# 8

# Rivers in the Landscape

This final chapter looks at interactions between rivers and landscapes across varying time and space scales, starting with geological time scales of $10^3$–$10^7$ years and entire continents. The second section explores distinctive climatic signatures of river process and form associated with high latitudes, low latitudes, and warm drylands. The third section examines the significance of spatial context and the potential for relatively abrupt spatial transitions in process and form within a drainage basin. The fourth section returns to the idea of connectivity, which was introduced in Chapter 1, and explores the implications of connectivity for the diverse river processes and forms discussed throughout the book. The fifth section examines contemporary river management in the context of the diverse topics introduced in earlier chapters.

Preceding chapters have introduced the basic processes of water, solute, sediment, and large wood movement into and through channel networks and the river forms and adjustments that result through time. This final chapter returns to the idea that river process and form reflect not only physics, but also distinctive processes and forms associated with a specific geographic location and its history.

## 8.1 Rivers and Topography

Having examined the details of how water, sediment, and large wood move down hillslopes and into channels, and then through a river network, it is useful to step back and consider the larger-scale distribution of rivers across continents. Important insights into interactions between rivers and topography can be gained by examining river configuration.

The manner in which rivers both respond to and shape surrounding topography has been investigated systematically for more than a century. Early work explored why some rivers cut through mountain ranges rather than simply flowing downward from high points in the landscape. Significant questions at the time of this late-nineteenth-century research included, What is the role of rivers (as opposed to glaciers or other processes) in cutting deep river canyons?, and How do large-scale structures (mountains, deep canyons) relate to movements of Earth's crust? Subsequent research has emphasized (i) how redistribution of mass at the surface by river erosion can influence redistribution of subsurface mass via movements of molten material in the crust and tectonic movements, and (ii) how river gradient and channel width can be used as indicators of spatial variations in rock uplift.

The most obvious topographic influences on river process and form occur in mountainous environments where rivers cut deep, narrow canyons as they flow down toward adjacent lowlands. For

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more than a century, however, investigators have recognized that rivers do not always follow topography. Among rivers that cut across mountain ranges in the western United States, Powell (1875, 1876) distinguishes *antecedent* drainage networks in which pre-existing channels maintained their spatial arrangement while the underlying landmass was deformed and uplifted, and *superimposed* channels, which incised downward to a buried structure. In both cases, the river flows through or across the mountain range, rather than being a consequence of the topography.

Today, these two types of drainages are commonly referred to as *transverse drainages*, which cut across bedrock topographic highs such as anticlines and upwarps (Douglass and Schmeeckle 2007). Transverse drainage subsumes antecedent and superimposed drainages, overflow, and drainage piracy. In *drainage piracy*, a drainage network on one side of a bedrock high erodes headward sufficiently to lower or breach the drainage divide and divert flow from a network on the other side. An ongoing example is the Casiquiare Canal, which is not a canal but rather a natural channel, a tributary to the Rio Negro in the northern extent of the Amazon River drainage in South America. The canal connects the Rio Negro and the Amazon with the adjoining Rio Orinoco drainage as a result of drainage piracy, with the canal capturing a portion of the Orinoco's headwaters (Eden 1971).

Research since the nineteenth century has developed tools that illuminate the influences of tectonics on the spatial arrangement of rivers and the geometry of individual river channels, as well as the influences of river incision on tectonics and topography. The manner in which tectonic forcing creates topographic patterns and spatial variability of relief in river networks gives rise to the *inverse problem*, in which topographic features are used to infer tectonic uplift rates. This approach to understanding uplift is challenging because river response time to tectonic perturbations governs which tectonic events are preserved in topography (Goren et al. 2014). In addition, rates of river incision into bedrock exist in non-steady-state even over measurement intervals of $10^4$–$10^7$ years as a result of episodic interruptions in river incision triggered by alluvial deposition (Finnegan et al. 2014).

The gradient and width of rivers incised into bedrock are the geometric parameters most commonly used to infer the spatial distribution and relative magnitude of tectonic forces. A river being incised into bedrock, rather than alluvium, implies that the channel's capacity to transport sediment exceeds the sediment supply (Howard 1980). Regardless of where they occur along a river's course, bedrock river segments typically have smaller width-to-depth ratios and steeper gradients than alluvial segments (Montgomery and Gran 2001; Wohl and David 2008). These differences in geometry effectively enhance the flow's limited ability to incise the channel bed and enlarge the channel cross-section relative to alluvial segments.

Bedrock river segments can be interpreted as geologically transient features that are not confined to headwaters. The middle and lower Danube River of Europe alternately flows across large alluvial basins and cuts through mountain ranges. The lower Mississippi River in the United States, commonly thought of as a fully alluvial river, is better described as a mixed bedrock–alluvial channel because of the presence of a cohesive, Pleistocene-age clay unit that influences river process and form in a manner analogous to bedrock (Schumm et al. 1994; Nittrouer et al. 2011).

The relative lack of erosive ability that produces a bedrock river segment can reflect greater erosional resistance where the river crosses a different lithology (Wohl 2000b) or changes in relative base level associated with base-level fall or with uplift of the drainage (Howard 1980; Seidl et al. 1994). Where the presence of bedrock river segments reflects enhanced incision in response to relative base-level fall, river incision is the primary nonglacial mechanism of transmitting base-level changes across the landscape (Hancock et al. 1998). Bedrock river incision steepens adjacent

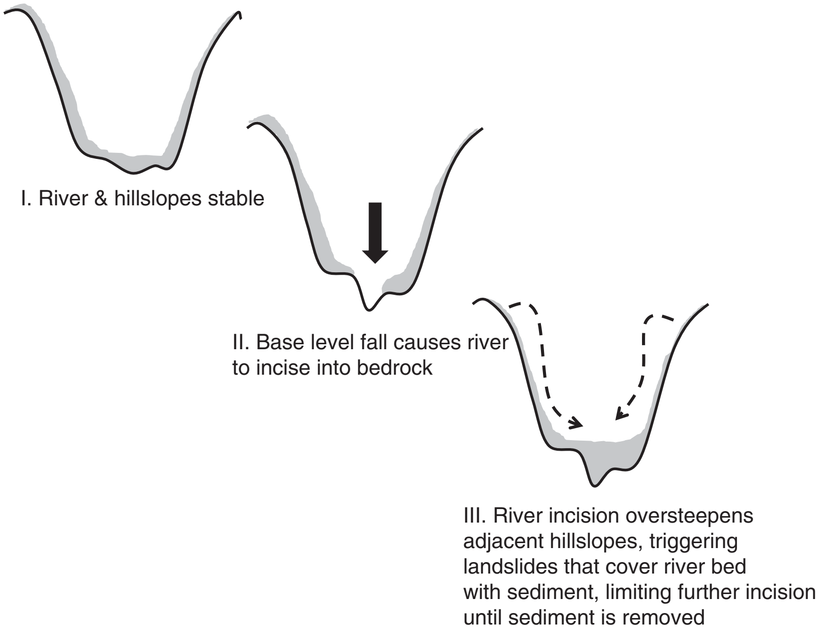


**Figure 8.1** Illustration of the effects of bedrock-channel incision on landscapes. In these schematic views looking upstream within a river valley, base-level change triggers river incision, which affects the stability of adjacent hillslopes and tributaries. Gray shading represents hillslope regolith and valley alluvium.

hillslopes, increases topographic relief between summits and valley bottoms, removes mass from the landscape, and ultimately sets the rate at which the entire landscape evolves (Figure 8.1) (Howard 1994; Burbank et al. 1996; Hancock et al. 1998; Whipple et al. 2013).

The idea that hillslopes and rivers mutually adjust was first expressed by Gilbert (1877) and subsequently formally stated in the context of *dynamic equilibrium* as a condition in which "every slope and every channel in an erosional system is adjusted to every other. When the topography is in equilibrium and erosional energy remains the same all elements of the topography are downwasting at the same rate" (Hack 1960, p. 80).

### 8.1.1 Tectonics, Topography, and Large Rivers

Although much of the research summarized in the preceding section focused on rivers in mountainous terrain, investigators have also examined the spatial arrangement of very large rivers in the context of tectonic history and topography (Figure 8.2). The location and configuration of most of Earth's largest river basins reflect the tectonic assembly and deformation of continental land masses (Potter 1978). The basic configuration of some major rivers has been extremely persistent. The Mississippi drainage, for example, has existed about 250 million years, or about 1/16 of Earth's history (Potter 1978). This persistence partly reflects the control of deeper crustal structures.

The 28 largest rivers discharge across trailing-edge coasts without compressional deformation, which reflects the continental asymmetry of many watersheds (Inman and Nordstrom 1971). The mouths of many large rivers occupy grabens or crustal downwarps. The alignment of several major

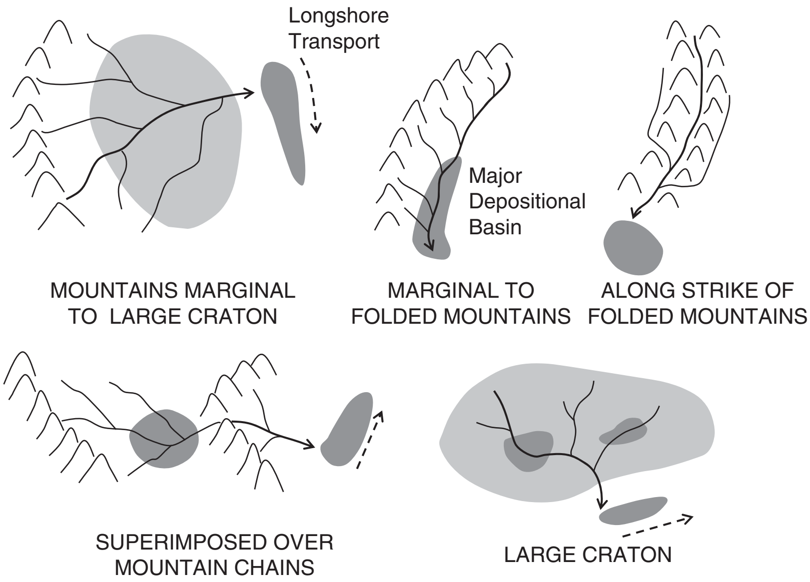


**Figure 8.2** Types of big river settings. Lighter gray shading indicates basement bedrock; darker gray shading indicates major depositional areas. Source: After Potter (1978), Figure 9.

rivers, including the Amazon in South America (Potter 1978), the Nile in Africa (Schumm and Galay 1994), and the Rio Grande in North America, correlate with large-scale crustal fracture patterns.

The Amazon River provides an example of the three scales at which tectonics can influence large-scale features of a drainage network (Mertes and Dunne 2007; Dunne and Aalto 2013). At the continental-scale ($5 \times 10^3$ km), the assembly of orogen (mountains), foreland basin, cratons, and grabens influences production of runoff, sediment supply, and accommodation space. Specifically, the Amazon heads on the Andean arc at the leading edge of the South American Plate. The Andes provide the majority of the sediment that the Amazon carries across a very broad lowland, before entering a graben that localizes the mouth of the river on the trailing edge of the continent.

At an intermediate scale ($10^2$–$10^3$ km), the spacing of crustal warping transverse to the river course influences gradient, valley width, channel sinuosity, accommodation space, and sediment distribution across the floodplain. Four major structural arches lie transverse to the main course of the Amazon between the Peru–Brazil border and the Atlantic Ocean (Mertes and Dunne 2007). As the Amazon crosses each of these arches, channel gradient increases, the valley grows narrower, and the channel becomes less sinuous.

At the local scale ($10^1$–$10^2$ km), brittle crustal fracturing influences channel orientation and gradient. Channel alignment follows fractures because these create localized zones of more readily eroded bedrock (Latrubesse and Franzinelli 2002; Roy et al. 2016).

These examples illustrate that, when examining river process and form, it is important to remember that deeper crustal structures and geologic processes occurring over millions of years can strongly influence river characteristics. These influences may be most readily detected in mountainous portions of a river network, but can also influence the world's largest lowland rivers, such as the Amazon and the Mississippi.

### 8.1.2 Indicators of Relations Between Rivers and Landscape Evolution

W.M. Davis (1899) first attempted to relate river geometry to landscape evolution in a conceptual model known as the *cycle of erosion*. This model posited high topographic relief and rivers with steep gradients in geologically young landscapes. As erosion gradually transferred mass to lower elevations, topographic relief and river gradients progressively decreased from mature to old landscapes.

The cycle of erosion, despite the name, assumed a highly linear landscape evolution with time and implied that an observer could readily interpret the relative geologic age of distinct landscapes based on their topography. This conceptualization is typically contrasted with the ideas of Davis' contemporary, G.K. Gilbert. Gilbert (1877) emphasized nonlinear change with periods of little net change, or equilibrium, as a result of feedbacks such as those subsequently recognized as tectonic aneurysms or isostatic rebound. *Isostatic rebound* is delayed upward flexure of Earth's crust in response to removal of mass such as a continental ice sheet that had previously depressed the crust. The implication of tectonic aneurysms or isostatic rebound is that elevation or relief may change relatively little over time spans of $10^3$–$10^4$ years, despite continued erosion and transfer of mass to lower elevations.

Many subsequent investigators have demonstrated that rates of landscape change fluctuate substantially through time and space (e.g. Bierman and Nichols 2004; Hahm et al. 2014). Conceptual models now tend to emphasize that most landscape change occurs during relatively short periods of time and is concentrated in relatively small portions of a drainage basin, although net change in elevation or relief may be minor.

Topographic metrics are still used to infer relative rates or stages of landscape evolution. Among these metrics are *hypsometric curves*, which illustrate the distribution of mass within a basin by plotting proportion of total basin height against proportion of total basin area. Strahler (1952) proposes that these curves could be used to distinguish relative basin age as a function of decreasing hypsometric integral – the area under the hypsometric curve – with increasing age. Subsequent research suggests that hypsometric curves can be used to infer the history and processes of basin development. The distribution of mass within a basin reflects uplift rates and variations in erodibility of different lithologic units (Walcott and Summerfield 2008; Pérez-Peña et al. 2009), as well as differences in diffusive (hillslope) versus fluvial sediment transport (Willgoose and Hancock 1998) and glacial versus fluvial erosion (Sternai et al. 2011). Hypsometric curves are likely to be concave-down everywhere, for example, within landscapes dominated by diffusive transport (Willgoose and Hancock 1998). Glacial valleys are more likely to have concave-up curves than are fluvial valleys (Sternai et al. 2011).

### 8.1.3 Tectonic Influences on River Geometry

Increased availability of topographic data in the form of electronic digital elevation models (DEMs) greatly enhanced the ability to detect irregularities in river longitudinal profile starting in the 1990s. Profile irregularities can reflect downstream variations in lithology and erodibility (Valla et al. 2010), glacial history (Hobley et al. 2010; Gran et al. 2013), sediment inputs (Cowie et al. 2008), and rock uplift (Snyder et al. 2000; Li et al. 2019), so interpreting the significance of irregularities typically requires knowledge of other characteristics of the river environment (e.g. Marrucci et al. 2018). Where investigators have independent evidence of uplift rate, as in the central Apennines of Italy (Whittaker et al. 2008) or the Santa Ynez Mountains of California, USA (Duvall et al. 2004), steeper gradients strongly correlate with greater rates of rock uplift (Whipple et al. 2013).

Spatial variations in channel width-to-depth ratio are not as readily detected using remote information as are changes in river gradient, but variations in the width of bedrock channels can also reflect differential uplift (Whittaker et al. 2007a,b; Attal et al. 2008; Yanites et al. 2010), as well as changes in rock erodibility (Wohl and Merritt 2001; Spotila et al. 2015). Typically, segments of higher uplift or more resistant rock have deeper, narrow cross-sectional geometry. Modeling suggests that incorporating channel-width adjustment or sediment-transport dynamics decreases the sensitivity of a river profile to rate of rock uplift (Yanites 2018), indicating the interconnectedness of bedrock-channel process and form as they influence response to uplift.

Adjustments of gradient and width in response to increasing substrate resistance or uplift are typically tightly coupled (Whipple 2004; Stark 2006). The most commonly used approach is to interpret downstream variations in scaling relations among channel width $w$, drainage area $A$, gradient $S$, and discharge $Q$ – in other words, downstream hydraulic geometry – as reflecting changes in rock erodibility or uplift rate (Duvall et al. 2004; Cowie et al. 2006; Jansen 2006; Whitbread et al. 2015). Scaling laws change along bedrock channels crossing an active fault in the central Italian Apennines, for example (Whittaker et al. 2007a), and along rivers crossing growing folds in New Zealand (Amos and Burbank 2007).

### 8.1.4 Effects of River Incision on Tectonics

Decades of research indicate that rivers can convey tremendous volumes of sediment from high-relief landscapes. Rivers remove up to five times more sediment per unit area from mountainous basins than from lowland basins (Corbel 1959; Willenbring et al. 2013). An estimated 96% of the approximately 7819 million tons of sediment delivered to the oceans by rivers each year originates in mountainous settings (Milliman and Syvitski 1992).

By the 1990s, investigators realized that one implication of this ability to remove mass from mountainous regions is that river incision can affect crustal structure in mountain belts by changing the distribution of stress in the crust (Molnar and England 1990; Hoffman and Grotzinger 1993; Beaumont and Quinlan 1994; Small and Anderson 1998). Local rheological variations arise in a deforming orogen as a result of deep and rapid incision by glaciers or rivers (Zeitler et al. 2001). The crust weakens as the strong upper crust is locally stripped from above by erosion. This causes the local geotherm (or rate of change in temperature with depth below the surface) to steepen from below as a focused, rapid uplift of hot rock occurs. In other words, incision by glaciers or rivers removes enough mass that molten material rises preferentially from Earth's interior into the eroding area. If efficient erosion continues, material continues to flow into the weakened zone, maintaining local elevation and relief (Koons et al. 2002; Booth et al. 2009a,b). This conceptualization of the interactions between river erosion, uplift, and topography is known as the *tectonic aneurysm model* (Zeitler et al. 2001).

A river's ability to incise depends partly on discharge and the climate that supplies runoff. Contemporary research emphasizes strong coupling among climate, erosion, and tectonics. Gradients in climate (Bookhagen and Burbank 2010) and tectonic forcing influence erosional intensity, which governs the development of topography, which in turn influences climate and tectonics (Roe et al. 2002). This is demonstrated in the Himalaya in southern Asia (Montgomery and Stolar 2006), where erosion along major rivers causes focused rock uplift. The uplift creates anticlines, and the anticlines correlate with local rainfall maxima because monsoon precipitation is advected up the river valleys. The greater rainfall in turn increases the erosive capability of the rivers (Figure 8.3). In some regions, however, climate can be decoupled from topography, so that topography reflects predominantly tectonic forces (e.g. Forte et al. 2016).

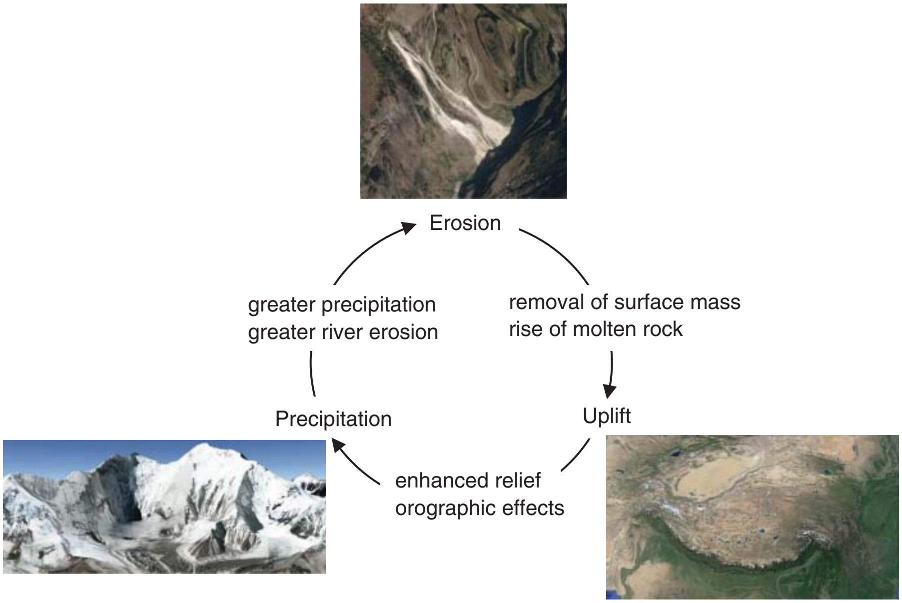


**Figure 8.3** Schematic illustration of the interactions among tectonics, topography and climate, as illustrated by research in the Himalaya in southern Asia. The inset photos illustrate (clockwise from top) a landslide along a valley wall in the Nepalese Himalaya, the Tibetan Plateau as seen from space, and snow, ice, and glaciers around Mount Everest. Source: Inset photographs courtesy of Google Earth. (*See color plate section for color representation of this figure*).

### 8.1.5 Bedrock-Channel Incision and Landscape Evolution

The processes and rates of bedrock-channel incision are integral to landscape evolution. As noted previously, upstream transmission of relative base-level fall can be limited by the rate at which a river incises into bedrock, and the rate of channel incision at least partly governs the stability of adjacent hillslopes. Consequently, the rate and spatial distribution of bedrock-channel incision in response to relative base-level lowering limit the rate of adjustment for the entire drainage basin (e.g. DiBiase et al. 2018).

Most investigations of bedrock-channel erosion infer rates of downcutting based on terrace ages or cosmogenic nuclide dating of bedrock surfaces. Such approaches integrate all erosive processes over time spans of hundreds of thousands to millions of years. Limited studies have directly measured bedrock erosion using high-precision repeat surveys (Hartshorn et al. 2002; Beer et al. 2015) and erosion pins (Stock et al. 2005; Turowski and Cook 2017). Directly measured short-term rates range from 4 to 400 mm/y (Tinkler and Wohl 1998) and greatly exceed long-term estimates of erosion rates, which range from 0.005 to 10 mm/y (Tinkler and Wohl 1998). This discrepancy suggests that bedrock-channel erosion is episodic over longer time periods.

Numerous equations have been proposed to model reach- to basin-scale bedrock erosion. Tests of these equations come from field and flume data. The simplest and earliest formulation, which remains widely used, is known as the *stream-power incision law* (Howard 1980) because it equates average erosion rate, $E$, with total stream power, substituting the more readily measured drainage area, $A$, for discharge

$$E = k\,A^m\,S^n \tag{8.1}$$

where $S$ is gradient and $k$ is a constant that includes the inherent bed erodibility and magnitude and frequency characteristics of the flow. If erosion rates were directly proportional to bed shear stress, $m$ would equal 0.38 and $n$ would equal 0.81 (Howard 1980). Channels described by Eq. (8.1) are known as *detachment-limited* because erosion depends on the erodibility of the bedrock. Under *transport-limited* conditions, volumetric transport capacity, $Q_{eq}$, is a function of stream power, sediment flux is equal to transport capacity, and erosion or deposition rate equals the downstream divergence of sediment flux (Willgoose et al. 1991)

$$Q_{eq} = K_t\,A^m\,S^n \tag{8.2}$$

where $K_t$ is a sediment transport coefficient and $m$ and $n$ are area and slope exponents as in Eq. (8.1). The distinction between detachment- and transport-limited conditions is incorporated in some numerical models (e.g. Davy and Lague 2009).

Numerous field studies now suggest that a single rate law cannot approximate incision across an entire channel network or among diverse networks because of differences in the dominant mechanism of erosion (Seidl and Dietrich 1992). Debris-flow abrasion can dominate steep tributaries, knickpoint propagation can dominate channels with rapid base-level fall, and fluvial abrasion or macroabrasion described by stream-power incision laws can dominate channels with relatively stable base level (Stock and Montgomery 1999; van der Beek and Bishop 2003; Cook et al. 2009). Ongoing work also calls into question some of the assumptions in the stream-power law (e.g. Lague 2014). A stochastic-threshold stream-power model, for example, in which a stochastic distribution of discharges is used to define a discharge threshold for channel erosion, better explains observed erosion rates in the Himalaya than does a simple stream-power model using drainage area or mean annual runoff (Scherler et al. 2017). A global compilation of more than 1400 basin-averaged erosion rates using $^{10}$Be indicates that the slope exponent in the stream-power law is generally $>1$, indicating that the relationship between erosion rate and channel gradient is nonlinear and supporting the hypothesis that bedrock-channel incision is a threshold-controlled process (Harel et al. 2016).

Equations for bedrock-channel erosion are commonly incorporated as one component of landscape-evolution models, which also include equations for processes such as bedrock weathering and diffusive sediment transport on hillslopes (Figure 8.4). Tucker and Hancock (2010) review the evolution of landscape-evolution models from late-nineteenth-century qualitative conceptual models such as W.M. Davis' cycle of erosion through contemporary quantitative numerical simulations, emphasizing the rapid advances in numerical simulation since circa the 1980s. "Model" is now used to refer to both the underlying theory and the computer programs that calculate approximate solutions to the governing equations of landscape evolution.

A landscape-evolution model includes representations of:

- continuity of mass;
- the production and transport of dissolved and particulate sediment on hillslopes;
- runoff generation and routing of water across the landscape;
- erosion and transport by water and water–sediment mixtures; and
- numerical methods used to discretize space and iterate forward in time to solve the governing equations (Tucker and Hancock 2010).

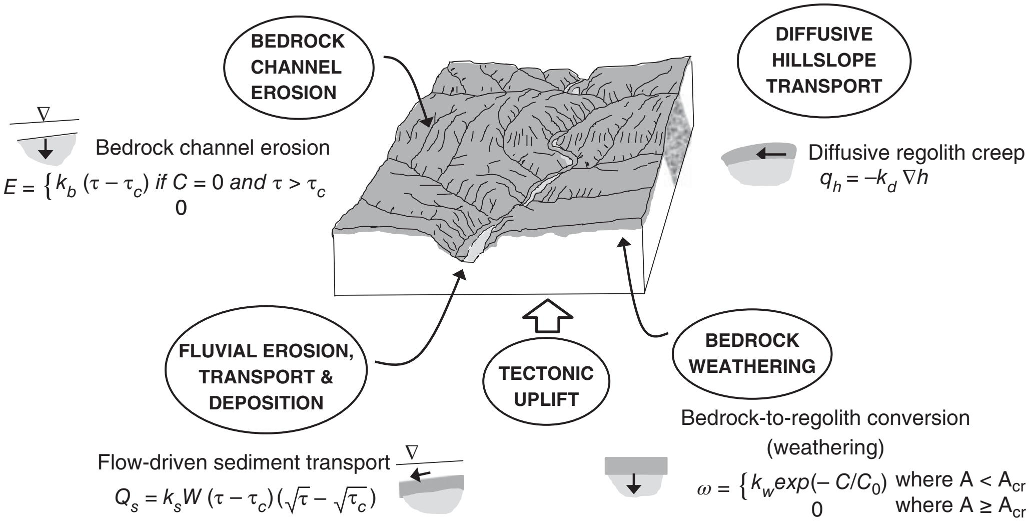


**Figure 8.4** Schematic illustration of the components of a landscape-evolution model, including primary processes as described by equations in the model. In the equations, $h$ is elevation, $C$ is regolith thickness, $\omega$ is the lowering rate of the bedrock surface due to weathering, $q_h$ is hillslope sediment transport rate per unit slope width, $Q_s$ is volumetric overland or channelized sediment transport rate, $\tau$ is shear stress, $\tau_c$ is critical shear stress for erosion by flow, $E$ is bedrock erosion rate, and $C_0$, $k_b$, $k_d$, $k_w$, and $k_s$ are constants. Source: After Tucker and Slingerland (1997), Figures 1 and 2.

Initial and boundary conditions on the system, such as climate forcing, base-level control, and substrate characteristics, must also be specified.

The development of landscape-evolution models has required the development of governing equations, sometimes known as *geomorphic transport laws*, for weathering of bedrock, hillslope mass movements, hillslope sediment diffusion, overland and channelized flow and associated erosion, sediment transport, and channel geometry. These equations are solved using finite-difference (e.g. DELIM; Howard 1994), finite-volume (Tucker et al. 2001; Campforts et al. 2017), finite-element (Simpson and Schlunegger 2003), or cellular automaton (CA) methods (e.g. CAESAR; Coulthard et al. 1997; Hancock et al. 2015).

A finite difference is a mathematical expression of the difference between two points that is used to numerically solve differential equations describing boundary value problems, such as fluxes between the points. A finite-volume method is based on computing fluxes in and out along the boundaries of a finite volume of space. A finite-element method is based on computing fluxes in and out along the boundaries of a small subdomain or finite element, which can be two-dimensional rather than a volume. CA models are based on a discrete universe made up of cells. Each cell has an internal state consisting of a finite number of information bits. The system of cells evolves in discrete time steps as automata that follow rules to compute their new internal state. The rule governing evolution of the system is the same for all cells and is a function of the states of the neighbor cells.

Regardless of the specific method, the basic idea underlying a landscape-evolution model is that the time rate of change of height in a spatial unit of the landscape reflects the difference between sediment inflows and outflows along the unit's boundaries. The unit is defined by discretizing the land surface into a regular or irregular grid (Tucker and Hancock 2010). Different types of mathematical expressions are then used to describe fluxes between grid elements. Models can be tested by comparing model output against landscape form and process measured over diverse time and space scales (e.g. Howard 1994).

## 8.2 Climatic Signatures

Many of the preceding chapters have briefly mentioned differences in river process and form in relation to climate. Climatically induced diversity in process and form has been relatively neglected in scientific river studies, however, because the great majority of studies have been conducted in the temperate latitudes where many scientists live. This imbalance and relative neglect of high latitudes, low latitudes, and drylands has been changing in recent decades, and this section reviews the implications of climatic differences for interactions between process and form.

### 8.2.1 High Latitudes

The salient feature of high latitudes with respect to interactions between river process and form is the occurrence of very cold temperatures that maintain seasonal ice cover on rivers and permanently frozen ground. As discussed in Section 3.2.8, the formation, presence, and break-up of ice create distinct hydrologic and hydraulic effects on stage and discharge. The presence of ice can also strongly influence channel and floodplain erosion, deposition, and connectivity (Figure 8.5).

Ice cover and ice-jams that form during break-up create backwater effects that enhance overbank flooding. When ice-jams break, the resulting surge can enhance overbank flooding downstream. Changing hydraulic forces during ice-jams and break-up, along with the mechanical effects of large chunks of moving ice, can enhance bank erosion and the overbank flooding and scouring that structure riparian vegetation (Beltaos 2002; Shen 2016). Avulsion induced by ice-jams has been described for both meandering and braided channels. Channel ice can facilitate bank erosion by gouging the banks, increasing the bank loading, and reducing vegetation growth along the banks (Ettema and Kempema 2012). Ice cover can alter lateral variations in flow depth and boundary shear stress within a channel (Ettema and Kempema 2012). Ice-backwater effects can alter the direction of flow within a channel and the connectivity between the main channel, secondary channels, and the floodplain (Prowse and Beltaos 2002). Ice that retards flow can decrease bed-material transport, but ice can also increase sediment transport by directly moving the bed sediment via ice rafting (transport of sediment by floating ice), ice gouging, or ice push (Ettema and Kempema 2012). Warming climate is causing a decrease in duration of ice cover and changes in ice thickness in at least some high-latitude rivers (Shiklomanov and Lammers 2014).

Ice-jams and the surges that result from their release can cause habitat degradation or loss, species stress or mortality, and deposition of fines and deterioration of spawning grounds. The highest suspended sediment concentrations occur during freeze-over and break-up, however, and ice-jams and surges also replenish adjacent floodplains with sediment and nutrients (Beltaos 2002).

Permanently frozen ground, known as permafrost, is sediment or bedrock that has a temperature at or below 0 °C for at least two consecutive years (Wright et al. 2009). Permafrost underlies an estimated 24% of land in the northern hemisphere (Zhang et al. 2003) and strongly influences rainfall–runoff relations, erosional resistance of channel banks and floodplains (Figure 8.6), and thus river process and form. Permafrost is overlain by an active layer that thaws during the warm season and can vary

(a)

(b)

**Figure 8.5** Aufeis along the Kongakut River, which flows north to the Arctic Ocean in northern Alaska, USA. Aufeis is shelf ice that forms along river margins as ground water continues to flow from adjacent uplands into the river corridor during autumn after air temperatures have dropped below freezing. (a) View of aufeis remaining along the braided channel in late June. Flow is toward the rear in this view, and the valley bottom is approximately 700 m wide. (b) Closer view of the river-side edge of the aufeis. Person in inflatable raft at right center for scale. (*See color plate section for color representation of this figure*).

**Figure 8.6** Permafrost exposed in a cutbank along the Yukon River in the interior of Alaska, USA. White stripes of ice alternate with frozen sediment in the cutbank exposure. Cutbank is approximately 3 m tall. (*See color plate section for color representation of this figure*).

from a few centimeters to greater than a meter in thickness. Warming air temperatures are causing permafrost boundaries to recede poleward, as well as leading to thinning of permafrost layers and increasing lateral disconnectivity in frozen ground. Permafrost degradation in turn results in hillslope erosion and development of thermokarst, which increases sediment yield to rivers (Gooseff et al. 2009; Lamoureux and Lafrenière 2009). Because the thickness of the active layer governs the depth to which plant roots can penetrate and thus what tree species can survive in permafrost terrain, permafrost degradation will change the species composition and distribution of vegetation within high-latitude watersheds, with associated changes in runoff, hydraulic roughness, and channel banks in high-latitude rivers (Osterkamp et al. 2009). Changes in permafrost thickness and distribution will also affect runoff, sediment, and organic matter delivered to rivers (Walvoord and Kurylyk 2016), river hydrology (Overeem and Syvitski 2010), and sediment transport (Kokelj et al. 2013). The magnitude and rate of change currently occurring in hydrologic and geomorphic processes in the high latitudes as a result of warming climate (Rowland et al. 2010) will significantly alter high-latitude river process and form in ways that investigators are still struggling to understand.

Although there is no unique type of cold-region river geometry, *sandur* (a valley segment undergoing rapid aggradation, with a downstream decrease in particle size), braided channels, meandering channels, and anastomosing channels in wetland environments are particularly common in cold regions (Vandenberghe and Woo 2002). For all of these channel types, the periods of dynamic change in seasonal ice cover – freeze-over and break-up – tend to be the periods of greatest channel and floodplain geomorphic change in cold-region rivers (Prowse and Beltaos 2002), even though these periods do not coincide with the greatest seasonal discharge. The enhanced erosion associated with ice also increases the frequency of changes in channel cross-sectional geometry, planform, and channel–floodplain connectivity (Ettema and Kempema 2012).

### 8.2.2 Low Latitudes

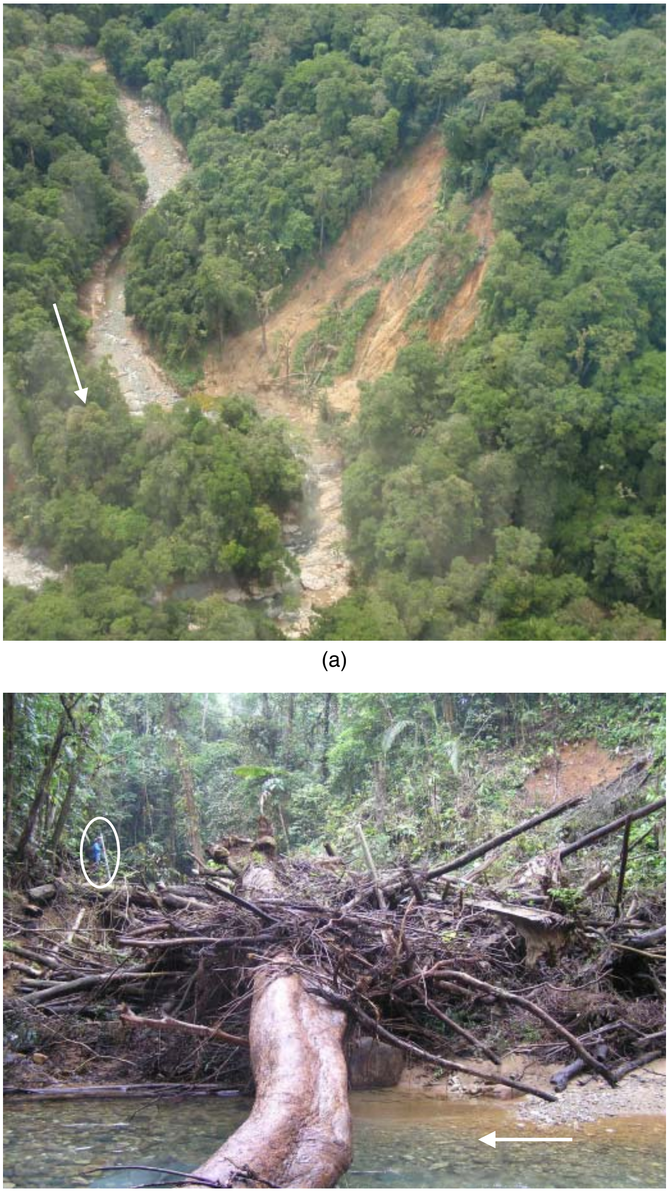
The salient features of low latitudes are the magnitude and speed with which various fluxes occur (Wohl et al. 2012a). Low latitudes here are synonymous with the tropics, the area of surplus radiative energy bounded by anticyclonic circulations near 30° N and S (Scatena and Gupta 2013). This region includes the humid tropics, where average annual rainfall is greater than potential evapotranspiration and precipitation is sufficient to support evergreen or semideciduous forests, and the dry tropics. The dry tropics are sufficiently similar to temperate dry regions to be treated in the next subsection.

The humid tropics can be further distinguished as seasonal and aseasonal (Gupta 1995). The aseasonal humid tropics typically have mean annual rainfall between 2000 and 4000 mm/y, whereas mean annual rainfall in the seasonal humid tropics varies between 1000 and 6000 mm/y and interannual variability in runoff can be large (Scatena and Gupta 2013). The seasonal humid tropics have a marked seasonal concentration of rainfall and runoff, typically reflecting the Intertropical Convergence Zone (ITCZ) or monsoonal circulation patterns, and 80% of the annual runoff can occur in 4 or 5 months of the year (Scatena and Gupta 2013). This can result in substantial variations in river process and form between wet and dry seasons, including distinctly different wet- and dry-season channel geometry (Wohl 1992; Gupta 1995).

Extremely intense rainfall and preferential shallow flow paths such as macropores (Section 2.2.1) result in large hydrologic inputs to tropical channels, which tend to have a very flashy flow regime in smaller drainages (Wohl et al. 2012a) and a prolonged peak flood (exceeding 3 months) in very large basins such as the Amazon and Congo (e.g. Rudorff et al. 2014b). Smaller catchments are more likely to have basin-wide intense storms than are equivalently sized catchments at higher latitudes. Monsoons, hurricanes, and ITCZ-related storms tend to cover sufficiently large areas that even larger catchments receive geomorphically significant rainfalls simultaneously across their area (Scatena and Gupta 2013). Widespread intense rainfall results in high percentages of contributing area and channel-modifying discharges that occur simultaneously throughout the catchment. These characteristics contrast with the more spatially restricted precipitation inputs and channel modifications of equivalently sized catchments at higher latitudes.

Continual high air temperatures and abundant vegetation combine with high values of precipitation to create rapid weathering of rock and soil and of organic inputs such as wood. Large inputs of material to channels occur in high-relief tropical environments when cyclones or hurricanes trigger widespread landslides that strip hillslopes of weathered rock and vegetation (Figure 8.7a) (Scatena and Lugo 1995; Goldsmith et al. 2008; Hilton et al. 2011b; Wohl et al. 2012b). Instream wood does not persist in low-latitude rivers. Although individual pieces of wood and large jams can create important geomorphic and ecological effects (Figure 8.7b) (Wohl et al. 2009, 2012b; Martín-Vide et al. 2014), the transience of wood as a result of combined rapid decay and high transport rates is particularly noticeable (Spencer et al. 1990; Soldner et al. 2004; Cadol and Wohl 2010; Wohl and Ogden 2013).

Although the hydrology of low-latitude rivers has distinctive characteristics, and process–form interactions occur more rapidly and frequently than in higher latitudes, Scatena and Gupta (2013) conclude that tropical rivers do not have diagnostic landforms that can be solely attributed to their low-latitude location. A key distinction relative to rivers in higher latitudes is the high frequency of geomorphically significant flows and channel changes.



(a)

(b)

**Figure 8.7** The Upper Rio Chagres in Panama. (a) Low-level aerial view of landslides that occurred during widespread intense rainfall shortly before the photo was taken. The landslides introduced substantial sediment and large wood into the channel. White arrow indicates flow direction. Active channel is approximately 35 m wide. (b) View up the mouth of a tributary channel. A logjam approximately 7 m tall formed at the mouth of the tributary and created a thick wedge of sediment and large wood (not visible here) on its upstream side, which extended more than 100 m up the tributary. Within 2 years, this jam was breached and much of the sediment wedge had been eroded. Person at upper left within white oval for scale. White arrow indicates flow direction on main channel. (*See color plate section for color representation of this figure*).

### 8.2.3 Warm Drylands

The salient feature of interactions between process and form within rivers in warm dryland regions is spatial and temporal discontinuities. As with tropical rivers, Tooth (2013) concludes that there are no features unique to warm dryland rivers, although certain characteristics are more common in drylands than elsewhere. Warm dryland here includes hyperarid, arid, semiarid, and dry subhumid environments, but excludes cold, high-latitude, and high-altitude regions. Warm dryland regions are particularly prevalent within the subtropical, high-pressure belts of the northern and southern hemispheres, and much of the scientific research on rivers in warm drylands has been conducted in the western United States, Australia, the Middle East, and southern Africa.

Warm drylands share high, but variable, degrees of aridity that reflect low precipitation and high potential evapotranspiration. Long periods with little or no precipitation and stream flow are interrupted by intense rainfall and runoff, which can generate short-duration flash floods (Figure 8.8). Irregular precipitation and low water tables keep many dryland channels ephemeral or intermittent, although rivers that originate in wetter mountainous highlands before flowing into dry regions can be perennial (Tooth 2013). Ephemeral and intermittent rivers are now increasingly referred to as temporary rivers (e.g. Datry et al. 2011, 2014).

Short periods of high water and sediment connectivity between uplands and channels in warm drylands can result from overland flow and limited upland vegetation (Bracken and Croke 2007). Limited riparian vegetation and sediment cohesion can create unstable banks that promote a braided

**Figure 8.8** Downstream view along Bumblebee Creek in central Arizona, USA. Although the wetted channel is only about 1.5 m wide under the base flow conditions shown here, the white oval highlights organic material deposited high along the channel margins by a flash flood. (*See color plate section for color representation of this figure*).

planform (Merritt and Wohl 2003), and floodplains (defined as frequently inundated) are limited in extent (Reid et al. 1998).

Flash floods within channels or across piedmonts are particularly characteristic of catchments less than 100 km$^2$ in size (Tooth 2013). Flash floods have steep rising and recessional limbs and may last only minutes to hours, but can generate very high values of discharge per unit drainage area and correspondingly substantial erosion and deposition (e.g. Reid et al. 1998; Segura-Beltran et al. 2016). Longitudinal declines in flow resulting from infiltration and evaporation can correspond to a lack of longitudinal continuity in a distinct channel form, as when channels end in floodouts (e.g. Sutfin et al. 2014; Larkin et al. 2017). Downstream transmission losses are a particularly important mechanism for recharging alluvial and regional aquifers in drylands (e.g. Morin et al. 2009; Mvandaba et al. 2018). Downstream transmission losses in dryland channels, along with limited contributing area where small convective storms affect only a limited portion of a large drainage basin, create large spatial variability in discharge and temporal variability between storms (Tooth 2013).

Larger river networks are likely to have more sustained flows, especially if they head in wetter uplands and then flow down into dry lowlands, as in much of the interior western United States. Because these perennial rivers provide vital water supplies for agriculture and urbanization in the lowlands, the natural flow regime is especially likely to have been altered by flow regulation, resulting in significant changes in river process, form, and connectivity (Williams 1978b; Nadler and Schumm 1981; Chin et al. 2017). Large dryland rivers are not typically considered to have substantial channel and floodplain large wood loads, for example, but perennial rivers in deserts historically had extensive woody riparian vegetation. Riparian deforestation and flow regulation in these rivers have significantly reduced historical wood loads (Minckley and Rinne 1985; Stout et al. 2018), contributing to loss of river ecosystem function, including habitat for endangered native fish species (e.g. Crook and Robertson 1999).

Although ephemeral dryland channels can have less dense riparian vegetation than perennial rivers, dryland vegetation can be concentrated in and along channels and can generate substantial flow resistance. Resistance can increase with stage as woody vegetation becomes immersed, particularly along the tops of banks and bars (Knighton and Nanson 2002; Griffin et al. 2005). Resistance associated with riparian vegetation can lead to a scenario of streambed scour at lower stages during a flood, when vegetation is not inundated and thus contributes little resistance, and to one of fill during the higher stages when bank flow resistance is strongly affected by vegetation (Merritt and Wohl 2003).

Dryland rivers typically transport large quantities of suspended and bed load and display strong hysteresis of bed scour during the rising limb and fill during the falling limb (e.g. Alexandrov et al. 2003). Scour is facilitated by the absence or poor development of coarse surface layers. Poorly developed coarse surface layers may reflect abundant upland sediment supplies, enhanced sediment mixing during scour and fill, high rates of bedload transport, and short-duration flows that minimize winnowing of fine particles from the bed (Tooth 2013). Lack of coarse surface layers also facilitates high rates of bed-load transport that increase more consistently with increasing flow because particles across a large size range are available for entrainment at the start of flow and the bed becomes highly mobile at even modest flows (Tooth 2013).

Much of the research on small- to medium-size dryland channels emphasizes abrupt transitions between incising and aggrading conditions across a channel network and through time (Schumm and Hadley 1957; Prosser and Slade 1994; Tucker et al. 2006; Nichols et al. 2016). This emphasis is exemplified by the extensive literature on arroyos in the US Southwest (Graf 1983, 1988; Harvey 2008: Miller 2017).

Repeated large floods appear to dominate process and form in many dryland channels, as evidenced by numerous studies of flood-related channel changes and by recovery times of decades or longer (Tooth 2013). Dryland channels may be particularly susceptible to change during floods because of limited bank cohesion in the absence of dense riparian vegetation and abundant silt and clay, and because of the lack of intervening smaller flows that could modify flood-generated erosional and depositional features (Tooth 2013).

In contrast to the emphasis on equilibrium conditions along perennial rivers, the ability of rare floods to cause substantial change along dryland rivers has led some investigators to describe dryland channels as non- or disequilibrium systems (Graf 1988; Tooth and Nanson 2000). Tooth (2013), however, emphasizes the global diversity of dryland river process and form as a result of varying degrees of aridity, tectonic activity, and structural and lithological settings (Tooth 2000; Nanson et al. 2002). In addition, the identification of equilibrium or disequilibrium is highly dependent on temporal and spatial frames of reference, so that individual dryland rivers can exhibit both conditions (Tooth and Nanson 2000).

Dryland river networks are especially vulnerable to consumptive uses of surface and ground water. The aquatic and riparian plants and animals living in dryland river networks have evolved distinctive adaptations to limited water supplies and to high temporal variability in water availability (Dodds et al. 2004). These organisms, however, cannot survive beyond some limit of hydrological alteration (Fausch and Bestgen 1997) and mechanical (e.g. grade control or irrigation intake structures) disconnectivity (Ficke and Myrick 2011). In the semiarid Great Plains of the western United States, for example, small-bodied native fish rely on brief periods of longitudinal flow connectivity and on the persistence of refuge pools that retain water year-round (Falke et al. 2011). As rates of ground-water withdrawal have exceeded recharge in the region, the duration and extent of longitudinal hydrological dysconnectivity have increased and the number and size of refuge pools have declined, severely stressing or eliminating populations of native fish (e.g. Falke et al. 2010).

The hydrologic regime of larger rivers in the western United States that head in mountains and are perennial because of snowmelt has also been altered by flow regulation, which tends to reduce the temporal variability of the hydrograph by storing the snowmelt peak flow and releasing it more gradually throughout the year. This has resulted in extensive narrowing of historically braided channels, which have become anastomosing or meandering within wooded floodplains (Williams 1978b; Nadler and Schumm 1981). Analogous examples of substantial hydrologic alterations causing changes in channel connectivity and channel and floodplain morphology come from dryland regions in Australia (Page et al. 2005; Crook et al. 2015), the southwestern United States (Figure 8.9) (Jaeger and Olden 2012; Goodrich et al. 2018), and the Mediterranean portion of Europe (Skoulikidis et al. 2017).

An extreme illustration of hydrological alteration in a dryland river is provided by large rivers that no longer flow to the ocean because of consumptive water use and flow regulation, such as the Colorado River of the western United States, the Indus River of Pakistan, Australia's Murray River, and China's Huanghe (Yellow River) (Postel 1999; Famiglietti 2014).

Water quality in dryland rivers is also especially vulnerable to human activities because even rivers that drain relatively large regions can have such low flow that their ability to dilute contaminants is limited. Water quality in Australia's Murray–Darling River, for example, is degraded by salts and excess nutrients (e.g. Holland et al. 2015).

Temporary rivers may also be especially vulnerable to urban encroachment because, if a channel is incised and remains dry much of the time, there is a tendency to assume that infrequent, relatively

**Figure 8.9** A portion of the Rio Grande in Big Bend National Park, Texas, USA. Here, the active channel has narrowed substantially as a result of upstream flow regulation and dense growth of invasive exotic plants (*Tamarix* spp., *Arundo donax*). Wetted channel is approximately 35 m wide. (*See color plate section for color representation of this figure*).

short-duration flows will be contained within the channel, rather than flooding overbank areas. This assumption can lead to enormous damage when incised channels widen or avulse during large floods within urban areas (e.g. Kresan 1988).

Finally, dryland rivers can provide unique challenges to management designed to sustain river integrity because river form and process are so changeable through time and space and because systematic records of water and sediment discharge are less likely to exist for these river networks. Water-quality standards developed for perennial rivers may be applicable only under certain circumstances or not at all. The Mediterranean Intermittent River Management (MIRAGE) project addresses many of these difficulties and has developed a toolbox designed for sequential use in characterizing the hydrological, ecological, and chemical status of temporary rivers (Prat et al. 2014). Analogously, specification of environmental flow regimes to sustain native biota in dryland rivers can be hampered by lack of systematic flow records. Under these circumstances, the community composition of macroinvertebrates can be used to differentiate rivers characterized in a natural state by longitudinal connectivity versus disconnected pools (Cid et al. 2016).

## 8.3 Spatial Differentiation Along a River

Turning to smaller spatial scales such as the subwatershed or reach level, distinct suites of geologic and climatic processes can create spatial differentiation within river networks. Schumm (1977) conceptualizes drainage basins as consisting of an upstream zone of production from which water and sediment are derived, a central zone of transfer in which inputs can equal outputs in a stable river, and a downstream zone of deposition. Although acknowledging that production, transfer, and deposition occur continuously throughout a drainage basin, this organization recognizes the existence of spatial zonation in dominant processes within a catchment.

Subsequent conceptual frameworks have also emphasized spatial zonation. Montgomery and Buffington (1997), for example, distinguish source, transport, and response segments in reach-scale classification of mountain channel morphology (Figure 4.15). Sklar and Dietrich (1998) hypothesize consistent changes in dominant incision mechanism (debris flow, fluvial) and substrate type (coarse-bed alluvial, fine-bed alluvial) at threshold slopes, regardless of drainage area (Figure 2.11).

Montgomery (1999) builds on this work in describing *process domains*, defined as spatially identifiable areas of a landscape or drainage basin characterized by distinct suites of geomorphic processes (Figure 2.8). The existence of process domains implies that river networks can be divided into discrete regions in which ecological community structure and dynamics respond to distinctly different physical disturbance regimes (Montgomery 1999). The delineation of process domains has subsequently proven useful in understanding spatial patterns of riparian vegetation (Polvi et al. 2011), sediment dynamics (Wohl 2010a), organic carbon stock in river corridors (Wohl et al. 2012c; Sutfin and Wohl 2017), aquatic ecosystem dynamics and biodiversity (Bellmore and Baxter 2014), channel geometry (Livers and Wohl 2015), and connectivity (Wohl et al. 2019a) within mountainous river networks.

As noted earlier, some river geomorphic parameters exhibit progressive downstream trends whereas others exhibit so much local variation that any systematic longitudinal trends which might be present are obscured (Wohl 2010b). Local variation that overwhelms progressive trends is particularly characteristic of mountainous terrain, where spatially abrupt longitudinal zonation in substrate resistance, gradient, valley geometry, and sediment sources can create substantial variability in river process and form. Under these conditions, characterizing river dynamics at reach scales can be more accurate than assuming that parameters will change progressively downstream. Examples of geomorphic parameters for which spatial variation is better explained by process domain classifications than by drainage area or discharge in mountainous drainage basins include riparian zone width (Polvi et al. 2011), floodplain volume and carbon storage (Wohl et al. 2012c), connectivity (Wohl et al. 2019a), instream wood load (Wohl and Cadol 2011), and biomass and biodiversity (Bellmore and Baxter 2014; Herdrich et al. 2018; Venarsky et al. 2018).

Process domains can also apply to very large drainage basins that have distinct spatial differences associated with topography or climate. The wet, high-relief, sediment-producing Ethiopian Highlands portion of the Blue Nile, for example, is distinctly different than the dry, low-relief mainstem Nile lower in the drainage (Wohl 2011a). Similarly, the steep, narrowly confined segments of the Danube that cut through mountainous terrain in Europe are distinctly different than the intervening anastomosing or braided segments in broad alluvial basins (Wohl 2011a).

Process domains can provide a useful organizational framework for delineating the spatial distribution and relative abundance of different valley and channel types (Wohl et al. 2007), and this can facilitate identification of sensitive or rare areas and formulation of different management strategies for distinct physical settings (Buffington and Tonina 2009b). The concept of process domains can be readily applied at the reach scale at which most river management occurs. With even minimal field calibration, process domains can also provide a framework for remotely predicting at least relative variations in numerous valley-bottom characteristics.

Other conceptual frameworks that emphasize spatial zonation include the *River Styles framework* (Brierley and Fryirs 2005), structured around the five spatial scales of:

- catchment;
- landscape units of relatively homogeneous topography within the catchment;
- reaches with consistent channel planform, assemblage of channel and floodplain geomorphic units, and bed-material texture;
- channel and floodplain geomorphic units such as pools; and
- hydraulic units of homogeneous flow and substrate characteristics.

River style is classified at the reach scale using a procedural tree that starts with lateral valley confinement and continues with characteristics such as river planform, geomorphic units, and bed-material texture, through to a descriptive classification of categories such as "bedrock-confined discontinuous floodplain" and "multichannel sand bed" (Brierley and Fryirs 2005). The catchment-wide distribution of river styles can be used to understand spatial distribution of controls on river process and form, relative abundance of different river styles, and potential sensitivity and resilience of different portions of the river network, in a way analogous to the application of process domains.

Stream biologists also emphasize zonation at differing spatial scales. This is exemplified by the widely used hierarchy of stream system ($10^3$ m length), stream segment ($10^2$ m), reach ($10^1$ m), pool/riffle ($10^0$ m), and microhabitat ($10^{-1}$ m) of Frissell et al. (1986).

Aquatic and riparian ecologists have also examined the relative importance of progressive trends versus local controls. One of the primary conceptual models of aquatic ecology, the *river continuum concept*, emphasizes continuous longitudinal gradients in the structure and function of ecological communities along a river network (Vannote et al. 1980). In contrast, the *serial discontinuity concept* focuses on how dams disrupt longitudinal gradients along river courses (Ward and Stanford 1983, 1995). *Hierarchical patch dynamics* (Pringle et al. 1988; Poole 2002) emphasizes the existence of relatively homogeneous units from the scale of microhabitat up to channel reaches, with distinct changes in process and form between patches. Reach-scale patches, like process domains or river styles, can result from changes in physical processes such as glaciation or differential rock erodibility (Ehlen and Wohl 2002) and from biotic influences such as beaver dams (Burchsted et al. 2010).

The appropriateness of conceptual models that emphasize progressive downstream changes versus patchiness varies depending on the river characteristic being described and the specific drainage basin. Recognition that a variety of river processes and forms can exhibit abrupt spatial transitions, however, illustrates the importance of considering landscape context when examining river process and form (Wohl 2018a). Although much of the work emphasizing patchiness and relatively abrupt changes in process domains and river styles comes from relatively high-relief environments in which rock structure, tectonics, or glacial history can create strong longitudinal changes in valley geometry, the presence of spatial differentiation can also be useful in explaining process and form in low-relief river networks (e.g. Jones et al. 2008). The presence and characteristics of connectivity exert an important influence on both spatially continuous and spatially discontinuous processes and forms.

## 8.4 Connectivity

Although the first chapter introduced the idea of diverse forms of connectivity, it is worth returning to this concept and exploring the implications of connectivity for several of the processes and forms

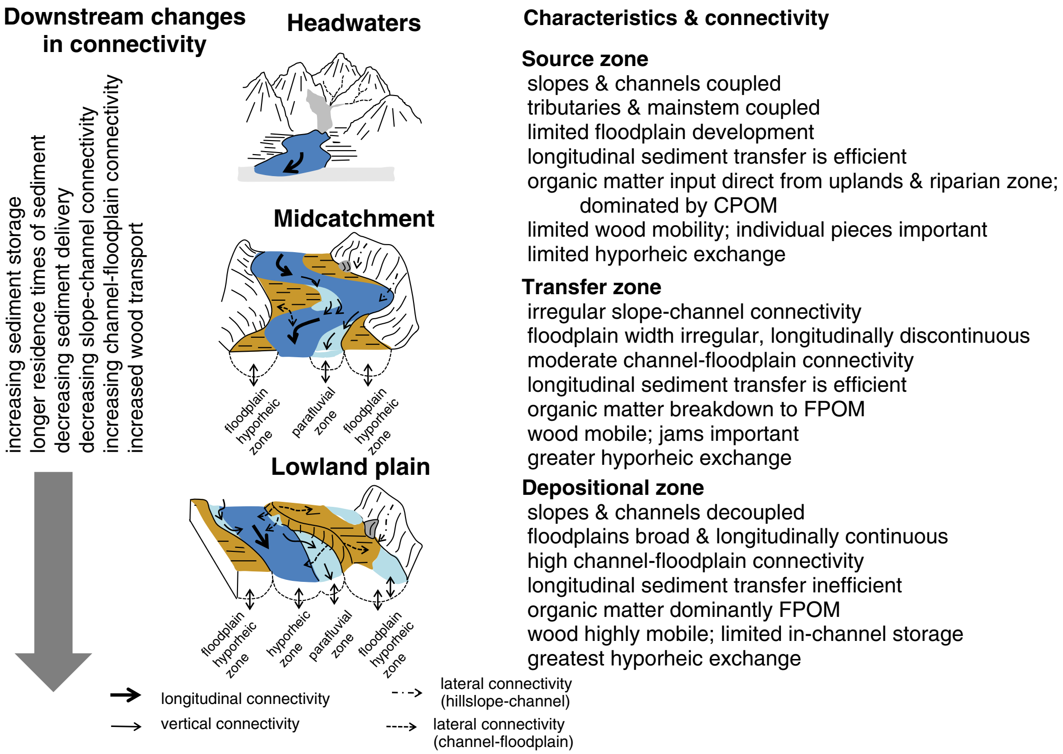


**Figure 8.10** Schematic illustration of changes in connectivity with distance downstream along a river with high-relief headwaters. Moving downstream, the river flows through headwater valleys with relatively thin, narrow alluvial veneers over bedrock and then through progressively wider and deeper alluvial valleys with greater floodplain development and hyporheic exchange. The presence of a floodplain buffers the mainstem river from hillslope and tributary inputs by creating depositional zones along its length, and progressively more extensive floodplains typically equate to greater average residence time of sediment, surface flow during overbank floods, and subsurface flow. CPOM is coarse particulate organic matter (>1 mm in diameter), FPOM is fine particulate organic matter (0.45 μm–1 mm). Source: After Brierley and Fryirs (2005), Figure 2.10, p. 44. (*See color plate section for color representation of this figure*).

discussed to this point, including: interactions between hillslope, floodplain, channel, and hyporheic environments; sources, transport, and residence times of water, solutes, sediment, and large wood; and spatial zonation within a drainage basin. Figure 8.10 illustrates how various forms of connectivity change throughout a basin.

High connectivity implies that matter and organisms move rapidly and easily within a river network. Landscapes typically include some characteristics that create at least temporary storage and limit connectivity. Subsurface units of low permeability can limit the downslope transmission of water from hillslopes to channels, or limit hyporheic and ground-water exchanges along channels (e.g. Gooseff et al. 2017). Lakes, broad floodplains with extensive wetlands, and numerous channel-spanning obstructions such as beaver dams and logjams can substantially decrease the rate at which floods move through a river network (e.g. Lininger and Latrubesse 2016; Wegener et al. 2017). Analogously, depositional features such as alluvial fans can limit the rate at which sediment is introduced from hillslopes to channels (Fryirs et al. 2007a). Extensive floodplains can increase the time necessary for sediment entering a river network to move completely through that network. As described in Section 7.1.4, sediment can reside on the floodplains of the Amazon River for thousands to millions of years.

Erosionally resistant portions of a river network can influence landscape connectivity. Segments of bedrock channel commonly act as local base levels, for example, and the upstream transmission of base-level change is limited to the rate at which the river can incise the bedrock segment (DiBiase et al. 2018). Large waterfalls (May et al. 2017) and portions of an ephemeral or intermittent river network (Jaeger and Olden 2012; Cid et al. 2016) that are dry can limit migration of organisms and thus biological connectivity. Naturally occurring lakes and artificial reservoirs can limit the downstream transmission of large wood (Seo et al. 2008; Kramer and Wohl 2015; Senter et al. 2017).

Features that limit connectivity can be conceptualized as reservoirs that store materials, as exemplified by alluvial fans storing sediment or floodplains storing peak flows during a flood. An alluvial fan can also be conceptualized as a buffer that restricts sediment delivery to a channel (Fryirs et al. 2007a). Features that limit connectivity can be conceptualized as barriers, as in the case of a local base level that limits profile adjustment or a dry stream segment that limits fish dispersal. Whether a reservoir or a barrier, these aspects of river networks exert critical controls on fluxes of material and organisms, and must be included when understanding or quantifying all aspects of river networks, from production of water, solutes, and sediment, to movement of these materials downslope into channels and through channel networks.

Connectivity is not *a priori* good or bad in terms of river ecosystem functionality. Some river networks naturally have high levels of connectivity, whereas others include many features that limit connectivity (e.g. Burchsted et al. 2010; Mould and Fryirs 2017). The three dimensions of connectivity commonly have different relations to reach-scale characteristics: channel obstructions such as logjams and beaver dams, for example, promote lateral and vertical connectivity for water, solutes, and particulate organic matter, but limit longitudinal connectivity for these materials. High sediment inputs that promote channel avulsion and high rates of lateral migration may increase lateral connectivity for water, solutes, sediment, and large wood, but restrict longitudinal connectivity for these materials.

There is no single method that adequately measures diverse forms of connectivity (Wohl et al. 2019a). Methods used to date include those that (i) quantify fluxes and use the measurements to infer the degree of connectivity in the transport system at a single point in space (e.g. Jaeger and Olden 2012) or numerically model fluxes at multiple points simultaneously (e.g. Coulthard and Van De Wiel 2017); (ii) infer fluxes of materials by measuring the key drivers that govern connectivity (e.g. inferred sediment connectivity based on drainage area, mean slope, and travel distance; e.g. Cavalli et al. 2013); (iii) infer fluxes of materials by measuring sediment storage and assessing topographic parameters that influence sediment storage and flux (e.g. Nicoll and Brierley 2017); and (iv) represent the geomorphic system under consideration as a network composed of source or storage elements (nodes) connected by pathways of potential transport (links) and then use analytical techniques such as network or graph theory to quantitatively estimate connectivity (e.g. Tejedor et al. 2015).

The issue of scale is critical when quantifying connectivity, because the degree of connectivity varies with the temporal and spatial scales under consideration. Most transport processes are intermittent, for example, so connectivity should increase when measured over longer characteristic time scales but decrease as spatial scale increases, because transport occurs over finite distances during any transport event (Bracken et al. 2013, 2015). This suggests that measurements should be made at a sufficiently large multiple of the fundamental temporal and spatial scales of the phenomenon of interest in order to include a representative sample of transport events (Wohl et al. 2019a). Because the available tools and methods used to collect data constrain the scales at which connectivity can be analyzed, technological advances such as terrestrial LiDAR and structure-from-motion photogrammetry (e.g. Smith and Vericat 2015) are enhancing the ability to quantify connectivity.

Among the challenges in managing rivers are those of quantifying connectivity and understanding how human activities have increased or decreased connectivity within a landscape (Kondolf et al. 2006). As discussed in Chapter 1, most human activities decrease hydrological, sediment, biological, and landscape connectivity within a river network, although a few alterations such as flow diversions and removal of naturally occurring obstructions such as beaver dams can increase connectivity. In contrast, many human activities (e.g. tile drains, impervious surfaces) increase connectivity between hillslopes and river corridors (Covino 2017).

Unanticipated side effects of altered connectivity can require many decades to become apparent. Before the 1970 completion of the Aswan High Dam on the Nile in Egypt, the river annually carried more than a hundred million tons of silt to the Nile Delta. The dam now traps much of this sediment, causing subsidence and erosion in the delta: former delta villages are now 2 km out to sea. Plankton formerly nourished by nutrients in the river flow have dramatically decreased in abundance, contributing to a collapse of the sardine populations that fed on them. Reduction of sediment connectivity along this major river has thus altered physical, chemical, and biological characteristics of the lower river and the nearshore zone (Wohl 2011a).

In Siberia, the Novosibirsk Dam reduces seasonal peak flows along more than a thousand kilometers of the Ob River. The Ob historically provided an important commercial fishery, but many species of fish require access to the floodplains for spawning and nursery habitat during the spring peak flows. Fish in the Ob need at least 20 days of flooding in order to spawn, hatch, and grow. The Novosibirsk Dam has reduced floodplain habitat by half during years of average flow, and eliminated this habitat during dry years. This dam, along with several others in the Ob catchment, also limits longitudinal movements by fish, creating genetic isolation and constraining the ability of each fish population to find appropriate habitat during dry periods. The commercial fishery along the Ob has largely collapsed since construction of the dams (Wohl 2011a).

The effects of altered connectivity along the Nile and the Ob may appear obvious in retrospect, but the challenge of anticipating not only the type, but also the magnitude of altered connectivity in connection with river engineering remains substantial. Numerical simulation can be particularly useful in this context by facilitating the ability to evaluate alternative scenarios, but any model must be accurately parameterized and underpinned by a solid understanding of the sources and characteristics of connectivity within a drainage basin. Again, knowledge of landscape context is critical to effective understanding and management of river process and form (Wohl et al. 2019a).

Connectivity receives so much attention in river science at present because it ultimately reflects geomorphic context and governs the extent to which a river network or a reach of a river is integrated into the greater landscape. Geomorphic context includes spatial dimensions of river corridor geometry, location within a drainage basin, and location within a global context. Context also includes temporal dimensions of the frequency and duration of specific processes influencing the river corridor and the historical sequence of natural and human-induced processes that continue to influence the river corridor (Wohl 2018a).

## 8.5 River Management in an Environmental Context

This portion of the chapter focuses on river management undertaken specifically to restore rivers in an environmental context. People have been managing – or at least attempting to manage – rivers for millennia. Past management actions were typically undertaken with the intent of making rivers or associated resources more conveniently accessible to humans: damming rivers to ensure water supply, for example, or building levees and channelizing rivers to enhance agricultural use or settlement on floodplains. Although river restoration and rehabilitation are sometimes viewed as being fundamentally different than past river management, they can also be viewed as the latest iteration of the attempt to reconfigure rivers to conform to human expectations; in the case of restoration, expectations of more natural or ecologically functional rivers.

Restoration activities such as the planting of riparian vegetation to stabilize streambanks date to the seventeenth century in Europe (Evette et al. 2009). Projects designed to restore rivers have increased dramatically in number and scope since the 1990s (Bernhardt et al. 2005), particularly in the United States, western Europe (e.g. Muhar et al. 2016), and Australia (Brooks and Lake 2007). As with any form of river management, some projects have largely achieved their original purpose whereas others have been thorough failures. The rationales that underpin river restoration and the factors that result in success or failure are worth examining because the ability to restore rivers provides an effective measure of our understanding of river process and form.

### 8.5.1 Reference Conditions

Any river restoration is undertaken to achieve some desired end result of river process and form. Restoration is undertaken for a variety of reasons, including those related to recreation, water quality, esthetics, protection of aquatic and riparian species, bank stabilization, fish passage, flow modification and dam removal, and the creation of a more natural environment (Table 8.1) (Bernhardt et al. 2005). The latter point is perhaps the most difficult, because achieving a more natural environment entails addressing at least one fundamental question: What is natural? (Graf 1996; Wohl 2011c).

"Natural" is commonly assumed to imply minimal human alteration, although natural is increasingly being defined in terms of *physical integrity* (Graf 2001) or the ability of a river to adjust to existing conditions (Fryirs and Brierley 2009). Humans have been manipulating natural landscapes for many thousands of years, by using fire to alter land cover, selectively hunting some animals to extinction, domesticating plants and animals and then altering ecosystems to favor domesticated species, and cutting trees for fuel and building materials (Wohl et al. 2017c). So, at what point in history do we consider a given ecosystem to have last been natural: prior to agriculture, prior to the Industrial Revolution, or prior to some arbitrary human population density?

Whatever (pre) historical period is chosen, the characteristics of rivers during that period are typically known as *reference conditions*, which can also be defined as the best available conditions that could be expected at a site (Norris and Thoms 1999). The latter definition can be highly problematic, however, because great disagreement or uncertainty can arise as to what constitutes "best available." Reference conditions encompass all of the aspects of river process and form discussed to this point, including: flow, sediment, and wood regimes; water chemistry; substrate; bedforms; channel morphology, planform and gradient; and longitudinal, lateral, and vertical connectivity.

In a region where some river basins have undergone minimal human alteration, contemporary rivers can provide reference conditions for altered river basins (e.g. Larned et al. 2008). This approach

**Table 8.1** National River Restoration Science Synthesis (NRRSS) working group list of goal categories and operational definitions for river restoration projects.

| Category | Description |
|---|---|
| Esthetics/recreation/education | Activities that increase community value: use, appearance, access, safety, and knowledge |
| Bank stabilization | Practices designed to reduce or eliminate erosion of banks |
| Channel reconfiguration | Alteration of channel geometry: includes restoration of meanders and in-channel structures that alter river thalweg |
| Dam removal/retrofit | Removal of dams and weirs or modifications to existing dams to reduce negative ecological impacts (excludes dam modifications solely intended for the improvement of fish passage) |
| Fish passage | Removal of barriers to longitudinal migration of fishes: includes physical removal of barriers, construction of alternative pathways, and construction of barriers to prevent access by undesirable species |
| Floodplain reconnection | Practices that increase overbank flows and the flux of organisms and materials between channel and floodplain |
| Flow modification | Practices that alter the timing and delivery of water quantity (does not include stormwater management) |
| Instream habitat improvement | Alteration of structural complexity (bedforms, cross-sectional geometry, substrate, hydraulics) to increase habitat availability and diversity for target organisms and provide breeding habitat and refugia from disturbance and predation |
| Instream species management | Practices that directly alter aquatic native species distribution and abundance through the addition (stocking) or translocation of plant and animal species or the removal of exotic species |
| Land acquisition | Practices that obtain lease, title, or easements for streamside land for the explicit purpose of preservation or removal of impacting agents or the facilitation of future restoration projects |
| Riparian management | Revegetation of riparian zone or removal of exotic species of plants and animals |
| Stormwater management | Special case of flow modification that includes the construction and management of structures (ponds, wetlands, flow regulators) in urban areas to modify the release of storm runoff |
| Water-quality management | Practices that protect existing water quality or change the chemical composition or suspended load, including remediation of acid mine drainage |

Source: After Bernhardt et al. (2007), Table 1.

must be used with caution, however, because contemporary conditions constitute a snapshot in time that reflects only a single state or a limited portion of the fluctuations that naturally occur in rivers (SER 2002).

In many regions of the world, there are no relatively unaltered rivers, so reference conditions must be inferred from historical, botanical, and geologic records (Morgan et al. 1994; Nonaka and Spies 2005; Stoddard et al. 2006; Wohl 2011c). Lack of information on reference conditions, as well as continuing change in catchment parameters, can limit the usefulness of reference conditions (Hughes et al. 2005; Newson and Large 2006; Dufour and Piégay 2009). Consequently, reference conditions may be most appropriate as an ideal rather than as a goal for restoration (Osborne et al. 1993). This thinking underlies balanced sediment regimes (Wohl et al. 2015b) and target wood regimes (Wohl et al. 2019), both of which describe regimes that are not natural but that can create and sustain desired conditions within the river corridor.

A tremendous amount of effort may be necessary to characterize reference conditions, not least because river process and form can vary substantially across even a relatively small drainage basin and because rivers are never static in time. Even in the absence of human manipulation, rivers undergo fluctuations in process and form associated with natural events such as floods or droughts, landslides, wildfires, tectonic uplift or subsidence, and continuing adjustment to long-term changes in climate or tectonics. Consequently, a key component of understanding reference conditions is being able to quantify the *natural or historical range of variability* (NRV) for a given parameter or set of parameters (Morgan et al. 1994; Nonaka and Spies 2005; Wohl 2011c; Rubin et al. 2012; Brierley and Fryirs 2016; Grimsley et al. 2016).

Ongoing climate change, abundant and widespread invasive species, and human population growth and resource use cause some scientists and managers to question the relevance of NRV (Safford et al. 2008; Dufour and Piégay 2009). If the world already looks fundamentally different than it did prior to human manipulation, and if it will grow increasingly different in the future, what do past river process and form matter? Other scientists and managers contend that, even if a river cannot be restored to NRV, detailed, quantitative understanding of prior and existing river characteristics can inform management by constraining the range of potential river process and form and providing insight into the conditions necessary to sustain native species (e.g. Koel and Sparks 2002).

Knowledge of NRV provides insight into the conditions that native riverine species or communities might require for survival, as well as the thresholds or minimum values of process or form that must be maintained in order to sustain biological communities (e.g. flood threshold for overbank flooding that provides fish access to the floodplain for spawning and nursery habitat). Knowledge of NRV also facilitates delineation of the spatial distribution of different suites of geomorphic processes, such as portions of a mountainous headwater catchment dominated by debris flows versus portions dominated by fluvial processes. This facilitates evaluation of the location, relative rarity, and connectivity of sensitive stream segments that are likely to respond to alterations or that contain biologically unique communities (McDonald et al. 2004; Brierley and Fryirs 2005; Wohl et al. 2007). Insight into NRV provides information on the relative magnitude of variation in specific river attributes among process domains (Wohl 2011c). Knowledge of NRV thus underpins our understanding of process and form in any river network (Wohl 2018a).

### 8.5.2 Restoration

Restoration is undertaken for many reasons and at many scales, from a single river segment only a few hundred meters in length to entire large drainage basins. The National River Restoration Science Synthesis database includes more than 37 000 restoration projects in the United States. Most of the projects in the database were implemented on river segments less than 1 km in length (Bernhardt et al. 2005), but the most high-profile are those involving much larger segments, such as the Grand Canyon of the Colorado River in Arizona (Melis 2011; Melis et al. 2015) or the Kissimmee River in Florida (Toth et al. 1993; Warne et al. 2000; Wohl et al. 2008; Koebel and Bousquin 2014), both in the United States, and the Danube River in western Europe (Tockner et al. 1998, 1999; Bloesch and Sieber 2003; Hein et al. 2016). These basin-scale restoration projects overseen by governmental agencies are more likely to include independent oversight and monitoring and to have integrated restoration plans that span diverse spatial scales and river processes than are projects that are smaller in spatial extent.

Restoration in the context of this chapter is used to include both *restoration* – a return to a close approximation of the river condition prior to disturbance (however disturbance may be defined) – and *rehabilitation* – improvements of a visual nature, sometimes described as "putting the channel back into good condition" (however good condition may be defined) (National Academy 1992).

River restoration can be described as following one of three approaches (Palmer et al. 1997; McDonald et al. 2004). The *field of dreams approach* uses traditional engineering techniques to modify river form to a desired condition, with the expectation that this will create the processes necessary to maintain that form (e.g. Lepori et al. 2005). This is the most widely used approach to restoration on relatively short river segments. This approach is named in reference to the movie *Field of Dreams*, which became famous for the phrase, "If you build it, he will come." In the case of river restoration, the implication is that restoring river form will also restore function, so that organisms such as fish will return and thrive. This approach to restoration can also be characterized as involving active intervention within the river corridor, in contrast to passive restoration that focuses on processes outside of the corridor, such as upland reforestation to reduce sediment yields to the river.

The *system function approach* to river restoration identifies and alters the initial conditions required to achieve restoration goals. This could involve modifying fine sediment inputs to a targeted segment of river by establishing riparian buffer strips, for example, or adding large wood to increase flow resistance and sediment retention. The underlying rationale is that modifying initial conditions such as water or sediment inputs will cause river process and form to adjust in a desired manner.

The *keystone method* identifies and incorporates crucial components of process and form and recognizes uncertainty in the resulting river responses. Riffle–pool sequences might be the keystones of river form and process in a project designed to restore fish habitat, for example, so that restoration would focus on the parameters necessary to create and maintain riffles and pools.

River restoration can also be distinguished as focusing on reconfiguration or reconnection (Bernhardt and Palmer 2011; Wohl et al. 2015c). As the name implies, reconfiguration focuses on changing channel form and is analogous to the field of dreams approach. Reconnection emphasizes connectivity, as in removal of artificial bank protection and grade controls and widening of the portion of the floodplain actively connected to the channel in order to restore braided planforms on European rivers (Tockner et al. 1998, 1999; Habersack and Piégay 2008; Muhar et al. 2008; Theule et al. 2015).

River restoration as currently practiced is commonly not scientific because hypotheses regarding river response to a given restoration action are not posed and tested. A large-scale survey of river restoration in the United States found that fewer than 10% of projects included any form of monitoring or assessment, although projects with higher costs were more likely to be monitored (Bernhardt et al. 2005). Less than half of all projects set measurable objectives, but nearly two-thirds of project managers felt that their projects were "completely successful" (Bernhardt et al. 2007). This reflects the fact that perceived ecological degradation typically motivated the projects. Post-project appearance and positive public opinion were the most commonly used metrics of success (Bernhardt et al. 2007), however, rather than more objective metrics or metrics grounded in scientific understanding of river process and form. At present, monitoring is still not routinely included in small-scale restoration projects, but is at least becoming more common than during the first decade of the twenty-first century.

The lack of monitoring for restoration effectiveness is highlighted by a consideration of the history of river restoration. The design of instream structures such as rock and log dams and deflectors used for habitat improvement goes back to at least the 1880s in the United States, and even earlier in Europe (Thompson and Stull 2002). Many of these structures are still used today with very little modification of initial designs, although systematic examination indicates that such structures do not necessarily guarantee demonstrable benefits for fish communities (Thompson 2006), and may in fact decrease habitat abundance and diversity over a period of many decades (Thompson 2002) (Figure 8.11). In other words, because we typically do not objectively and systematically evaluate the

(a)

(b)

**Figure 8.11** Instream structures used for restoration. (a) Vortex weir along a river in Charlotte, North Carolina, USA. A vortex weir is u- or v-shaped, with the apex pointing upstream. The structure is designed to deflect flow toward the channel center and promote bed scour, which forms a pool. (b) Collapsed lunker in the Catskills region of New York State, USA. Lunkers are designed to stabilized stream banks and promote edge cover for fish. Source: Both photographs courtesy of Douglas M. Thompson.

success of restoration projects over periods of several years following project completion, we are not learning from our mistakes.

In this context, the relatively new practice of stream mitigation banking has the potential to facilitate continued degradation of rivers. Stream mitigation banking, as practiced in the United States, gives developers the option to offset construction impacts to streams by purchasing credits. The credits are generated by for-profit companies that restore streams on a speculative basis and are approved by federal regulatory agencies (Lave et al. 2008). Critical issues such as the location and proper amount of compensation, as well as how stream credits should be measured and certified, remain unresolved (Lave et al. 2008). This strongly suggests that at least some stream mitigation banking practices will provide a cover for stream degradation and lead to net loss of river health (Lave 2018).

Small- to medium-scale river restoration has become an industry dominated by consulting firms with a background in civil engineering rather than in river science, with designs developed and implemented by those with relatively little knowledge of river process and form. The scientific community has become increasingly vocal in criticizing restoration practices (e.g. Pasternack 2013; Palmer et al. 2014; Wohl et al. 2015c). Numerous papers emphasize that river restoration must be based on or include five factors (Kondolf and Larson 1995; Hughes et al. 2001; Kondolf et al. 2001; Ward et al. 2001; Hilderbrand et al. 2005; Wohl et al. 2005; Kondolf et al. 2006; Sear et al. 2008; Brierley and Fryirs 2009; Hester and Gooseff 2010).

First, restoration should be designed with explicit recognition of complexity and uncertainty regarding river process and form, including the historical context of variations in process and form through time. A well-documented example of failed restoration imposed a stabilized single-thread channel on a river segment that had repeatedly alternated between multi- and single-thread planforms during previous decades in response to fluctuations in flood magnitude and frequency (Kondolf et al. 2001). The restored channel was completely altered by a flood within 3 months of project completion.

Second, restoration should emphasize processes that create and sustain river form, rather than imposition of rigid forms that are unlikely to be sustainable under existing water and sediment regimes. Perhaps the most egregious and common example is braided river segments that are restored to sinuous, single-thread rivers without addressing the water and sediment yields that produced a braided planform, and without any consideration of meander dynamics (the constructed bends are commonly stabilized to prevent migration) (e.g. Kondolf et al. 2001). This practice likely reflects a cultural preference for single-thread, meandering channels in North America and Europe (Kondolf 2006; Le Lay et al. 2013a). Sometimes, the re-meandered rivers were historically straightened, but in other cases the rivers have a braided planform reflects historical conditions of flow and sediment regime. Cuneo and Uvas Creeks are two well-publicized examples in California, USA in which restoration that imposed a meandering planform failed spectacularly within a few years as moderately sized floods converted the restored river reaches back to a braided form (Kondolf et al. 2001; Kondolf 2006). In each case, practitioners ignored historical evidence of large sediment fluxes and braided planform, and imposed a single-thread, sinuous channel with stabilized banks.

Examples of restoration strategies designed to initiate processes are forms of stage 0 restoration (see Section 5.7) and beaver dam analogs. Stage 0 restoration refers to the reestablishment of a multichannel planform. This approach can involve introducing substantial quantities of large wood and allowing flows to redistribute the wood, which is likely to result in logjams and formation of secondary channels. Stage 0 restoration can also involve excavation of legacy sediments and the introduction of widely spaced, temporary obstacles (e.g. large wood pieces, hay bales) that deflect flow in a manner likely to facilitate formation of swale-shaped channels and a multichannel planform (e.g. Booth and Loheide 2012). Stage 0 restoration can also employ beavers, with beaver dam analogs built in locations in which real beavers can enhance and maintain the dams (Pollock et al. 2014, 2015).

Third, projects should be monitored after completion, using the set of variables most effective for evaluating achievement of objectives, and at the correct scale of measurement (Comiti et al. 2009b provides an example of effective monitoring). If the primary objective of restoration is to enhance biodiversity, for example, then monitoring habitat heterogeneity under the assumption that habitat heterogeneity always correlates with biodiversity is not as appropriate as directly monitoring metrics of biodiversity. A synthesis of restoration project designed to restore habitat and biodiversity found that most projects did restore heterogeneity, but almost none resulted in greater macroinvertebrate biodiversity (Palmer et al. 2010b). Comiti et al. (2009b) provide an example of the monitoring of changes in channel process along mountain streams in Europe, where organic matter retention and benthic macroinvertebrate biodiversity were higher in river segments with morphologically based artificial steps constructed of logs and boulders than in river segments with traditional concrete check dams.

Fourth, consideration of the watershed context, rather than an isolated segment of river, is crucial because of the influences of physical, chemical, and biological connectivity on alterations undertaken for river restoration. The Carmel River in California, USA provides an example where restoration using native riparian vegetation was not initially successful because decades of ground-water withdrawal had lowered the water table below a depth that could be accessed by the vegetation (Kondolf and Curry 1986). Consequently, the native plants had to be artificially irrigated to ensure their survival.

Fifth, accomodation of the heterogeneity and spatial and temporal variations inherent in rivers is necessary for successful restoration (Brierley and Fryirs 2009). Rivers continually adjust parameters such as bedform configuration, bed grain-size distribution, and channel width-to-depth ratio in response to fluctuations in water, sediment, and wood yields to the channel. These adjustments are commonly not synchronous or of exactly the same magnitude between distinct reaches of the river. Allowing the channel some freedom to adjust to changes imposed during restoration, as well as changes that will inevitably occur afterward, increases the likelihood that the objectives of restoration will continue to be met over a period of many years.

Numerous papers examine how numerical simulations can be used to predict restoration outcomes prior to project implementation (e.g. Brooks and Brierley 2004; Singer and Dunne 2006; Dixon et al. 2016). However, as Bernhardt et al. (2007) emphasize in a survey of river practitioners, publishing more scientific studies of river restoration will not by itself change the existing situation. River restoration can only improve through direct, collaborative involvement among scientists, managers, and practitioners.

Such collaborations appear to be an obvious next step, but can be very difficult to achieve. Interdisciplinary scientific teams face significant challenges because of differences in terminology, conceptual models, qualitative versus quantitative knowledge, and temporal and spatial scales of interest (Benda et al. 2002). These challenges multiply when the pool of participants is broadened beyond the scientific community. There is no question, however, that river restoration requires an interdisciplinary approach. As reviewed by Pasternack (2013), wetland rehabilitation provides a model. Wetland rehabilitation is facilitated by a certification program hosted by the Society of Wetland Scientists, which includes research scientists, governmental regulators, and practitioners. There is no equivalent for river restoration, partly because the river science community is diverse and oriented toward specific academic disciplines, as well as being strongly divided between research scientists and practitioners and poorly organized (Castro 2008; Pasternack 2013). Although regulators and practitioners would like to establish a universal restoration approach that would standardize methods, research scientists remain highly skeptical that such a "cookbook" technique can be effective. At present, there is no scientific consensus about the scientific foundations for restoration, what the practice should entail, or who should be allowed to undertake restoration (Darby and Sear 2008; Pasternack 2013; Wohl et al. 2015c).

An important consideration in river restoration is that it is not an all-or-nothing process. A river does not have to be – and typically cannot be – restored to some completely natural condition that existed prior to intensive resource use. Partial restoration within the constraints existing in a watershed can nonetheless restore a great deal of physical and ecological form and function. Small watersheds in the central United States that are effectively completely devoted to agriculture, for example, have highly channelized streams. These streams cannot be restored in the traditional sense. River engineering is ubiquitous, and land cover has been altered throughout the watershed, so that water and sediment yields are completely altered (Rhoads et al. 1999). The physical and ecological function of these streams can be improved with *naturalization*, however, which defines a viable management goal for watersheds within landscapes intensively modified by humans. A naturalized channel has sustainable hydraulic and morphologic diversity that supports greater biodiversity than in an unrestored channel, even though the naturalized channel may still be completely altered relative to its natural state. A naturalized channel might be deepened but not straightened, for example, allowing the development of limited sinuosity and associated physical diversity in hydraulics, substrate, and channel geometry (Rhoads et al. 1999), or limited secondary channels might be constructed or allowed to form to create a multichannel planform (e.g. Škarpich et al. 2019).

Primary considerations in restoring selected reaches of a river or river network are, how many and where? Bernhardt and Palmer (2011) discuss the "fuzzy logic" of attempting to reverse catchment-scale degradation by restoring small segments of an entire river network. In scenarios where catchment-scale restoration is limited, however, identifying portions of the river corridor that can be disproportionately influential in retaining excess nutrients, for example, or increasing habitat abundance and diversity, can enhance the effects of restoration. The concept of river beads becomes important in this context.

Because river restoration is commonly spatially constrained by existing land ownership and use, scientists undertaking basin-scale restoration in the Missouri–Mississippi River drainage of the United States proposed a *string of beads approach*. In this approach, land acquisition and restoration activities focus on key floodplain habitats such as floodprone areas near tributary confluences or remnant backwaters that form beads along the string of the otherwise-altered river corridor (Galat et al. 1998; Lemke et al. 2017). This spatially discontinuous approach to river restoration yields demonstrated improvement in water quality, flood hazard mitigation, and biodiversity. Questions remain, however, regarding the number and location of beads that will maximize desired river responses to restoration (Wohl et al. 2018b).

The European Water Framework Directive provides an example of a governmental approach that may help to organize efforts toward common objectives and enhance river restoration at a national or transnational scale (European Commission 2000). The directive was designed primarily to improve and protect water quality, with a set deadline for achieving "good status" for all surface waters within member nations by 2015. This status was to be achieved by meeting requirements for ecological protection and minimum water quality standards analogous to those enforced by the US Environmental Protection Agency. These goals, although laudable, were difficult to implement: 95% of England's rivers, for example, were at risk of failing legislated environmental objectives prior to 2015 (Green and Fernández-Bilbao 2006; Pasternack 2013). Now that the first 6-year planning cycle has finished (as of 2015), river basin management plans are required to establish measurement programs for bodies of water falling below the benchmark in order to improve their status and become compliant over subsequent planning cycles (Hughes et al. 2016).

One relatively recent and high-profile approach to restoration via reconnection comes from dam removal and experimental high flow releases (Sections 3.2.9 and 4.9). High flow releases can be used to restore river process and, indirectly, form downstream from a dam. Dam removal effectively restores all forms of longitudinal connectivity (i.e. water, solutes, sediment, large wood, and organisms) and, indirectly, lateral and vertical connectivity within the river corridor. The restoration of natural sediment and wood regimes, however, can require years to decades as the downstream portion of the river adjusts to the substantial pulse of sediment that typically enters following dam removal (e.g. East et al. 2015). Dam removal and experimental high flow releases grew from a progressive recognition of the importance of environmental flows.

### 8.5.3 Instream, Channel Maintenance, and Environmental Flows

A vital aspect of river restoration at many sites is preserving or restoring a natural, as opposed to regulated, flow regime. As discussed earlier, the natural flow regime (Poff et al. 1997) outlines the importance of magnitude, frequency, duration, timing, and rate of change of flow in river networks for physical process and form and for ecological communities. When flow regime is altered directly by flow regulation or indirectly by changes in land cover that alter water yield to a river, channel characteristics and riverine biota are affected. Subsequent papers have documented how flow regulation tends to homogenize river flow regimes, with the consequence that riverine physical characteristics and biotic communities also become more homogeneous with time (Moyle and Mount 2007; Poff et al. 2007; Peipoch et al. 2015). Growing awareness of the importance of all aspects of a river's flow regime led to the current emphasis on environmental flows.

Initial efforts to protect river flow focused on minimum flows. In arid and semiarid regions such as the western United States, dams and diversions designed to manipulate water for consumptive uses including agricultural irrigation can result in river segments that are completely dewatered for some or all of the year. As two fish biologists wrote in one of their papers about rivers in such regions, "it is obvious that without water, there can be no fish" (Fausch and Bestgen 1997).

The concept *of instream flows* developed as a means to preserve some minimum flow level within the channel. An early version of this was based on the Instream Flow Incremental Methodology (IFIM) (Bovee and Milhous 1978). IFIM uses a biological model that describes the habitat preference of individual fish species in terms of depth, velocity, and substrate, and a hydraulic model that estimates how habitat availability varies with discharge. The intent behind this method is to be able to specify the minimum flows below which individual species likely cannot be sustained in a river segment, as well as the inferred gains in habitat and potentially in fish biomass as flow increases. Although the method has been criticized for being overly simplistic – the model does not account for biological interactions such as competition or predation, for example – IFIM remains widely used in evaluating alternative water management options (Stalnaker et al. 1995; Macura et al. 2017).

Minimum flows can allow river organisms to survive for a period of time, but a river that in essence has only continual base flows will eventually lose its capacity to support a diverse aquatic community. Periodic high flows are indirectly necessary to biotic communities because higher flows maintain habitat by performing functions such as scouring pools, winnowing fine sediments from the bed, and limiting channel narrowing through encroachment of riparian vegetation. High flows are also directly necessary because they provide a window of opportunity during which organisms can disperse longitudinally and laterally, accessing new habitat for breeding and feeding, as well as maintaining lateral connectivity between the channel and floodplain.

Recognition of the importance of higher flows first led to the concept of *channel maintenance flows*, typically defined as the components of a river's flow regime necessary to maintain specific physical channel characteristics, such as sediment transport or flood conveyance (e.g. Andrews and Nankervis 1995). Channel maintenance flows are an applied equivalent of the concepts of bankfull, effective, or dominant discharge. In this applied context, channel maintenance flows can specify a particular magnitude and frequency of flow to achieve a limited objective, such as pool scour, or they can incorporate a broader range of flow magnitudes designed to maintain a physically diverse channel (Andrews and Nankervis 1995). Analogous to instream flows, the intent behind channel maintenance flows is to quantify and then legally establish or protect the magnitude and frequency of flow necessary to maintain specific components of river process and form.

The latest iteration in this progressively expanding view of the components of the flow regime necessary to preserve physical and ecological integrity in a river is *environmental flows*. The concept of environmental flows grew out of experimental flow releases from dams, such as those on the Colorado River through the Grand Canyon, USA in 1996, 2004, 2008, 2010, and continuing at present (Melis 2011; Melis et al. 2015; Mueller et al. 2018). An experimental flood is tied to a qualitative or quantitative model of a river ecosystem that predicts some beneficial effect from the flood. In the case of the Colorado River, the floods are designed primarily to deposit finer sediment (silt and sand) along the channel margins in order to restore riparian and backwater habitat that has been lost through progressive erosion of sand bars and backwater habitats since construction of Glen Canyon Dam in 1963. Ideally, the experimental flow release is conducted in an *adaptive management* context in which the results of the flood are systematically assessed and the underlying model of the river ecosystem is modified as needed (Melis 2011). Experimental releases from dams are now documented for several rivers in diverse settings (e.g. Mürle et al. 2003; Konrad et al. 2011; Mueller et al. 2018). For example, experimental flow releases designed to restore channel–floodplain connectivity have been conducted along multiple rivers in southeastern Australia, although these have had limited success in reversing environmental degradation because the flows are relatively small and of short duration (e.g. Lind et al. 2007; Rolls et al. 2013).

*Environmental flows* now refer both to such experimental releases, which are typically limited in duration, and to an annual hydrograph that specifies magnitude, frequency, timing, duration, and rate of change in flow, commonly for diverse conditions such as wet years and dry years (Figure 8.12) (e.g. Rathburn et al. 2009). As with other forms of river restoration, developing the guidelines for environmental flows is time-consuming and challenging because this process forces geomorphologists and riverine ecologists to specify flow thresholds related to targets such as winnowing fine sediment, mobilizing the entire bed, creating overbank flows for channel–floodplain connectivity, and maintaining diversity of species and individual ages within a riparian forest. The complexity and uncertainty associated with river process and form, as discussed at length in Chapters 3, 4, and 5, mean that this task is sometimes straightforward, but more often includes a great deal of uncertainty. Uncertainty that can be acceptable in scientific research becomes more challenging in a management context in which every cubic meter of water released from a hydroelectric dam during an experimental flood, for example, equates to a loss of revenue for the entity operating the dam.

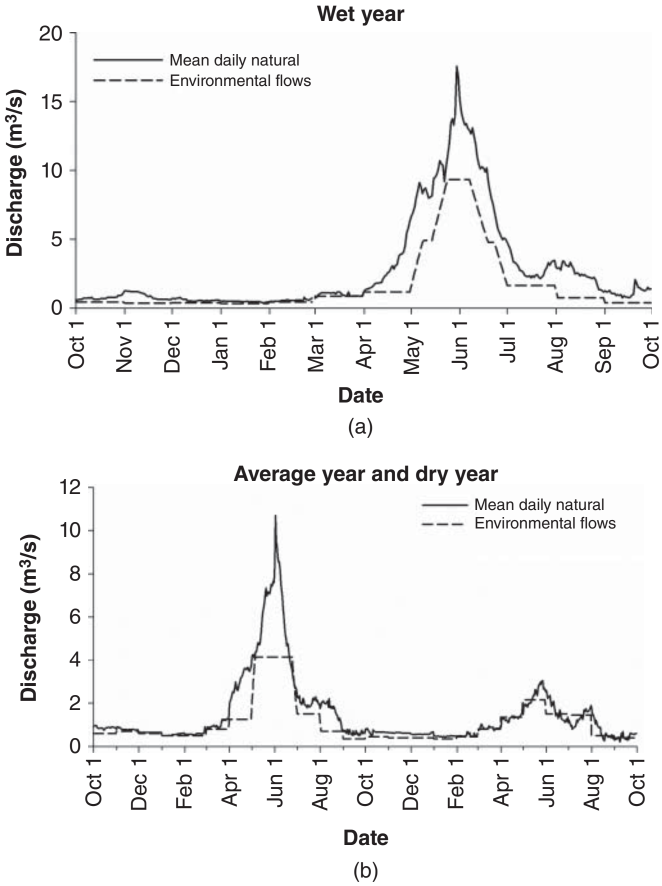


**Figure 8.12** Suggested annual hydrographs for (a) wet and (b) dry or average years in the North Fork Poudre River drainage basin, Colorado, USA. Each hydrograph shows the average flows that would occur under natural (unregulated) conditions and the minimum environmental flows recommended to protect desired ecosystem attributes including winnowing fine sediment from spawning gravels, maintaining pool volume, and creating overbank inundation for riparian vegetation. Source: After Rathburn et al. (2009), Figures 13 and 14.

The procedure of assessing environmental flow requirements has gradually assumed characteristic steps of (i) quantifying natural and altered stream flows and the changes in the flow regime in terms of relevant hydrologic metrics (Richter et al. 1996; Gao et al. 2009; Mackay et al. 2014) and (ii) quantifying relationships between hydrologic metrics and physical and biological river attributes, which essentially involves coupling physical and biological models (Sanderson et al. 2011; Webb et al. 2015). A large-scale example comes from the Okavango River system in southern Africa, where multiple response curves for individual metrics of river function and biota were combined using Decision Support Software to model potential river ecosystem response to different scenarios of flow regulation (King et al. 2014).

Once recommendations are developed for environmental flows, the process moves into the policy arena, in which a community much broader than scientists typically weighs in on water availability and use. As Arthington and Pusey (2003, p. 377) describe the process in an Australian context, the two vital questions are: "How much water does a river need? and How can this water be clawed back from other users?" In southern Africa, predictions of the tradeoffs between water development and river ecosystem response are being used in a social context to define *development space* – the acceptable balance between flow regulation and loss of river health (King and Brown 2010). An extensive literature has come into being during the past decade that describes environmental flow assessments and recommendations, as well as a variety of case studies (e.g. Tharme 2003; Arthington et al. 2006; Shafroth et al. 2010; Foster et al. 2018). However, Poff (2018) emphasizes the need to move beyond static, regime-based flow metrics to dynamic, time-varying flow characteristics, as well as the importance of expanding the ecological metrics used to design and assess environmental flows. Poff (2018) also highlights the importance of non-flow parameters such as water temperature and sediment dynamics.

Environmental flows are in many cases driven by the need to preserve endangered species, and ecologists tend to focus on flow regime. Geomorphologists increasingly emphasize the equal importance of sediment dynamics in maintaining channel complexity, habitat heterogeneity, and nutrient cycling (Pitlick and Wilcock 2001; Wohl et al. 2015b). Altered flow regimes are commonly accompanied by altered sediment dynamics as a result of sediment trapping behind dams or changed ability of flows to entrain and transport sediment present along the river corridor. A body of scientific literature on sediment dynamics in the context of environmental flows is just beginning to appear (Rubin et al. 1998; Wiele et al. 2007; Wohl et al. 2015b). The conceptualization of critical inputs and fluxes of materials in river corridors has recently expanded to include large wood (Wohl et al. 2019).

Environmental flows are also closely connected to ecohydrology and ecohydraulics. *Ecohydrology* is the investigation of integrated biological and hydrologic processes, at the scale of a river network or river reach, and the resulting changes to hydrologic, physical, chemical, and ecological attributes of river corridors (Zalewski 2000). Ecohydrology can be used to guide river restoration by quantifying the relationships between hydrologic drivers, other environmental stressors (e.g. connectivity, water quality), and stream organisms (e.g. DuBowy 2013). *Ecohydraulics* focuses on how the magnitude and spatial distribution of hydraulic variables such as flow depth and velocity vary in relation to discharge and channel morphology, under the assumption that hydraulic characteristics provide a useful means of predicting, evaluating, and designing habitat conditions favorable to targeted species (Leclerc et al. 1996; Clifford et al. 2006). Ecohydrology and ecohydraulics are increasingly used to develop specific prescriptions for river restoration on a wide range of rivers (e.g. Mallen-Cooper and Zampatti 2018; Entwistle et al. 2019).

### 8.5.4 River Health

Global and regional syntheses indicate that aquatic and riparian species are becoming increasingly homogeneous – a few hardy generalist species tend to dominate many communities – because of flow regulation (Dynesius and Nilsson 1994; Moyle and Mount 2007; Poff et al. 2007; Braatne et al. 2008). A common theme among diverse case studies of regulated rivers is the loss of physical and ecological complexity (Surian 1999; Graf et al. 2002; Peipoch et al. 2015). This can be conceptualized with changes in hydrology, sediment supply, and large wood dynamics as first-order effects, changes in hydraulics, substrate mobility, and channel form as second-order effects, and changes in biota as third-order effects (Burke et al. 2009).

River restoration in any form is driven by the perception that a river is to some extent unhealthy and can be improved. The concept of river health is intuitively appealing to many people and easy to communicate at a general level to nonscientists (Karr 1999). Scientists debate whether such a conceptualization is useful or appropriate, however, as well as how to quantify river health (Boulton 1999; Fairweather 1999; Harris and Silveira 1999; Gippel et al. 2017). Much of this debate occurs in the biological literature, partly because river health is an example of ecosystem health (Norris and Thoms 1999).

River health is related to *ecological integrity*, which is the ability of an ecosystem to support and maintain a community of organisms with species composition, diversity, and functional organization similar to those within natural habitats in the same region (Parrish et al. 2003). This definition of ecological integrity emphasizes biota, but implicitly includes physical and chemical processes that sustain the biota.

Biologists typically explicitly include physical and chemical aspects of rivers in the consideration of river health, as exemplified by defining *river health* as the degree to which a river's energy source, water quality, and flow regime, plus its biota and their habitats, match the natural condition at all scales (Karr 1991; Harris and Silveira 1999). Numerous qualitative and quantitative metrics of river health have been developed. These are typically focused on biological metrics (Harris and Silveira 1999; Karr 1999; Everall et al. 2017), although cumulative metrics sometimes include measures of water quality (Bunn et al. 1999), habitat (Maddock 1999; Norris and Thoms 1999; Kim and An 2015), or flow regime (Richter et al. 1996; Poff et al. 2010; Mackay et al. 2014).

Many of the biological metrics used to characterize river health focus on some aspect of biodiversity. *Biodiversity* is typically defined in terms of number of species within a given ecosystem, but can be quantified in a wide variety of ways, each of which provides specific information about the ecosystem under consideration. Biodiversity reflects biological influences such as competition and predation, as well as physical influences such as the diversity, abundance, and stability of habitat, and the connectivity of habitat (Gaston and Spicer 2004).

Geomorphologists have been slower to develop metrics of physical river condition to facilitate quantification of difference between contemporary and reference conditions for a river, as well as evaluation of river health. Geomorphic conceptualizations of rivers emphasize diversity of form and process through space and through time (McDonald et al. 2004; Brierley and Fryirs 2005; Pasternack 2013). Diversity of form and process reflects the hydrology, sediment supply, large wood, hydraulics, substrate, geomorphic history, and biota at the site. A desirable level of physical diversity can constitute *physical integrity*, which Graf (2001) defines as a set of active fluvial processes and landforms such that the river maintains dynamic equilibrium, with adjustments not exceeding limits of change defined by societal values. In other words, a river has physical integrity when river process and form are actively connected under the current hydrologic and sediment regime.

A geomorphic perspective on river health would characterize a healthy river as having two basic characteristics. First, a healthy river has the ability to adjust form and process in response to changes in water, sediment, and wood inputs, whether these changes occur over many decades to centuries (e.g. climate variability) or over relatively short time periods (e.g. a large flood or landslide). Second, a healthy river has spatial and temporal ranges of water, sediment, and large wood inputs and river geometry similar to those present under natural conditions. Discussions of how to evaluate river health have taken on increased importance as broad governmental regulations such as the European Union's Water Framework and Habitats Directive have mandated delineation of diverse aspects of river health (Newson and Large 2006; Wernersson et al. 2015).

One danger involved in this type of national or transnational evaluation is that of oversimplifying what constitutes a natural or healthy river. Some rivers are naturally depauperate in species, for example, because of harsh physical or chemical conditions or a history of geographic isolation (e.g. Tolkinnen et al. 2015). Some rivers receive large sediment inputs and exhibit substantial channel instability because of natural factors such as semiarid climate or erodible lithology in the watershed (e.g. Constantine et al. 2014; Rickenmann et al. 2016). Some rivers have low levels of longitudinal connectivity as a result of natural flow intermittency or large numbers of in-channel obstructions such as logjams and beaver dams (e.g. Mould and Fryirs 2017). Recognition of complexity and diversity as inherent properties within a river network and between river networks remains crucial for research and management of rivers. This takes us back to viewing rivers in the context of the greater landscape.

## 8.6 Rivers with a History

As explained in Chapter 6, a river is a physical system with a history. The influence of previous climatic and tectonic regimes on river form and process can extend back in time beyond the Quaternary because of the slow response of some aspects of river networks to change. Among these aspects are:

- topography;
- the spatial arrangement of river channels within a network;
- relief ratio;
- drainage density for river segments larger than first- and second-order channels;
- river longitudinal profiles; and
- valley geometry.

Consequently, inherited characteristics of these features can continue to influence contemporary process and form, as illustrated by continental-scale controls on large rivers (Figure 8.2) (Potter 1978).

At smaller spatial scales, a single river channel flowing across different lithologies, structural features, or tectonic zones can exhibit striking differences in river and valley geometry and rate of incision in response to geological controls that formed millions to hundreds of millions of years ago. Examples include the lower Mississippi River in the eastern United States. This sinuous river can be subdivided into reaches that differ in gradient and sinuosity where the river crosses more erosionally resistant Tertiary-age sediments and fault zones, even though many of these faults show relatively little recent activity (Schumm et al. 2000). Rivers with drainage areas larger than 10 $\text{km}^2$ in the Central Apennines of Italy have long-profile convexities where they cross faults that have undergone an increase in displacement during the past million years, whereas those crossing faults with constant displacement rates lack such convexities (Whittaker et al. 2008).

Landscape configurations or persistent erosional and depositional features relict from Quaternary glaciation provide another example of how past events continue to influence river form and process. Glaciated mountains can have distinctly different valley geometry above and below the elevation limits of Pleistocene valley glaciers, with greater cross-sectional area and steeper valley walls in glacial valleys relative to fluvial valleys (Montgomery 2002; Amerson et al. 2008; Livers and Wohl 2015). Glaciated and fluvial portions of a mountain range can also be eroding at different rates in response to the effects of differing sediment supply and base-level controls (Anderson et al. 2006c). Tributary glacial valleys that eroded to a base level defined by the upper level of the main valley glacier can persist as hanging valleys with large vertical drops between the tributary valley mouth and the main valley floor for thousands of years after glacial ice retreats.

Recessional moraines are persistent depositional features perpendicular to valley orientation that create local base levels and valley segments with lower river gradient and finer substrate than segments immediately up- and downstream, even long after the moraine is incised by a river. Recessional moraines that fill with meltwater as valley glaciers retreat can fail catastrophically. Although individual moraines fail only once, failure of successive moraines along a valley can create numerous outburst floods along a river network over periods of decades to centuries as moraines successively up-valley are abruptly drained. The discharge and stream power of these *outburst floods* typically greatly exceed the discharge and stream power generated during annual floods induced by rainfall or snowmelt (Cenderelli 2000; O'Connor et al. 2013), and annual floods may be largely incapable of modifying the outburst-flood erosional and depositional features (Cenderelli and Wohl 2001). Portions of a valley subject to repeated outburst floods can also become less responsive in that earlier floods have already modified valley morphology to convey exceptionally large discharges (Cenderelli and Wohl 2003).

The continental-scale ice sheets that covered portions of North America, northern Europe, and northern Asia also left enduring signatures on river networks, diverting existing channels, altering water and sediment supply to channels beyond the ice margins, and changing local river gradients via isostatic flexure of the crust. One of the most spectacular categories of ice-sheet effects on river networks is the occurrence of megafloods during periods of glacial retreat. *Megafloods* are relatively short-duration flows that constitute the largest known freshwater floods, with discharges that generally exceed 1 million m$^3$/s (Baker 2013). Although other mechanisms, such as failure of rock dams or caldera lake impoundments, can generate megafloods, most were associated with ice-marginal lakes or water released from within the ice sheet. Among the megafloods documented thus far (Baker 2013) are those of:

- the Channeled Scabland in Washington, USA;
- the Laurentide Ice Sheet ice-marginal lakes in north-central North America, which flowed down the Mississippi, St. Lawrence, Mackenzie, and Hudson rivers;
- the Patagonian Ice Sheet of southern Argentina and Chile;
- Icelandic jökulhlaups;
- the Fennoscandian Ice Sheet, which drained southward and influenced the English Channel and the North Sea; and
- the northern mountain areas of central Asia, including Kirgizstan, Mongolia, and Siberia.

These exceptionally large floods created erosional and depositional features of such large magnitude and extent that subsequent geomorphic processes during the Holocene have only partially – or in some cases, little – modified megaflood terrains.

More recent Holocene history can also influence river process and form. River response to disturbance partly depends on the time elapsed since the last disturbance of a similar magnitude. Along mountainous headwater catchments in which wildfires and subsequent rainfall induce debris flows, such flows strongly influence channel morphology only if a minimum period has passed since the last debris flow (Wohl and Pearthree 1991). This minimum period is necessary for sufficient sediment to accumulate in the channel to be eroded by the next debris flow. Another example comes from the Drôme River in France, where a flood in 1978 caused avulsion, channel straightening, and incision (Toone et al. 2014); 53 years had passed since a flood of equivalent or larger magnitude. In contrast, a hundred-year flood in 1994 caused relatively minor channel changes, partly in response to inherent channel structural features imposed by the 1978 flood.

Human use of resources can also continue to influence river process and form long after the relevant human activity has ceased. Earlier chapters provided numerous examples of such influences, including mill dams along rivers in the eastern United States (Walter and Merritts 2008). A 1998 study in the southern Appalachian Mountains found that whole-watershed land use in the 1950s was the best predictor of contemporary invertebrate and fish diversity because of persistent effects on aquatic habitat (Harding et al. 1998). A century after cut logs for railroad ties were floated down streams in the Medicine Bow National Forest of Wyoming, USA, the streams used for log floating had less instream wood, lower densities of large riparian trees, lower channel complexity, a greater proportion of riffles, and fewer pools than did otherwise analogous streams that were not used for log floating (Young et al. 1994; Ruffing et al. 2015). As noted earlier, 200 years may be required before instream wood volumes completely recover following timber harvest (Bragg et al. 2000; Stout et al. 2018).

The cumulative effects of historical processes occurring over different temporal and spatial scales continue to influence contemporary river process and form (Wohl 2018a). Failure to recognize this influence can limit understanding of rivers and lead to erroneous predictions of river response to ongoing climate change and management actions.

## 8.7 The Greater Context

Isaac Asimov once wrote – perhaps in a moment of frustration – that the only constant is change. This phrase can be adapted to rivers in at least two contexts. First, natural rivers are continually adjusting process and form – spatial distribution of hydraulic forces; water chemistry; sediment entrainment, transport, and deposition; instream and floodplain wood; bed configuration; channel cross-sectional geometry; channel planform; reach gradient and longitudinal profile – in response to changing inputs of water, sediment, and wood, or to continuing development of the river. Indeed, one definition of a natural – as opposed to a completely engineered – river is that a natural river possesses physical integrity because it is able to adjust to changing inputs. River process and form reflect some balance between continually changing external inputs of water, solutes, sediment, and large wood, and ongoing adjustments within the river. Under these circumstances, considerable insight can be gained by asking why, under variable external forcing, rivers do not change even more.

The second context for adapting Asimov's phrase to rivers is that, although any river or river segment follows the basic laws of physics and chemistry, characterizing feedbacks between channel process and form using a numerical equation or qualitative conceptual model that applies to all rivers is limited by the place-specific effects of lithology, tectonics, weathering regime, landscape history, river history, seasonal presence of ice cover or cyclones, and so forth. The only constant within a river network is changes through time and space. The only constant among river networks is river-specific changes in the interactions between process and form. Recognition of these characteristics further emphasizes the importance of understanding landscape context for any particular river network or river segment.

The nineteenth-century Scottish-American conservationist John Muir famously wrote in 1911, "When we try to pick out anything by itself, we find it hitched to everything else in the Universe." Many other thinkers have stated the same concept in different words, recognizing the interconnectedness of natural systems and people. Rivers are no exception to this rule, as I have emphasized from the opening pages of this book. As the intensity and extent of human alteration of river form and process have accelerated globally since the mid-twentieth century, abundant evidence has appeared that reflects riverine influences on the entire critical zone. Changes in coastal environments provide a vivid example.

Human activities now dominate nitrogen budgets in regions such as Asia, Europe, and North America (Boyer et al. 2006). Substantial increases in nitrogen yields to rivers result from industrial-scale agriculture, feedlots, and septic systems. Riverine corridors have been simplified via channelization, removal of riparian vegetation, levees, and flow regulation, all of which reduce channel–floodplain connectivity. This simplification reduces nitrogen retention and processing by rivers. Greater inputs and less storage create a “one-two punch,” resulting in substantially increased nitrogen fluxes down rivers to coastal areas. This has created eutrophication of estuaries and other nearshore environments. Consequently, fluxes of nitrogen now exceed planetary boundaries for sustainability and resilience (Steffen et al. 2015).

For the most part, we cannot yet predict in detail how diverse changes in rivers resulting directly and indirectly from human activities will affect the greater landscape. Synthesizing studies in the northern high latitudes, for example, Woo (2010) and Carmack et al. (2016) explain how freshwater discharge during spring snowmelt influences numerous and diverse processes in the nearshore zone and greater Arctic Ocean (Figure 8.13). Freshwater discharge influences the dynamics of coastal sea ice, terrestrial sediment and organic matter plumes into the ocean, and thermohaline circulation in polar seas. The complex effects of global warming on these interactions remain largely unknown. Less sea ice may modify existing energy and moisture fluxes, for example, and thus alter coastal storm patterns and inland water balances (Woo 2010; Carmack et al. 2016).

Unfortunately, we too commonly recognize the importance of landscape context and connectivity within and between river networks once our activities have altered connectivity and caused unintended negative consequences. Examples span spatial scales from headwaters to the world’s largest rivers, climatic zones from hot and cold deserts to rainforests, and tectonically active to passive terrains with varying lithology and structure. The point is not to induce despair as we contemplate past failures to account for the importance of connectivity, but rather to highlight the importance of being fully cognizant of various forms of connectivity as we move forward with river management. Rivers

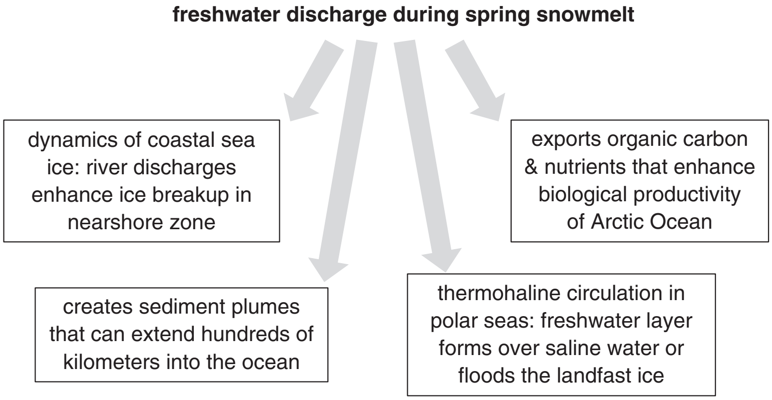


**Figure 8.13** Schematic diagram of the effects of freshwater discharge during spring snowmelt from rivers draining to the Arctic Ocean.

are physical systems with a history and rivers exist within a global landscape that includes the atmosphere, land masses, oceans, and ground water, as well as all the wondrously diverse organisms that live on our planet. Rivers are at the heart of nearly every landscape on Earth, and river form and process are more integral to human communities than is any other single landscape component. The challenge of developing ways to coexist with healthy, functional rivers is integral to both a scientific understanding of rivers and the application of that understanding through river management. This challenge can only be met by treating rivers as part of the greater landscape. If we do not view rivers in this integrative, holistic context, we make the same mistakes over and over, risking nothing less than the survival of our own societies.