change and climate change. Early work on this topic includes seminal studies by Boardman et al. (1990) and Walling (1990). This section presents a few examples to illustrate the nature of the work that needs to be done. The topic of climate change effects on rivers is covered by other chapters in this volume (*see* Chapters 9.1 and 9.40) and by Volume 13.

Relationships between land use and climate can be considered in at least three ways:

1. effects of land use on climate,
2. effects of global regional climates on land-use types, and
3. how climate and climate change affect interactions between land use and erosion and sedimentation.

Land use can certainly affect microclimates through changes such as shading at ground level by canopy, albedo, and water budgets. Shading and albedo directly govern local energy budgets, whereas moisture drives latent heat exchanges associated with water vapor flux (evapotranspiration). Advection may geographically extend these effects to neighboring areas by the transfer of energy and moisture through air temperature and humidity. Until the mid-twentieth century, however, the effects of land use on global climate were largely dismissed on the premise that the impacts of human activities were restricted to local microclimates and ineffective to the global climate system (Thornthwaite, 1956). This changed quickly, however, as the importance of atmospheric chemistry to surface warming became apparent (Plass, 1956; Landsberg, 1970). An early anthropogenic climate change hypothesis has recently extended the link between land use, atmospheric CO_2 and methane, and global warming back as much as seven millennia through anthropogenic forest clearance (Ruddiman, 2003, 2007). Subsequent studies have estimated carbon emissions generated by LU/LC change that were insufficient to generate such an early rise of CO_2 (Pongratz et al., 2008, 2009). In fact, CO_2 shows a linear increase, whereas population growth was exponential (**Figure 5**). An explanation for this apparent discrepancy has been advanced based upon formerly higher per capita land clearance rates (Ruddiman and Ellis, 2009). The argument is that land use was formerly less intensive but much more geographically extensive.

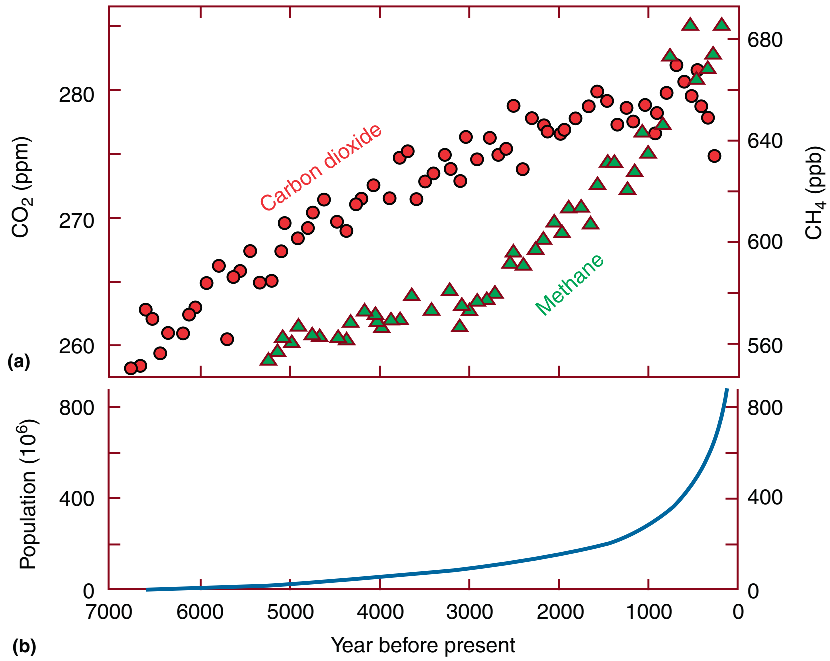

Figure 5 Time-series plots over the past 7000 years. (a) Atmospheric CO_2 and methane increased at different rates. CO_2 increases were almost linear with time, whereas methane increased at closer to an exponential rate. (b) Population growth shows exponential growth with a strong acceleration in the past millennium. If areas of forest clearance were proportional to population, then increases in greenhouse gases were not proportional to deforestation. If, however, early hominids cleared more land per capita than later societies, then increases in greenhouse gases may have been caused by deforestation. Adapted from Ruddiman, W.F., Ellis, E.C., 2009. Effect of per-capita land use changes on Holocene forest clearance and CO_2 emissions. Quaternary Science Reviews 28(27–28), 3011–3015.

The use of fire and shifting agriculture was widespread, so relatively small groups of hominids could clear large areas of land. Ruddiman and Ellis (2009) suggested that slash and burn and other forms of intensive land use release much more carbon than their modern counterparts on a per capita basis, so atmospheric carbon increased faster than population growth as early agriculture spread.

Regional climates clearly affect land use and geomorphic processes. For example, monocrop agricultural systems that work well in mid-latitude regions generally fail in the tropics, whereas slash-and-burn agricultural systems do not fare well in perennially moist climates. Relationships between climate and geomorphic processes have long been a topic of climatic geomorphology, which is covered elsewhere in this treatise (*see* Chapter 13.8). Several nonlinearities exist in the relationships between climate, vegetation, soil erosion, and sediment yields. Some of these relationships have been explained on a conceptual basis. For example, Langbein and Schumm (1958) presented an empirical analysis of effective precipitation and sediment yield data for the United States that indicated maximum sediment yields occur in semi-arid environments (**Figure 6**). This implies that decreasing precipitation in a subhumid forested region that causes a shift toward prairie or shrubland is likely to result in an increase in sediment yields. A further decrease in precipitation to full aridity may result in decreased sediment yields. Knox (1972) presented a theoretical biogeomorphic response model in which a simple sudden increase in precipitation can generate an episodic pulse of sediment that ceases once vegetation is established (**Figure 7**). Such nonlinear responses to simple climatic shifts are complicated by human manipulations of vegetation through land use.

9.37.3.6 Impacts of Water Transfers and Allocations

Changes in LU/LC may have indirect effects on rivers through regional transfers of water resources. Numerous examples have been noted where water use has altered the hydrologic regimen of rivers downstream, resulting in morphologic changes. For example, streamflow in the lower Platte River decreased dramatically after the 1930s, which led to substantial channel narrowing and floodplain expansion (Eschner et al., 1983; Simons and Simons, 1993). By 1979, channel top widths for most of the lower river were only 8–50% of the widths recorded by surveys in the 1860s. Interbasin transfers and groundwater pumping may augment surface water supplies, enough to substantially influence low flows, mean annual flows, aquatic ecosystems, and upland LU/LC. These water transfers may support major irrigation works or municipal supply systems that result in changed land uses over large areas. Large interbasin transfers in the western United States include the Los Angeles Aqueduct, the Colorado Aqueduct, the Central Valley Project of California, the California Water Project, and the Central Arizona Project (NRC, 1992). A plan to transfer 25–50 km^3 yr^{-1} of water south from the Ob River in Siberia to the Aral Sea was abandoned following dissolution of the former Soviet Union (Golubev and Biswas, 1985). Ironically, smaller-scale interbasin diversions via the Karakum Canal that carried water away from the Aral Sea into the Kara-Kum Desert initiated regional desiccation (Micklin, 1988). Large withdrawals for irrigation between 1960 and 1990 caused the Aral Sea to drop 13 m (43 ft), lose two-thirds of its volume, and increase in salinity threefold (Clarke, 1993). The physical and environmental changes associated with desiccation of the Aral Sea and irrigation of the surrounding area are extreme (Tsytsenko, 2003). Major storage and conveyance facilities (e.g., reservoir and canal systems) may have additional impacts on fluvial systems (*see* Chapter 9.38).

Water transfers are also common in small urbanizing watersheds where domestic water supplies provide water for domestic irrigation, thus increasing base flows during dry periods. Even if these changes in water supply can be critical to the management of local watersheds, water resources, and aquatic ecosystems, their direct influence on

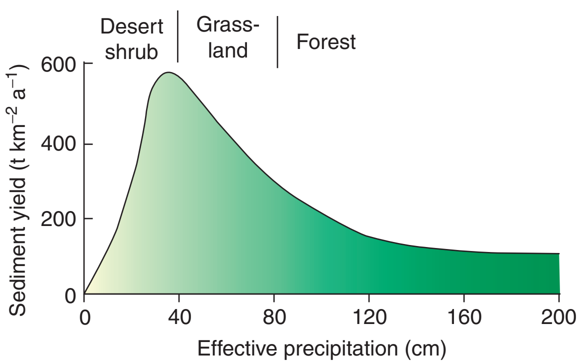

Figure 6 Mean annual sediment yields in the United States are related to climate through interactions with land cover. Maximum yields occur in regions with small effective precipitation where vegetative cover is sparse. In more humid regions, higher precipitation is moderated by thicker vegetation protecting soils from erosion. Adapted from Langbein, W.B., Schumm, S.A., 1958. Yield of sediment in relation to mean annual precipitation. EOS, Transactions. American Geophysical Union 39, 1076–1084, with permission from AGU.

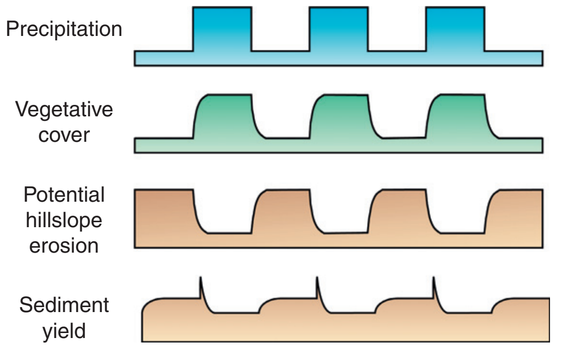

Figure 7 The biogeomorphic response model explains how an episode of high sediment yields may be generated by a simple step-functional increase in precipitation. Time lags between moisture availability and vegetative cover and soil erodibility can be translated into an episodic increase in sediment yields with increased precipitation and a moderate increase in yields when precipitation decreases. Adapted from Knox, J.C., 1972. Valley alluviation in Southwestern Wisconsin. Annals of the Association of American Geographers 62, 401–410, with permission from Association of American Geographers.

fluvial geomorphology is largely constrained to changes in vegetation that influence flood magnitudes and sediment loads. Although water resources allocations go beyond the scope of this chapter on land use, their potential should be considered for a full understanding of the extent of hydrogeomorphic influences of human activities.

9.37.4 Impacts on Fluvial Systems

Fluvial systems are highly responsive to the water and sediment loadings from their watersheds. The linkage between hillslope erosion and sediment deliveries to channels can be weak or lagged in time (as demonstrated by low SDRs), but high magnitudes of upland erosion will ultimately result in downstream adjustments. The nature of these adjustments will depend, in part, on the longitudinal connectivity between uplands and fluvial systems. Given the extensive hydrologic impacts that land-use changes may have on water and sediment production, drainage systems downstream often display remarkable responses to changes in LU/LC.

9.37.4.1 Rills, Gullies, Headwater Streams, and Longitudinal Connectivity

The interface between fluvial systems and uplands is a critical linkage between hillslope areas where most of the water and sediment is generated and channels that can efficiently convey it downstream (Harvey, 1997, 2002; Chiverrell et al., 2009). Most hillslope conveyance systems are inefficient relative to the concentrated flows in channels, so the delivery of water and sediment to downstream channels governs rates and magnitudes of floods and sediment fluxes in larger fluvial systems. Sediment transport and storage processes at the interface between colluvial and alluvial systems determine sediment budgets, SDRs, storage locations, and geomorphic responses. This potential sediment storage zone may account for much of the storage indicated by low SDRs. To some degree, this critical interface is represented by the extent of headwater streams, commonly defined as first- or second-order channels, that is, unbranched tributaries and channel segments immediately below pairs of unbranched tributaries (Meyer and Wallace, 2001; Gomi et al., 2002; Fritz et al., 2006). Headwater streams are the subject of another chapter in this volume (*see* Chapter 9.27).

The interface between hillslope and fluvial systems is commonly governed by rills and gullies that may or may not be included on headwater stream maps. Rills are small erosional channels that concentrate flows and tend to form an integrated drainage network (Schumm, 1956; Carson and Kirkby, 1972; Selby, 1993). Rills may be enlarged into gullies that are variously defined as channels too large to be crossed by farm equipment (Hutchinson and Pritchard, 1976; Foster, 1988) or wider than 0.3 m and deeper than 0.6 m (Selby, 1993). Thus, gullies are too large to be removed by normal tillage procedures. Gullies not only have a dramatic effect on hillslope geomorphology but also deliver large volumes of sediment downstream and destroy the utility of the land (**Figure 8**). They are often located on steep hillslopes, but in

Figure 8 View up small hillslope gully ~1.6 m deep in Chester County, South Carolina, USA. V-shape reflects young age of gully that is beginning to widen below root mat. Photo by LA James (March 2005).

arid and semi-arid regions arroyos gullies may form in the bed of broad ephemeral channels farther down in the drainage network. Processes of arroyo formation may differ from hillslope gullies in some respects, so the type of system involved should be specified. In some watersheds, gullies produce from 50% to 80% of the historical alluvium (Poesen et al., 2002). Furthermore, gully formation is often associated with human activities – including the introduction of grazing animals – that remove vegetation and increase runoff, so increased sediment production by gullies may be attributable to land-use change. Topographic data from airborne LiDAR can be used to construct digital elevation models (DEMs) and map gullies under forest canopy (James et al., 2007), and to detect change where canopies are sparse (Perroy et al., 2010) (**Figure 9**).

Gully remediation is important owing to the large amounts of sediment produced and the serious damage to land. Once initiated, gully erosion becomes increasingly difficult to control, so preventative programs are far better than reaction to advanced conditions. For example, the success of vegetation planting depends on the stage of gully development (Betts et al., 2003). Remediation has generally focused on armoring headwalls and managing vegetation on surrounding lands that contribute runoff. Gully sidewall erosion is extremely important to sediment production, however, and may produce more than 50% of gully sediment (Piest et al., 1975; Blong et al., 1982; Martínez-Casasnovas et al., 2009). Sidewall erosion processes can involve entirely different vegetation interactions, however, than on contributing uplands. In fact, colonization of gully sidewalls by vegetation is an indicator of gully stabilization (Ireland et al., 1939; Crouch and Blong, 1989). Mitigation attempts have often focused on surface vegetation that controls the kinetic energy of raindrops and sheet flows. Although aboveground vegetative cover is critical to controlling splash and sheet erosion, plant roots become important for armoring against concentrated flows and mass wasting in rills and gullies (Gyssels et al., 2005; De Baets et al., 2007).

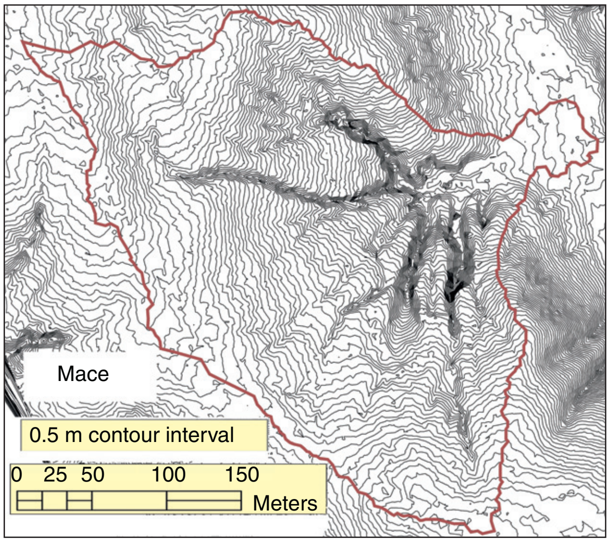

Figure 9 Contour map of Macedonia Lake gully system, Union County, South Carolina, generated from bare Earth point data derived from airborne LiDAR swath mapping. A morphometric and network analysis of this gully system is present in James, L.A., Watson, D.G., Hansen, W.F., 2007. Using Lidar to map gullies and headwater streams under forest canopy: South Carolina, USA. Catena 71, 132–144.

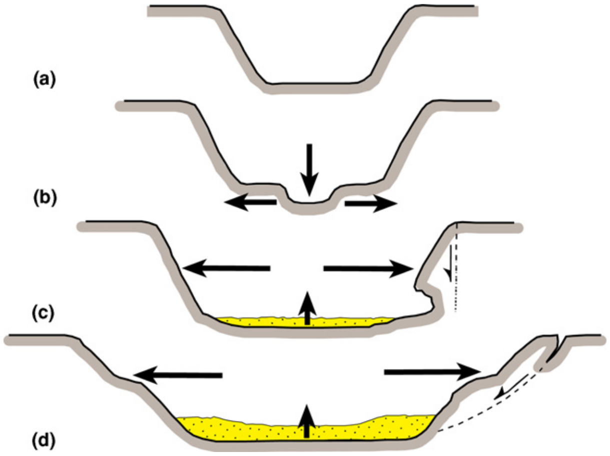

Figure 10 Model of channel evolution in response to initial degradation (a, b), followed by bed widening, mass wasting of banks, and alluviation (c, d). Adapted with permission from Schumm, S.A., 2005. River Variability and Complexity. Cambridge University Press, Cambridge, 220 pp.

9.37.4.2 Morphologic Changes due to Changing Flood Magnitudes and Sediment Production

Hydrologic and sedimentologic changes induced by land use can generate significant responses in channel morphology. Downstream river responses to land-use change vary greatly with landscape sensitivity and increases in runoff and sediment deliveries. Increased storm runoff volumes and peak flows tend to enlarge channels, whereas increased sediment production tends to cause channels to aggrade. To complicate matters, both of these processes are time transgressive, so one part of a watershed may be responding differently from another at a given time and responses may shift downstream through time. These relationships are further complicated by variations in sediment texture, the partitioning of sediment between in-channel and overbank deposits, and potential armoring of the channel bed. These factors also may be time transgressive as fine-grained, in-channel deposits are rapidly delivered downstream while lag gravels and overbank deposits are slowly conveyed. For example, a major land-use change, such as deforestation or urbanization that increases water and sediment production, may initially result in sediment storage and channel aggradation near the source accompanied by channel widening as coarse materials are introduced to the bed (Gomez et al., 2004). Later, headwater channels may enlarge – especially by widening if coarse materials were introduced – and downstream channels may aggrade as sediment and bed waves arrive (Gomez et al., 2003). Such a sequence may explain entrenchment of streams in small mid-Atlantic watersheds (drainage areas less than 25 km^2), as evidenced by greater decreases in bankfull channel recurrence frequencies than larger channels (Costa, 1975; Jacobson and Coleman, 1986; Jacobson et al., 2001).

Channel enlargement can involve a combination of vertical adjustment by incision or floodplain aggradation, or widening by lateral channel migration. Models of channel response to aggradation indicate that channel morphology evolves through a series of stages that commonly involve degradation in a narrow zone, followed by widening, then by channel-bottom aggradation to achieve a new equilibrium state (Harvey and Watson, 1986; Simon and Hupp, 1986; Simon, 1989; Lecce, 1997; *see* Chapter 9.29). Schumm (1991, 2005) presented a model of channel incision in which initial deepening is followed by widening, bank undercutting, and bank failures (**Figure 10**). A similar model was advocated for arroyos along the Rio Puerco (Elliott et al., 1999). The remobilization of sediment by widening results in a prolonged sediment flux following aggradation so that sediment waves tend to be asymmetrical with respect to time. Furthermore, channel erosion rates often decrease during the widening phase. Lisle and Church (2002) presented a conceptual model of decreasing sediment-transport capacity for degrading alluvial storage reservoirs consisting of two phases. The first phase is characterized by abundant sediment and a high sensitivity of local sediment storage to changes in supply. The second phase of degradation is associated with channel armoring and form roughness that impede vertical incision and lateral migration and determine spatial patterns of transport and storage.

Channel enlargement influences energy conditions that govern channel adjustment, the frequency of floodplain inundation, and the delivery of water and sediment downstream. Thus, channel enlargement in upstream areas has downstream consequences. As channels enlarge, they can contain larger flows that – if energy slopes are not decreased – may generate higher in-channel stream powers and shear stresses, leading to further incision or channel widening. These morphologic changes can decrease the downstream attenuation of flood waves, further increasing flood peaks downstream (Woltemade, 1994). Larger, more frequent overbank flows coupled with increased upland soil erosion can increase bank heights through vertical accretion on floodplain surfaces. Continued channel widening decreases flow depths for a given flow frequency, requiring larger flood magnitudes to generate the same stream power as previously. Several studies in the Driftless Area of Wisconsin, USA, have shown that channel enlargement began in tributaries before propagating downstream (Knox, 1987; Lecce, 1997; Lecce and Pavlowsky, 2001). The enlargement of channels in tributaries reduces overbank flow frequencies and floodplain sedimentation rates. This sediment is more efficiently conveyed downstream by high-energy channels that can contain larger flood flows. Thus, at the same time that tributary channels are undergoing declining sedimentation on the original floodplain surface, valleys that are a short distance downstream may be aggrading with sediment routed through the enlarged tributary channels.

Sediment deliveries are clearly related to channel bedforms, but the specific effects of the sediment must be scaled by the ability of the stream to carry its load. Linkages between sediment production and specific bed forms in mountain rivers have been identified by examining ratios of sediment-transport capacity to sediment production (Montgomery and Buffington, 1997). In small mountain tributaries where transport capacities are high relative to deliveries, valley bottoms can have abundant bedrock exposures and boulder deposits and channel form is dominated by cascades (**Figure 11**). Downstream within small watersheds, as sediment production increases and gradients and transport capacities decrease, bed forms transition from step pools to upper-regime plane beds. Farther downstream, where sediment supplies greatly exceed transport capacities, bedforms give way to pool and riffle sequences and dune and ripple forms. This conceptualization illustrates the importance of sediment production to river form. As sediment deliveries to mountain rivers govern the nature of channel bed forms, so do changes in land use that alter these deliveries. Clearly, such a dependency is not restricted to mountain rivers. In fact, rivers may be transformed from single-thread to braided with increased sediment deliveries (Gilbert, 1917) or increase in the ratio of bed material to suspended material (Brice, 1982).

The lateral connectivity between channels and their floodplains can be influenced as a direct or indirect consequence of land use. Levees constructed to protect floodplains from flooding and sedimentation for urban and agricultural land uses directly reduce connectivity. Levees may cause an almost complete hydrologic isolation of the channel from its floodplain and a substantial ecologic separation (Opperman et al., 2009). Channels may also become isolated from their floodplains as an indirect consequence of land use that generates an ADE. As channels aggrade, the bed rises and the frequency of floodplain inundation rises. The increased lateral connectivity may be accompanied by substantial changes to the floodplain. When aggradation ceases and degradation begins, lateral connectivity decreases, often to less than pre-aggradation conditions. The tendency for channels to vertically incise, prior to widening after an aggradation episode, was described in the previous section. As phase II of the readjustment, that is, the widening phase, tends to proceed more slowly (Lisle and Church, 2002), a narrow entrenched channel may persist for a relatively long period. In any case, the former floodplains constructed of anthropogenic sediment during the period of maximum aggradation are left as relatively high terraces (**Figure 12**). Relative to the lower surfaces

(a)

(b)

Figure 11 Bedforms in upper Greehhorn Creek, Sierra Nevada, northern California. (a) View up cascade in bouldery bed materials. (b) View up planar gravel-bed channel ~200 m downstream of first photograph below abundant supply of relatively fine gravel from hydraulic mining sediment tailings fan. Photo by LA James (December 2004).

Figure 12 Fluvial terraces along Greenhorn Creek, California, composed of hydraulic mining sediment. Arrow points to field assistant holding reflector. Photo by LA James (May 2007).

prior to aggradation, the frequency of flooding on the higher terrace surface and the accessibility to aquatic organisms are reduced.

9.37.4.3 Episodic Erosion and Sedimentation

Humans are environmental engineers who rearrange hydrologic and ecologic systems in order to garner resources and control their habitats. The resulting changes to geomorphic systems can be gradual or punctuated, and purely anthropogenic or superimposed on effects of climatic and tectonic change. Thus, the stratigraphic, sedimentologic, and geomorphic evidence of human influences can be abrupt and clear, or diffuse and obscure. In accordance with fluvial theories of thresholds and complex response (Schumm, 1977, 1979), even gradual changes may be manifested in the alluvial record as the sudden onset of a complex series of cut-and-fill features that occur in response to a disruption of system stability. Nonlinear episodic responses to simple change were also postulated by the biogeomorphic response model presented earlier (**Figure 7**). Alluvial responses that appear to be gradual on contemporary timescales may also be considered episodic where observed in a longer stratigraphic record.

9.37.4.3.1 Time, episodicity, and neocatastrophism

The responses of watersheds and river systems to land-use changes can be relatively rapid when considered over long time periods, that is, decadal to millennial change (10^1–10^3 yr). A considerable body of geomorphic theory concerned with rapid change can be applied to watershed responses to human activities over these timescales. Much of this theory emerged without consideration of anthropogenic processes, but can be adapted for this purpose. Testing these theories with anthropogenic applications should draw upon principles and methods of both geologic and cultural history (e.g., Brierley, 2010). Many alluvial events over the past several millennia – a period germane to discussions of intensified land use and the emergence of civilization – have been decidedly episodic. The implication of these events should be considered in light of philosophical debates over uniformitarianism versus catastrophism (Gould, 1987; Huggett, 1989, 1990). Rapid floodplain and channel changes may be characterized by an application to geomorphic systems of the concept of 'punctuated equilibria', borrowed from evolutionary biology (Eldredge and Gould, 1972). This may seem antithetical to purely uniformitarian theories of gradualism (Playfair, 1802; Lyell, 1830; cf. Wolman and Miller, 1960). Nevertheless, it is fully compatible with modern concepts of neocatastrophism (Dury, 1980; Albritton, 1989; Huggett, 1990) that are clearly distinguished from the long-discredited religious dogma of classical catastrophism (Chorley et al., 1964). In fact, even extreme examples of the episodicity of anthropogenically induced fluvial sedimentation pale in comparison with the bolides and Spokanian floods of neocatastrophism (Bretz, 1923, 1925; Baker, 1973). The important point is that fluvial landforms are generally formed by gradual ongoing processes, but very large events such as a flood or period of severe aggradation may also be important to morphogenesis. To the well-established neocatastrophist principles, we must add human agency that may initiate highly effective and enduring episodes of geomorphic change.

9.37.4.3.2 Aggradation, degradation, bed waves, and sediment waves

The effects of major land-use changes on downstream river systems can occur over fairly large scales, namely, an entire drainage basin may respond over the course of decades or centuries. On these timescales, sediment produced by a large erosion event can be delivered downstream causing a period of channel aggradation, that is, a rise in the channel bed, and floodplain overbank deposition. When high sediment production rates decrease, the bed will ultimately degrade, thus defining an aggradation-degradation episode (ADE) (*see* Chapter 13.4). Such episodes have been noted in many contexts including stratigraphic and historical records of events ranging from prehistoric to pre- and postcolonial periods. The rise and fall of channel beds during an ADE has been described as a 'sediment wave' (**Figure 13**), although this term has also been used to describe smaller bed forms or an intense episode of sediment flux. The latter is preferred because Gilbert (1917) described the passage of a sediment wave as analogous to the passage of a sediment hydrograph. The various uses of sediment wave terminology have been reviewed by Hoey (1992), Nicholas et al. (1995), James (2006, 2010), and Lisle (2008). Related terms include bed waves, bed material waves, bedload sheets, sediment slugs, and sediment pulses (Wathen and Hoey, 1998; Lisle et al., 2001; Madej et al., 2009). Given confusion between concepts, and important potential differences in timing between the bed response and the passage of sediment stored in a reach, James (2006, 2010) advocated a distinction between bed waves that are topographic changes in the bed and sediment waves that represent the passage of a mass of sediment through a reach over time (sediment flux).

The distinction between bed waves and sediment waves allows a comparison between the timing of these responses during an ADE. Substantial changes in land use that generate massive sedimentation events may initiate an episode that is accompanied by both a bed wave and a sediment wave. In most severe aggradational events generated by land-use change, the sediment introduced to the bed will be fine relative to preexisting channel lag materials, and some sediment will be stored on floodplains. The channel bed will incise back to pre-aggradational levels relatively quickly as noted earlier for large and small rivers (**Figure 10**), possibly defining a relatively symmetrical bed wave. Sediment reworking typically remains high during the prolonged period of widening, however, maintaining high sediment loads and producing a skewed sediment wave (**Figure 14**). Recognizing the extended period of high sediment activity is an important dynamic to river management.

9.37.4.3.3 Legacy sediment

Alluvium deposited following human disturbances is generally referred to as 'legacy sediment'. The term has been applied to postcolonial alluvium in the Americas and Oceania; however, it can also be applied to older anthropogenic alluvium. Legacy sediments (also known as postsettlement alluvium) are ubiquitous on many floodplains where they overlie a

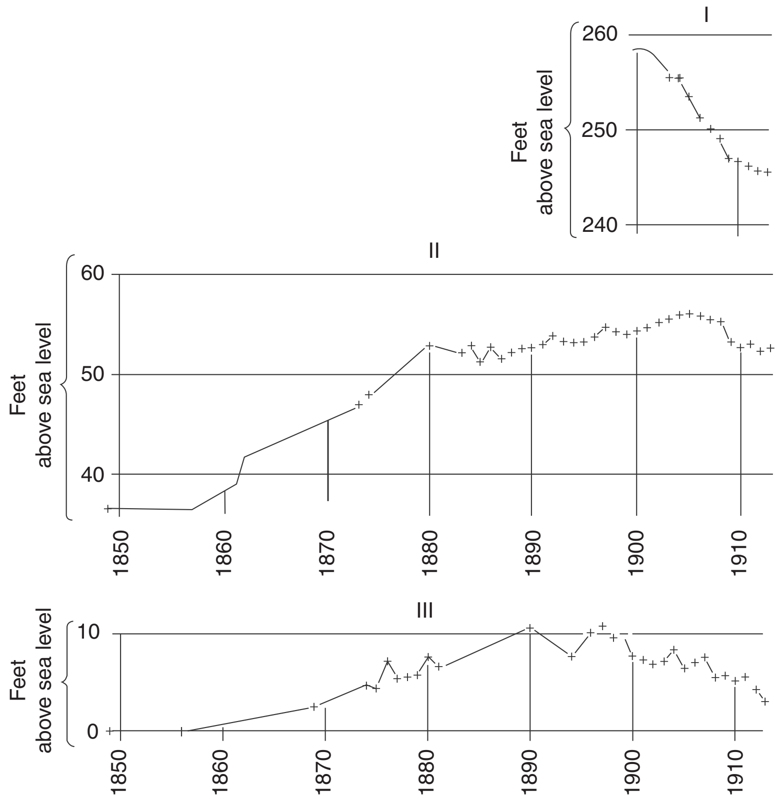

Figure 13 Original figure by Gilbert (1917) showing bed waves during the beginning of an aggradation–degradation episode generated by hydraulic mining sediment at three locations in California. Channel beds rose 3–6 m (10–20 ft) and were degrading by 1900. (I) Lower Yuba River at the Narrows. (II) Lower Yuba River near Marysville. (III) Sacramento River at Sacramento. Reproduced from Gilbert, G.K., 1917. Hydraulic-mining debris in the Sierra Nevada. US Geological Survey Professional Paper 105. Government Printing Office, Washington, DC, with permission from USGS.

presettlement soil (Knox, 1977, 1987) (**Figure 15**). They represent sedimentation in response to episodic erosion induced by land clearance, mining, or other activities. Extensive historical alluviation occurred in the Mid-Atlantic states (Costa, 1975), the Southeast (Happ, 1945; Trimble, 1974; Jackson et al., 2005; James, 2006), and the upper Midwest (Knox, 1972, 2006; Magilligan, 1985; Faulkner, 1998; Lecce and Pavlowsky, 2001). In Europe and Asia, legacy sediment may have been generated by multiple ADEs, resulting in a complex anthropogenic alluvial stratigraphy (Lang et al., 2003; Dotterweich, 2005; Vanwalleghem et al., 2006; Macklin and Lewin, 2008). Sediment from early metal mining has been documented in the United Kingdom (Lewin et al., 1977; Macklin et al., 2006), the USA Southeast (Leigh, 1994; Lecce et al., 2008), Midwest (Knox, 1987; Lecce and Pavlowsky, 1997), and West, including the Rocky Mountains (Hilmes and Wohl, 1995; Wohl, 2001), the Sierra Nevada of California (James, 1989, 1991), and Alaska (Van Haveren, 1991). Similar episodic deposition of sediment occurred in Australia (Brooks and Brierley, 1997) and New Zealand (Gomez et al., 2004).

9.37.4.4 Contamination from Mining and Industrial Pollutants

Some aspects of sediment chemistry can have severe impacts on water quality and ecological diversity. For example, excessive nutrient loadings from agricultural chemicals can lead to eutrophication. When sediment chemistry is an important consideration to river management, it may motivate geomorphic studies of the systems that drive channel stability and sediment reactivation. Interactions between geomorphic processes and sediment dynamics may govern flux rates of nutrients, heavy metals, and other chemicals in aquatic environments. These chemicals may also be directly introduced by land use, so they have an importance to river science and watershed management that goes beyond geomorphology. Although nutrient loadings and eutrophication are important impacts of land-use change, here the discussion focuses on sediment contamination from mining and industrial pollutants.

Mining and industrial activities may produce large amounts of point or nonpoint source pollution. Large-scale contamination from these sources can be quite extensive because fluvial processes can disperse particulate wastes up to several hundred kilometers downstream (Brook and Moore, 1988; Leenaers, 1989; Horowitz et al., 1990). In some regions, mining activities are widespread and acid-mine drainage can be particularly devastating to fluvial systems. Geomorphic processes and sediment dynamics are important to explaining heavy metal concentrations in the fluvial environment because metal concentrations are usually much greater in sediment than in water (Horowitz, 1991), and because fluvial erosion can remobilize metal-contaminated sediments stored previously in the fluvial

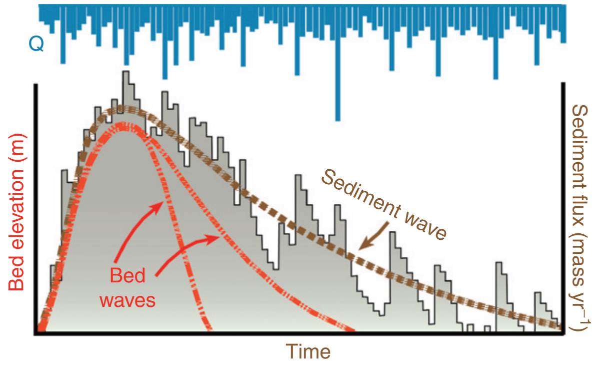

Figure 14 Two bed waves and a skewed sediment wave. Sediment waves represent the flux of sediment and are commonly skewed with respect to time if long-term storage is involved. Bed waves represent the rise and fall of the channel bed and may be symmetrical or skewed depending on local flow hydraulics and bed sediment characteristics. Adapted from James, L.A., 2010. Secular sediment waves, channel-bed waves, and legacy sediment. Geography Compass, doi:10.1111/j.1749-8198.2010.00324.x, and James, L.A., 1999. Time and the persistence of alluvium: river engineering, fluvial geomorphology, and mining sediment in California. Geomorphology 31, 265–290, with permission from Wiley.

Figure 15 Laminated historical silt and fine sand alluvium overlying a presettlement soil on Blue River, Wisconsin. Photo by S Lecce.

environment. Thus, floodplains play an important role as both sinks and sources of metal contaminants in mined watersheds (Bradley, 1989; Horowitz, 1991; Lecce and Pavlowsky, 1997; Coulthard and Macklin, 2002).

Grain size is one of the most significant factors controlling the capacity of sediments to concentrate and retain trace elements (Horowitz, 1991). A strong negative correlation occurs between grain size and metal concentrations due to the larger surface areas of fine-grained particles (Horowitz and Elrick, 1987). In many industrialized and urbanized rivers, the silt and clay fractions contain most of the metals of anthropogenic origin. However, large quantities of coarse metalliferous sediments are commonly supplied to the channel during ore processing associated with mining, and these particles are transported in association with the coarser sediment fractions (Bradley and Cox, 1986). These coarse ore particles consist of heavy minerals that are relatively dense, so that their hydrodynamically equivalent particle size is much finer than that of the nonmetalliferous sediment (Rubey, 1933). The importance of the heavy mineral fraction as a source of metal pollution in mined watersheds, therefore, generally decreases downstream (Lewin et al., 1977; Macklin and Dowsett, 1989).

Metal concentrations are not uniformly distributed in fluvial sediments because hydraulic forces sort sediment by size and density. Silts and clays tend to become stored in vertically accreting overbank deposits, sands in laterally accreting point bar deposits, and gravels in floodplain splay and channel lag deposits (Bradley and Cox, 1986). In areas with rapid overbank sedimentation rates, the resulting increase in bank heights and decrease in flood inundation frequencies can shift the locus of deposition downstream through time (Knox, 1987; Lecce and Pavlowsky, 2001). The combination of both chemical and hydraulic processes produces a generally logarithmic decrease in metal concentrations downstream from contaminant sources (Wolfenden and Lewin, 1978; Yim, 1981; Leenaers et al., 1988; Marcus et al., 2001). The most common explanation for the longitudinal decrease in metal concentrations is the dilution of metal-bearing sediments with uncontaminated tributary sediments (Lewin et al., 1977; Yim, 1981). Whereas dilution processes are clearly an important explanation of the down-source reduction of metal concentrations, other factors can affect the spatial variability of metal concentrations in fluvial sediments. For example, departures from the expected logarithmic decline of metal concentrations in river sediments have been attributed to downstream variations of the hydraulic energy present in the reach (Graf, 1990). Locally, variations in metal concentrations tend to be related to hydrodynamic conditions and the sedimentological characteristics of the particles in transport.

9.37.5 Historical Perspective: Episodic Land-Use Change and Sediment Production

The dominant causes of anthropogenic soil erosion are land clearance for farming, deforestation by grazing or silvaculture, farming, and fires (Butzer, 1982; Van Andel et al., 1990). The clearance of vegetation can have dramatic effects on channels (*see* Chapter 13.2). Agricultural practices can be highly erosive, have the potential to rapidly accelerate erosion and sedimentation, and can have a great influence on fluvial systems. The history of agriculture extends back more than 10 millennia and differs from continent to continent in timing, cultivars, and technologies (*see* Chapter 13.4). The impacts of agriculture on fluvial systems, therefore, are complex and require multidisciplinary perspectives to understand fully. The nature and severity of human impacts on environmental systems by indigenous cultures and colonists in the Americas recently have been debated and largely revised by geographers, anthropologists, archeologists, and paleoecologists (Butzer, 1992, 1996; Denevan, 1992). A case for substantial precolonial disturbances and relatively little disturbance associated with European colonization has recently been advanced for New South Wales, Australia (Butzer and Helgren, 2005). Assumptions that European land-use practices were introduced to pristine landscapes in the Americas and Australia, and that these practices were suddenly followed by episodic erosion, should be critically evaluated on a case-by-case basis as results can vary greatly between watersheds or regions. Some pre-Columbian landscapes in the Americas and pre-First Fleet landscapes in Australia had strong anthropogenic imprints, and European colonization did not always generate rapid soil erosion and sedimentation responses. Numerous examples of postcolonial ADEs have been clearly documented, however, at many locations in the United States and Australasia. This section provides a brief introduction to the broad topics of early agricultural developments and anthropogenic changes to the environment. It briefly describes the origins of agriculture, development of intensive Eurasian agricultural technologies, prehistoric episodes of erosion in Europe, and the relatively rapid introduction of highly erosive agricultural technologies to North America, often resulting in massive ADEs. A more detailed account is provided elsewhere in this treatise (*see* Chapter 13.4).

9.37.5.1 The Development and Spread of Agriculture

Agriculture emerged in many centers at various times during the early Holocene and increased in intensity long before written documents. Knowledge of the histories and the geomorphic impacts on fluvial systems is imperfect, therefore, and must be reconstructed from stratigraphic, paleobotanical, and archeologic records (Hassan, 1979; Macphail et al., 1990; Macklin, 1995; Brown et al., 2003). Agriculture emerged primarily during the Neolithic stage of cultural history and included the domestication of plants and animals, development of polished stone tools, and the beginning of forest clearance. The Neolithic was widespread but time transgressive, occurring on most of the continents in isolated locations at different times. It occurred as a slow transition from hunting and gathering, rather than as a sudden change (Moore, 1982; Pringle, 1998). Groups of hunters and gatherers began to select and manipulate plants, clear forest lands, burn brush and grasslands, drain wetlands, break sod, and manage grazing animals (Flannery, 1969; Pringle, 1998). The slow transition from hunter–gatherer to a sedentary reliance on agriculture during the Neolithic transition took ~3000 years in the Near East, ~6000 years in Mexico, and 4000 years in eastern North America (Smith, 1998). The gradual transition to agriculture may have begun as early as 13 000 BP in the Near East, 10 000 BP in China, 10 000 BP in Mexico, 10 000 BP in South America, and by 7500 BP in the Rhine Basin of western Europe (Van Andel et al., 1986; Pringle, 1998; Bintliff, 2002; Lang et al., 2003).

Early agricultural expansion in China generated extreme erosion and sedimentation due to the highly erosive loess soils and a high sensitivity to climate change. After the introduction of agriculture in the late Holocene, sediment yields to the ocean from the Huang He Basin increased an order of magnitude (Milliman et al., 1987). Sediment yields from the Huang He Basin experienced two periods of rapid sedimentation in the last 2300 years: from 600 to 1000 BP and in the late nineteenth century (**Figure 16**; Xu, 2003). In the early period, the combination of a drier climate and intensifying land use led to the rapid degradation of forests that protected the loess hills (Xu, 2003). When humid conditions returned after AD 1100, sedimentation rates remained high as forest regeneration was inhibited by land use driven by population growth and expanded cultivation.

In Northern Europe, Neolithic forest clearance and expansion of agriculture was conducted with stone axes and fire (Darby, 1956). Pollen evidence indicates that most of Northern and Central Europe had been covered by thick broadleaved forest through much of Roman time. The spread of Neolithic farming was associated with local clearings around settlements where the dominant pollen shifted to weeds and grain. In the Rhine Basin, Holocene anthropogenic changes – including forest clearance, population growth, and mining – were associated with rapid erosion and local sedimentation (Lang et al., 2003). During the Neolithic, connections between upland sediment production and channels were weak, so sediment deliveries to fluvial systems relied on large storm events to convey sediment downstream. Most agriculturally derived sediment produced in the Rhine Basin during the Neolithic remained on hillslopes until the Bronze and Early Iron Ages, when gullying was initiated and deposition began to reach lower slopes and floodplains (**Figure 17**). In some cases, small bands of Neolithic people generated severe erosion, but – later during the Bronze Age – large groups were often able to maintain stable settlements for long periods without episodic erosion. Butzer (1996) noted that such stability could indicate a cumulative cultural experience that

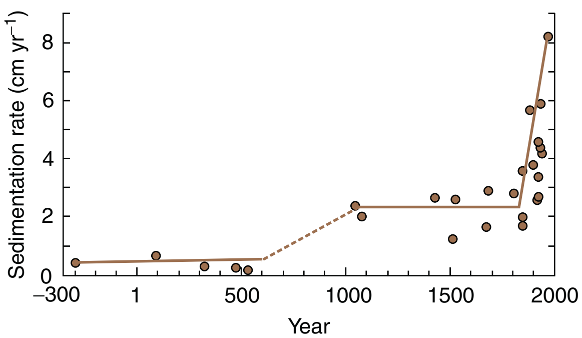

Figure 16 Three stages of sedimentation along the Yellow River, China, showing rapid acceleration in the last 130 years. Adapted from Xu, J., 2003. Sedimentation rates in the lower Yellow River over the past 2300 years as influenced by human activities and climate change. Hydrologic Processes 17, 3359–3371, with permission from Wiley.

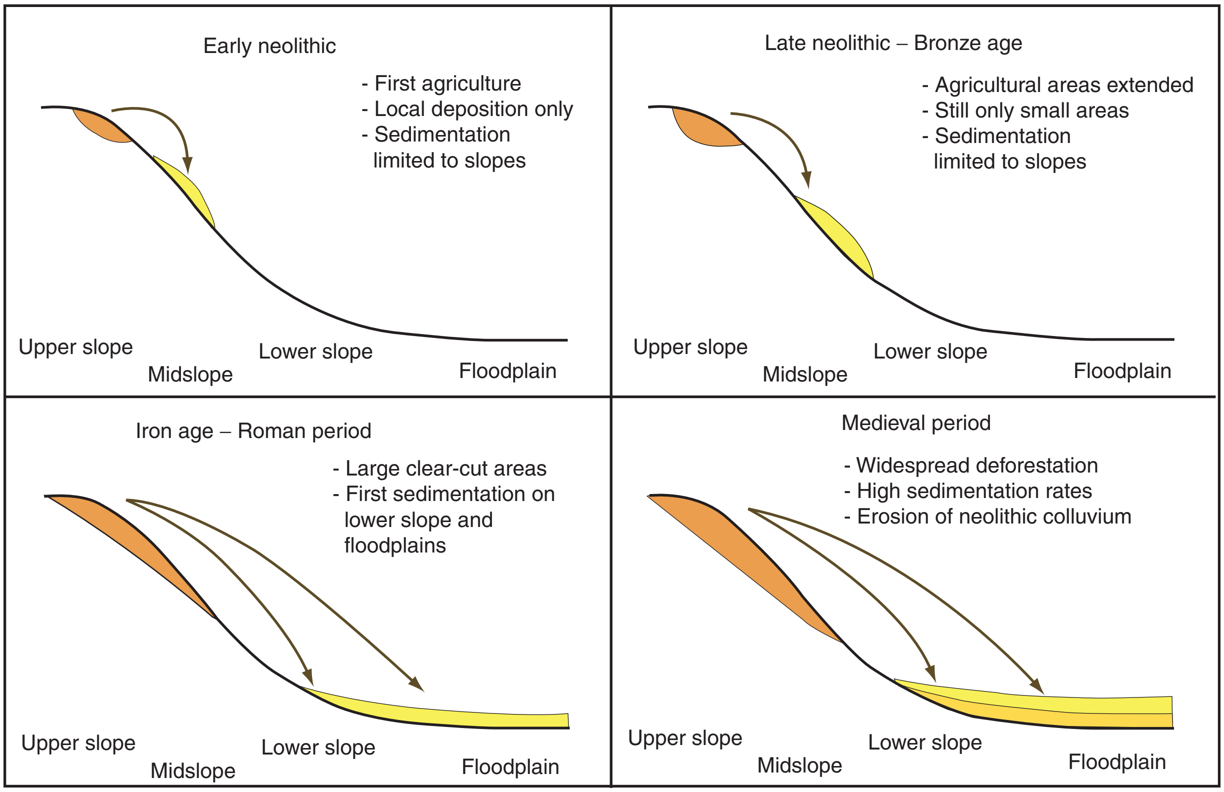

Figure 17 Conceptual model of increasing slope–channel coupling from the early to middle agricultural period in central Europe. Adapted from Lang, A., Bork, H.-R., Mäckel, R., Preston, N., Wunderlich, J., Dikau, R., 2003. Changes in sediment flux and storage within a fluvial system: some examples from the Rhine catchment. Hydrologic Processes 17, 3321–3334, with permission from Wiley.

selected for conservationist practices. Rapid erosion generally followed after social destabilization or out migrations.

A series of technologic developments followed the Neolithic in Afro-Eurasia including invention of the wheel, steel plow shares, and the harness, increasingly intensive use of draught animals, and, ultimately, the development of heavy-wheeled plows. These technologies were introduced at various times in different regions and greatly increased the geomorphic effectiveness of agriculture. The result was the increased potential for episodic upland erosion and lowland sedimentation associated with colonization, although it generally lagged behind initial settlement by some time. In the Near East, the agricultural technology of Mesopotamia spread to the eastern Mediterranean, and by 2000 BP agriculture in the Mediterranean region was greatly altered (Heichelheim, 1956; Van Andel et al., 1990). Several contemporary accounts in the region describe geomorphic processes associated with severe land use such as silty rivers and delta progradation (Chorley et al., 1964). The Romans assimilated much Mesopotamian agricultural technology from the Assyrians and Greeks and introduced these technologies across their domain including Northern and Western Europe (Cunliffe, 2008).

By the Medieval period, some basins in Europe had experienced more than one episode of settlement, forest clearance, erosion, and sedimentation. For example, two periods of soil erosion and alluviation occurred in the Geul River of the Netherlands: after Roman occupation and in the Middle Ages (1000–1500 AD) (De Moor et al., 2008). Most of Germany was reforested by the mid-sixth century AD, but erosion recommenced later with renewed land clearance (Bork et al. (1998) cited in Lang et al. (2003)). Rill and gully erosion became so extensive in the Medieval period (AD 1300–1700) that widespread lowland sedimentation led to the cessation of farming in some areas (Lang et al., 2003). The introduction of heavy-wheeled plows with iron plowshares and draught animals accelerated agricultural expansion, deforestation, and deep, extensive plowing in Northern and Western Europe. The harnessing of waterpower during the mechanical revolution led to the development of grist and saw mills and rising exports of grain and timber. By the 1500s, forest clearance had progressed to the point in some areas that timber shortages, severe erosion, and sedimentation began to be noted (Darby, 1956). By the Industrial Revolution, advanced technology – coupled with colonialism, export economies, and mercantilism – promoted the expansion of aggressive land clearance for agriculture and resource extraction overseas. As a result of these developments colonists were motivated and capable of rapid land clearance that had the potential to induce severe erosion and sedimentation.

9.37.5.2 Pre-Columbian Land Use, Erosion, and Sedimentation in the Americas

The severity of pre- and post-Columbian anthropogenic erosion in the Americas has been a subject of much debate over the past two decades. For most of the twentieth century, it was commonly assumed that pre-Columbian agricultural impacts in the Americas were negligible. Challenges to this assumption have documented extensive pre-Columbian environmental changes in the Americas, including intensive land management and erosive land use (Butzer, 1996). Pre-Columbian populations were much greater than previously estimated but declined greatly after 1492 in response to the introduction of European diseases (Denevan, 1992). The rapid population decline after 500 BP and subsequent forest regeneration may explain a reduction in biomass burning noted in the tropical Americas that represents sequestration by the biosphere of 5–10 Gt C or 2% of the global atmospheric CO_2 (Nevle and Bird, 2008). Early agriculture in the Americas was technologically sophisticated, especially with regard to manipulating field cropping and irrigation systems, and was capable of making major environmental changes (Doolittle, 2000; Whitmore and Turner, 2002; Denevan, 2003). A 4000-year record of erosion based on sediment cores from Lake Pátzcuaro in central Mexico documents two periods of accelerated sedimentation: the late Preclassic/early Classic periods (2500–1200 years BP) and the later Postclassic period (850–350 years BP) (O'Hara et al., 1993). Erosion rates were at least as high as rates after the Spanish conquest, indicating that erosion after the Spanish introduction of plowing was no more than that produced by traditional indigenous agricultural methods. Deforestation in the tropical lowlands of Central America was initiated by Mayans around 4500 BP and intensified from 3500 to 3300 BP (Pohl et al., 1996; Rosenmeier et al., 2002). Accounts of Spanish explorers include descriptions of extensive agricultural developments such as the observations by Hernando de Soto's party of extensive fields of maize, beans, and squash in northern Florida (Doolittle, 1992, 2000). Denevan (1992) argued that the most pristine period for the Americas was not the time of initial contact with colonists in the early sixteenth century, but two centuries later around 1750 after decimation of Indian populations.

Pre-Columbian human impacts to flora and fauna in the Americas were substantial and many landscapes experienced anthropogenic changes including accelerated erosion and sedimentation from agricultural clearance and fire. In some locations, agricultural land clearance was intensive and involved terraces, irrigation canals, and mounded or ridged fields. In Latin America, especially in tropical and mountainous areas, several cases of pre-Columbian anthropogenic alluvial episodes have been documented. Such erosional episodes, however, have not been documented in all physiographic regions of North America. For example, evidence for high pre-Columbian erosion rates sufficient to generate major ADEs in subhumid mid-latitude areas of the eastern and central United States is less convincing than for Meso America. The new evidence of widespread pre-Columbia agricultural practices in the region is compelling, populations were much greater than previously supposed, and the use of fire was presumably effective in clearing land. Nevertheless, a stratigraphic record of massive anthropogenic erosion and sedimentation has not been demonstrated for the region. In the southeastern and midwestern USA, deep historical alluvium commonly rests abruptly over well-developed floodplain soils, indicating stable fluvial environments prior to European colonization (Happ, 1945; Knox, 1972, 1977; James, 2006).

A research challenge for geomorphologists and geoarcheologists is to test the hypothesis that indigenous cultures were geomorphically effective, that is, their land clearance and land-use practices could be highly erosive on a basin-wide scale. The geomorphic effectiveness of pre-Columbian agriculture in the Americas was limited by the lack of animal power or the wheel for plowing or hauling freight (Goudie, 2005). By comparison, the intensive land use associated with European agriculture was much more geomorphically effective and had the capacity to generate rapid soil erosion and sediment redistributions from hillslopes to small watersheds.

9.37.5.3 Introduction of Intensive Agriculture to the Colonies

Several questions have been raised about the geomorphic effectiveness of initial European colonization in the Americas. A common assumption that European colonization invariably was followed quickly by severe erosion has been referred to as the "myth of the devastated Colonial landscape" (Butzer, 1992, 1996). For example, a debate emerged in the 1990s over the degree of land degradation caused by the introduction of grazing animals to the Valle del Mezquital, Mexico, by early Spanish settlers. One pervasive theory postulated that sheep introduced by the Spaniards destabilized vegetation, resulting in a period of rapid erosion (Melville, 1994). Conversely, based on stratigraphic and sedimentologic criteria in a nearby valley, coupled with knowledge of careful Spanish livestock management practices, Butzer (1996) largely dismissed the degradational impacts of early Spanish livestock grazing. In fact, he described a sustainable, well-managed Mediterranean agricultural system that maintained productivity for 200 generations and was not highly destructive upon its introduction in a simplified form to Mexico and Central America. Only in the eighteenth century did accelerated soil erosion and alluviation appear in those regions (Butzer, 1996). Thus, presumptions that wherever European settlement occurred in the Americas or Oceania rapid soil erosion and sedimentation necessarily followed should be critically evaluated for each watershed based on geoarcheological evidence. Conversely, where agricultural practices based on prior environmental experience are introduced to a different physiographic environment, severe damage can ensue (Butzer, 1996). For instance, farming by the Incas in Peru and Ecuador utilized erosion-control practices such as terraces on steep slopes and floodplains that were maintained up to the time of Spanish conquest. Their subsequent failure, provoked by lack of maintenance and trampling by introduced grazing animals, led to severe erosion (Gade, 1992; Troeh et al., 2003). In spite of steep slopes, erosion in the former Inca region of northwest South America was mitigated by the maintenance of indigenous land-use practices that were gradually merged with selected Spanish practices, and by the geographic isolation of the region that impeded export of lumber and other products by sea (Gade, 1992).

The rapid introduction of land clearance and advanced agricultural techniques to several regions in North America and

Australasia during Anglo-European colonization drastically accelerated erosion and induced unprecedented sedimentation (Happ, 1945; Knox, 1972; Brierley et al., 2005). Agricultural technology and land-use practices introduced by colonists spread rapidly westward with the frontier. In many cases, frontier settlers cleared land, worked it for a few generations until soil erosion decreased its value, and then moved farther west to clear new lands. Little attention was paid to soil conservation by frontier farmers, so erosion was often severe. By 1940, ~1.14 million km^2 of land in the United States had been ruined or seriously damaged and another 3.14 million km^2 had experienced substantial erosion (Bennett and Lowdermilk, 1938; Bennett, 1939). The total land area of the United States at that time was 7.70 million km^2, so 15% of the total land area was seriously damaged and another 41% was substantially eroded. Erosion was especially extensive in the southern Piedmont of the USA. By 1945, Happ (1945) concluded that most Piedmont flood plains were covered with postcolonial anthropogenic sediment. All but ~10% of this sediment remained in small watersheds (Trimble, 1974). Based on comparisons of suspended sediment yields with volumes of legacy sediment stored on floodplains of a small Georgia Piedmont, Jackson et al. (2005) estimated that, at present rates of sediment transport, the stored historical alluvium will not be removed for six to ten millennia. In addition, fluvial systems were substantially changed by the extirpation of beavers (Wohl, 2001).

The nineteenth-century European colonization of Australia swiftly introduced advanced agricultural technology, land-clearance practices, and grazing animals that increased erosion and sediment yields. In some cases, sediment yields increased by a factor of more than 150 (Verstraeten and Prosser, 2008) and channels widened up to 340% (Brooks and Brierley, 1997). In most Australian river basins, sheet, rill, and gully erosion dominated sediment production (Olley et al., 1993). Overgrazing in small watersheds often initiated gullying. Sediment production in the upper Murrumbidgee River increased by a factor of ~150 compared to a twofold increase in sediment production that could have been induced by precipitation variability alone (Olley and Wasson, 2003).

Land-use intensification in many other regions began late due to distance to markets or climatic or physiographic conditions that are marginal for agriculture. After World War II, major agricultural transformations occurred in response to the introduction of mechanized farm equipment, synthetic fertilizers and pesticides, availability of fossil fuels for pumping irrigation water, and development of high-yield cultivars. Agriculture spread rapidly, often into areas that had not previously been farmed extensively. The geographic spread and intensification of cultivation are expected to continue owing to population growth. New agricultural technologies are likely to follow along with intensified irrigation. The question is whether or not innovations in soil conservation and near-site sediment retention practices will be implemented enough to keep up with intensifying land-use developments aimed at increasing food production or urbanization. To some degree, intensive land use has shifted from land clearance for agriculture to urbanization and this poses a new set of problems and LID strategies and mitigation.

9.37.6 Conclusion

A thorough understanding of geomorphic responses to global-scale land-use change requires an historical perspective. Change must be placed in the context antecedent conditions, such as earlier perturbations from which systems are responding. Accurate interpretations of modern observations of geomorphic responses to land use require an understanding of past land-use changes and trends in how systems have responded. Interdependencies between scales of time and space dictate that reconstructions of antecedent conditions over large areas, that is, global geomorphic change studies, should extend farther back in time than for local studies.

To place geomorphic impacts of land use into a proper perspective, contemporary sensitivities to change should be considered. Landscape sensitivity may increase with human activities such as agriculture or deforestation because it measures the susceptibility to change by frequently occurring events. The historical record indicates that many North American landscapes were relatively insensitive to change owing to thick forest cover and modest pre-Columbian human alterations relative to their Old World counterparts. Extreme geomorphic changes to some landscapes occurred with Anglo-European colonization in spite of low landscape sensitivities, because land clearance and agricultural practices were so severely disruptive that high thresholds of stability were exceeded. Logging and deep plowing on some landscapes exposed thick soils developed in deep regolith, which quickly rendered large areas vulnerable to erosion.

Human land use clearly can generate hydrologic and geomorphic responses in the form of increased runoff, soil erosion, and sedimentation that can have substantial effects on fluvial systems. These impacts can be traced back to the advent of agriculture in the early Neolithic, but the potential effectiveness of humans as hydrogeomorphic agents has grown greatly with technologic developments and population growth. The process mechanics of anthropogenic changes are fairly well understood, although simulation models are needed, especially for large spatial and temporal scales. Sediment storage and remobilization is a key area where complexities require that theory be joined with field verification and modeling efforts.

The effectiveness of pre-Columbian agricultural practices in the Americas has recently been revised to acknowledge substantial environmental changes prior to European contact. In some regions, pre-Columbian soil erosion was substantial but, in other regions, evidence is lacking. The hypothesis of substantial pre-Columbian ADEs remains to be tested in many regions of North America or Oceania, based on stratigraphic evidence. Greatly accelerated rates of soil erosion and sedimentation immediately following the introduction of agricultural practices by European colonialists have also been questioned. Colonization did not always generate an episodic response in geomorphic systems, but, in some cases, it clearly did. Thus, the hypothesis of rapid post-European settlement alluviation should also be tested in each region. High spatial and temporal variability is to be expected for both hypotheses, so field evidence is needed for each region.

Anthropogenic land-use changes have had extensive effects on fluvial systems. Collectively, the hydrogeomorphic changes wrought by land use comprise one of the most pervasive anthropogenic changes to the environments of Earth. Many regions have undergone major ADEs. Recognition of past events and the legacies that they have left behind, protecting against the potential for new episodes, and developing an understanding of the likely behavior of the changed systems are challenges facing global change studies. A serious commitment is needed to land-change science, in parity with current efforts to understand the effects of climate change.

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