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GRAND CHALLENGES CENTENNIAL COLLECTION
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Forgotten Legacies: Understanding and Mitigating Historical Human Alterations of River Corridors

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Key Points:
- Historical human activities have altered river ecosystems in ways no longer visible
- Failure to recognize these alterations skews perception of river form and process
- Effective river management and restoration requires close attention to historical legacies

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Abstract Legacies are persistent changes in natural systems resulting from human activities. Legacies that affect river ecosystems can result from human alterations outside of the river corridor, such as timber harvest or urbanization, or from alterations within the river corridor, including flow regulation, river engineering, and removal of large wood and beaver dams. Human alterations of river ecosystems have been occurring for thousands of years in some parts of the world and are now ubiquitous, yet both river scientists and the public may be unaware of the persistent effects of historical activities. Failure to recognize the legacy of historical activities that no longer occur can skew perceptions of river process and form and the natural range of variability in river ecosystems. Examples come from rivers of the Mid-Atlantic Piedmont and the Pacific Northwest regions of the United States. Mid-Atlantic Piedmont streams in which legacy sediment accumulated behind now-abandoned mill dams experienced a complete transformation from wide, shallow, marshy valleys to sinuous rivers lined with tall cutbanks, but the existence and the cause of this river metamorphosis was not widely recognized until the first decade of the 21st century. Rivers of the Pacific Northwest from which large wood was removed have changed during the past century from spatially heterogeneous, multichannel systems closely connected to their floodplains via frequent channel avulsion and lateral migration to single-thread channels with more homogeneous floodplains and less lateral connectivity. Again, this river metamorphosis has only been recognized within the past two decades. In each of these regional examples, river process and form have changed so substantially that the river ecosystems can be described as having assumed an alternative state. In these and many other examples, the alternative state provides lower levels of ecosystem services such as habitat, biodiversity, and attenuation of downstream fluxes of water, sediment, organic carbon, and nutrients. River management designed to enhance and restore these ecosystem services can be more effective if the continuing effects of these historical legacies are recognized. The grand scientific challenges resulting from historical human alterations of river ecosystems include the following: (1) to recognize the existence of a legacy that continues to affect river ecosystem process and form; (2) to understand the source of the legacy with respect to chronology, type, spatial extent, and intensity of human activities; (3) to understand the implications of the legacy regarding how river process and form and river ecosystem services have changed; and (4) to design management or restoration strategies that can mitigate the loss of river ecosystem services. In summary, the existence of forgotten legacies challenges river scientists to recognize the continuing effects of human activities that have long since ceased and also poses challenges for the application of scientific understanding to resource management. Societal expectations for attractive, simple, stable rivers are commonly at odds with scientific understanding of rivers as dynamic, spatially heterogeneous, nonlinear ecosystems. Knowledge of how human actions, including historical actions that have long since ceased, continue to alter river ecosystems can help to bridge the gap between societal and scientific perceptions of rivers.

1. Landscape Legacies

The Oxford English Dictionary defines a legacy as a tangible or intangible thing handed down by a predecessor, or a long-lasting effect of an event or process. In river research, legacy has been used in connection with diverse past events including natural processes such as volcanic eruptions or wildfires that can leave a persistent signature in natural landscapes and biotic communities. Although legacy is still used to describe natural processes, since circa the 1980s legacy has become particularly associated with past human activities. In this sense, investigators refer to legacy sediments (James, 2010, 2013; Novotny, 2004), legacy pollution or contaminants (Singer et al., 2013), and legacy effects (Wohl, 2015). Legacy is used here to include any persistent change in a natural system resulting from human activities, but this paper focuses solely on legacy effects on physical components of river process and form.

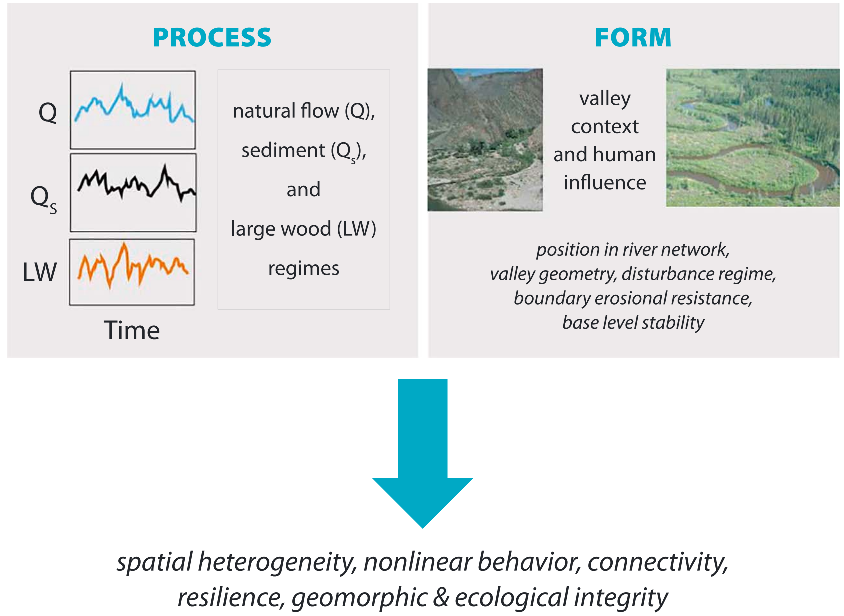

Figure 1. Schematic illustration of how the major physical inputs to the river corridor interact with watershed- to reach-scale form. These interactions result in characteristic ranges of spatial heterogeneity, nonlinear behavior, connectivity, resilience, and integrity in the river corridor. In a watershed with minimal human alteration, these characteristic ranges are described as the natural range of variability.

Rivers are fundamental landscape components that provide a variety of ecosystem services including vital supplies of drinking water. As such, extensive research has been devoted to quantifying and predicting river characteristics such as stream flow, sediment transport, and channel morphology and stability. I contend, however, that river scientists and society have not adequately acknowledged the degree to which contemporary river ecosystems have been altered by past human activities within the watershed and the river corridor. River corridor here refers to the active channel(s), floodplain and riparian zone, and underlying hyporheic zone (Harvey & Gooseff, 2015). The primary objective of this paper is to provide support for the contention that explicitly recognizing legacy effects and designing river management strategies to mitigate these effects constitutes a grand challenge in river science.

2. River Corridor Dynamics

A river corridor can be described with respect to process and form or, among ecologists, function and structure. Process describes the fluxes of materials within a river corridor and the interactions between materials in flux and the physical configuration, biogeochemical characteristics, and biotic communities of the river corridor. Process thus includes interactions as diverse as channel bank erosion, nitrate uptake, or germination of riparian vegetation on newly deposited sediment. Form of the river corridor includes the geomorphic configuration of the land surface, the vegetation occupying the land surface, and the stratigraphy underlying the surface. The process and form of the river corridor influence characteristics such as spatial heterogeneity, nonlinear behavior, connectivity, resiliency, and geomorphic (Graf, 2001) and ecological (Davies & Walker, 1986) integrity (Figure 1).

2.1. The Tripod That Supports River Ecosystems

The three primary physical inputs to river corridors, which interact with the valley geometry to influence the form of the river corridor, are water, sediment, and large wood. Each of these inputs has been described in the context of a natural regime. The natural flow regime describes stream flow in the absence of human alterations in land cover, river corridor form, flow regulation, and the water table. The natural flow regime can be characterized with respect to magnitude, frequency, duration, timing, and rate of rise and fall of water discharge (Poff et al., 1997).

The concept of the natural flow regime was first articulated in recognition of the vital importance of the temporal characteristics of flow to native river biota. The aquatic and riparian plants and animals present within a river corridor exhibit numerous adaptations to the details of flow. Riparian plants that disperse their propagules via hydrochory (water transport), for example, typically release seeds during seasonal peak flows that maximize transport and deposition of seeds in suitable locations (Nilsson et al., 2010). Stable low flows are required for successful spawning and recruitment of many fish species, whereas other species coordinate/schedule/conduct their spawning based on seasonally rising flows so that juvenile fish have access to nursery habitats such as inundated floodplains (Bunn & Arthington, 2002; Junk et al., 1989). Human alterations of the natural flow regime can disrupt the life cycle and habitat availability of native riverine biota to the point that some species can no longer survive. Human alterations of the natural flow regime can be quantified using indicators of hydrologic alteration (Poff et al., 2010; Richter et al., 1996) and other measures of flow deviation from the expected natural range of variability. Conceptualizations of the natural flow regime eventually gave rise to the idea of environmental flows, which quantify the flow regime necessary to maintain desired characteristics of a river ecosystem, including the resources and temporal cues that sustain native species (Arthington, 2012; Poff & Zimmerman, 2010; Richter, 2010).

The natural sediment regime describes sediment dynamics in a river corridor in the absence of human alteration of topography, land cover, and flow regime. The natural sediment regime can be characterized with respect to inputs, outputs, and storage of sediment within a specific length of river corridor, similar to a sediment budget (Wohl et al., 2015). Although systematic records of sediment flux analogous to those of gaged stream discharge typically do not exist, human alterations of the natural sediment regime can be inferred from the occurrence of sustained changes in river process and form associated with changes in land cover, flow regulation, or channel engineering that alter sediment dynamics within the river corridor (Wohl et al., 2015). The natural sediment regime was articulated as means of emphasizing that water alone cannot sustain river ecosystem process and form. If sediment fluxes are not maintained within a river corridor, progressive alteration of channel form, such as bank or bed erosion, is likely to alter habitat abundance and quality in ways that also stress native biota and reduce river ecosystem services (e.g., Bravard et al., 1997; Rollet et al., 2014). The key point is that water and sediment interact to sustain river ecosystems, and a change in the balance between them will result in a change in river process and form. Analogous to environmental flows, management designed to create a balanced sediment regime can be employed in highly altered rivers. A balanced sediment regime is present when the energy of flow available to transport sediment is in balance with sediment supply, such that the river form remains dynamically stable over a specified time period (Wohl et al., 2015).

The natural wood regime describes the dynamics of large wood in the absence of human alterations and can be characterized with respect to magnitude, frequency, duration, timing, rate, and mode of wood recruitment, transport, and storage within river corridors (Wohl, Kramer, et al., 2019). Water and sediment are more commonly considered the primary inputs to river corridors rather than large wood, but this likely reflects the significant declines in the presence of large wood within rivers because of centuries of active removal of wood and reduced inputs of wood associated with changes in land cover. Where natural abundances of large wood are present, the wood significantly influences fluxes of water and sediment within the river corridor, as well as the form and geomorphic and ecological function of the river corridor (e.g., Collins et al., 2012; Livers et al., 2018). Large wood forms an important input to river corridors in regions with forested uplands or forested river corridors (which can occur in deserts; Minckley & Rinne, 1985), but large wood is not a significant component of river form and function in naturally unforested river corridors with extensive marshes, for example.

As with sediment, insufficient systematic records exist of wood flux in the absence of human influences to quantify changes in the natural wood regime, but the effect of human influences can be inferred from sustained changes in river process and form (e.g., Collins et al., 2012). Analogous to environmental flows and a balanced sediment regime, a target wood regime can be used in managed rivers to restore desired process and form. A target wood regime is present when wood recruitment, transport, and storage balance desired geomorphic and ecological characteristics with mitigation of wood-related hazards (Wohl, Kramer, et al., 2019).

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2.2. The Context of a River Ecosystem

At the reach scale, inputs of water, sediment, and large wood interact with the existing configuration of the river corridor as governed by valley context, substrate erosional resistance, and base level stability (Figure 1). Valley context refers to two components: the physical setting of the river corridor and the disturbance regime of the river corridor. The physical setting includes position within the river network and valley geometry (downstream gradient and lateral confinement). Position within the river network can influence the sensitivity of a reach to fluctuations in relative base level (e.g., Berlin & Anderson, 2009; Bloom & Törnqvist, 2000; Wobus et al., 2006): Typically, portions of the lower river network are more likely to incise when relative base level falls or to accumulate sediment when relative base level rises. Position in the network also influences whether inputs from adjacent uplands are more likely to dominate, as in headwater portions of the network, or whether inputs come predominantly from upstream portions of the network (Gomi et al., 2002; Meade, 2007; Walling & Collins, 2008). Consequently, position in the network can influence the relative sensitivity of the different segments of the river corridor to human alterations in local base level (e.g., dam construction or removal; Foley et al., 2017; Skalak et al., 2013) or inputs from adjacent uplands (e.g., changes in land cover; Trimble, 2013).

Disturbance refers to natural processes initiating renewal or change (Penaluna et al., 2018). Disturbances include relatively infrequent events such as valley or continental-scale glaciation, which have recurrence intervals of tens to hundreds of thousands of years; moderately frequent events with recurrence intervals of decades to millennia, such as extreme floods or severe wildfires; and relatively frequent events that recur approximately every year, such as seasonal snowmelt or rainfall peak flows. Disturbance regime describes the magnitude, frequency, and type of disturbances within a river corridor. Although disturbances such as continental ice sheets alter entire large drainage networks, disturbance regime is characterized here at the reach scale because spatial variations in disturbance regime are common even within moderately sized drainage networks. Disturbance regime in mountainous river networks can vary over downstream lengths of a few kilometers, for example, between channels in steep, narrow valley segments that receive periodic inputs of hillslope sediment and large wood from debris flows, and wide, low-gradient valley segments in which floodplains buffer the channel from hillslope inputs. Over longer distances in mountainous drainage basins, elevation-related changes in temperature and precipitation can result in primarily snowmelt or glacier melt peak flows in upper portions of the network and rainfall-runoff peak flows in lower portions of the network (Jarrett, 1990).

Human activities commonly alter some characteristics of disturbance regimes. The most widespread alteration is likely to be changes in the magnitude and frequency of relatively frequent disturbances, as in flow regulation that reduces peak flows (e.g., Magilligan et al., 2003) or wildfire suppressions that alter upland inputs of water, sediment, and large wood (Rieman et al., 2010). Reducing the magnitude and frequency of disturbances such as floods and wildfires can reduce the abundance and diversity of habitat and biota (e.g., Bisson et al., 2003; Penaluna et al., 2018).

Valley geometry influences the energy available to change river form, as well as the space available to accommodate change. Steep river reaches commonly correspond to relatively narrow valleys and coarse (cobble to boulder) sediment that requires a high level of flow energy to move (Livers & Wohl, 2015; Wohl et al., 2007). Lower gradient river reaches are more likely to have relatively wide valley bottoms and floodplains or secondary channels that can absorb some of the excess energy during floods, thus limiting erosion during floods, although flood deposition is likely to be greatest in these low-gradient reaches (e.g., Righini et al., 2017; Shroba et al., 1979). Although human activities do not typically alter the actual valley geometry, they do commonly alter the effective valley geometry. Artificial levees, or flow regulation that reduces peak flows, for example, can reduce the width of the channel migration zone, disconnect the channel from its floodplain, and reduce habitat diversity in the floodplain (e.g., Larsen & Greco, 2002).

Substrate erosional resistance describes the ability of the river corridor substrate to resist erosional changes. Resistance derives from substrate composition (grain size, stratigraphy, bedrock lithology, and exposure; e.g., Finnegan et al., 2005) and from the presence of aquatic and riparian vegetation (e.g., Gurnell, 2014). Substrate erosional resistance can be modified by human activities, such as land drainage of the floodplain or stabilization of the channel bed and banks. The type and extent of vegetation can also

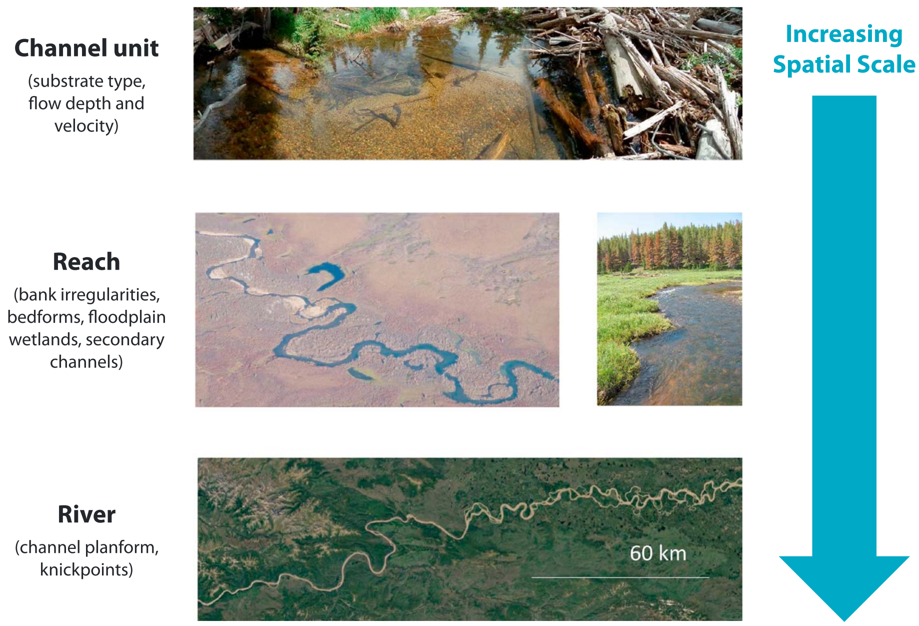

Figure 2. Spatial heterogeneity occurs at varying scales, from a single-channel unit such as a pool or bar; through a reach that is a length of river corridor with consistent form (typically 10^1–10^3 m in length, depending on the size of the river); to the entire length of a river or an entire river network.

be altered by human activities, causing substantial changes in erosional resistance (e.g., Dean & Schmidt, 2011; Griffin et al., 2005).

Base level stability influences river corridor configuration in that a river reach may be incising or aggrading irrespective of inputs of water, sediment, and wood because of base level instability (e.g., Merritts et al., 2011; Schumm, 1993). Base level in this context includes local base levels created by resistant bedrock outcrops (e.g., Berlin & Anderson, 2007) or large logjams (Larsen et al., 2016) and the ultimate base level of global sea level, as well as ongoing response to past base level change. Human alterations such as mining of aggregate from the channel (e.g., Kondolf, 1997) or construction of grade controls (e.g., Florsheim et al., 2001) can also affect base level stability.

2.3. The Characteristics of a River Ecosystem

The interactions between water, sediment, and large wood inputs and the valley context vary through time and space. Fundamentally, a river corridor is a dynamic system that can be characterized in terms of spatial heterogeneity, nonlinear behavior, connectivity, resilience, and integrity.

Spatial heterogeneity describes the physical diversity of the river corridor. One of the hallmarks of a natural river is that it typically exhibits greater spatial heterogeneity than a managed river. Spatial heterogeneity occurs at diverse spatial scales from a single-channel unit to an entire river network (Figure 2), and individual rivers can exhibit greater or lesser spatial heterogeneity (e.g., Fryirs & Brierley, 2009), but the details of spatial heterogeneity reflect the interaction of process and form in a river.

Spatial heterogeneity in a river corridor is important for several reasons (Wohl, 2016). First, heterogeneity is important because, in the form of habitat diversity, it can correlate with greater biomass of riverine organisms (Herdrich et al., 2018) and greater biodiversity (Bellmore & Baxter, 2014; Wyzga et al., 2012). Second, spatial heterogeneity influences downstream fluxes of water, solutes, sediment, particulate organic matter, and large wood. Heterogeneity can promote flow separation within the channel, hyporheic exchange flows, and overbank flows, all of which can enhance transient storage (e.g., Boano et al., 2014; Gooseff et al., 2007; Jeffries et al., 2003). Third, heterogeneity can increase the resistance of the river corridor to change and the resilience of the river corridor in recovering from change (e.g., Hood & Bayley, 2008). Finally, heterogeneity both reflects and influences processes in rivers. Channel mobility can strongly correlate with habitat diversity, for example (Choné & Biron, 2016), and heterogeneity of the channel in the form of bars and islands can influence retention of sediment and large wood (Wohl et al., 2018).

Nonlinear behavior occurs when outputs or responses are not proportional to inputs or stimuli (Favis-Mortlock, 2013; Phillips, 2003). Nonlinear behavior in rivers includes system changes that occur without external forcing, such as channels that alternately aggrade and incise through time in the absence of substantial changes in water and sediment inputs (Schumm & Hadley, 1957). Nonlinear behavior is also expressed as patterns that emerge spontaneously, such as when wood accumulation leads to channel-spanning logjams, which in turn give rise to anastomosing channel planform (Collins et al., 2012; Wohl, 2011). Nonlinear behavior is expressed as asynchronous and contrasting responses within a system, such as aggradation in the downstream portions of a river network and simultaneous incision in the upper portions of the river network (Schumm, 1973; Trimble, 2013). Finally, nonlinear behavior is reflected in the presence of thresholds and feedbacks, such as those that characterize the alternative states of a wet, spatially heterogeneous beaver meadow that attenuates downstream fluxes within a river corridor versus a relatively dry, homogeneous elk grassland (Polvi & Wohl, 2012; Wolf et al., 2007).

Connectivity describes the degree to which matter and organisms can move among spatially defined units such as the channel and hyporheic zone (Bracken et al., 2013, 2015; Cavalli et al., 2013; Cote et al., 2009). River connectivity is typically described in longitudinal (upstream-downstream), lateral (channel-floodplain, channel-uplands), and vertical (subsurface, surface, and atmosphere) dimensions within the river corridor and the watershed (Covino, 2017; Ward, 1989; Wohl, 2017). Connectivity exists on a continuum from fully connected to disconnected over diverse temporal and spatial scales and strongly influences the response of rivers to natural and human disturbances, as well as the attenuation of downstream fluxes of water, solutes, sediment, and wood (Wohl, 2017; Wohl, Brierley, et al., 2019; Wohl, Kramer, et al., 2019).

Resilience describes the persistence of the river ecosystem and the ability of populations and processes to return to predisturbance conditions (Gunderson et al., 2002; Holling, 1973). Physical scientists also use resilience or sensitivity to describe the ability of a river corridor to return to its predisturbance configuration following disturbance (Brunsden & Thornes, 1979; Fryirs, 2016; Reid & Brierley, 2015). A resilient river corridor returns to its predisturbance configuration and relationships over a shorter time than the return interval of the disturbance. A large flood, for example, can cause substantial erosion and deposition along a river corridor. If the flood-created features persist longer than the recurrence interval of a flood of that magnitude, the river is not resilient. If, however, subsequent smaller floods completely reconfigure the river corridor before another large flood, the river is resilient. A river that is not resilient can also be characterized as having alternative states if the disturbance creates a new, persistent river configuration (e.g., Bellmore et al., 2019).

Physical integrity for rivers refers to a set of active river processes and landforms such that the river corridor adjusts to changes in water and sediment inputs within limits of change defined by societal values (Graf, 2001). Ecological integrity describes the ability of the river corridor 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). These two forms of integrity can be folded into river integrity, which describes the ability of the river ecosystem to adjust to changing water, wood, and sediment inputs (without constraints imposed by human manipulation such as dams or levees) and through these adjustments to maintain the habitat, disturbance regime, and connectivity necessary to sustain native biotic communities.

In summary, a river corridor changes continually through time and space. These adjustments occur in response to either changing boundary conditions, such as inputs of water, sediment, and large wood, or changes in base level, or in response to internal thresholds and feedbacks. The characteristics of river corridor process and form can be described in dimensions of space (heterogeneity), time (nonlinear behavior and resilience), and the integration of space and time (connectivity and integrity).

3. Human Alterations of River Corridors

An extensive body of literature describes specific examples of human-altered river corridors and synthesizes case studies to describe recurrent scenarios (e.g., Elosegi & Sabater, 2013; James & Marcus, 2006; McCluney

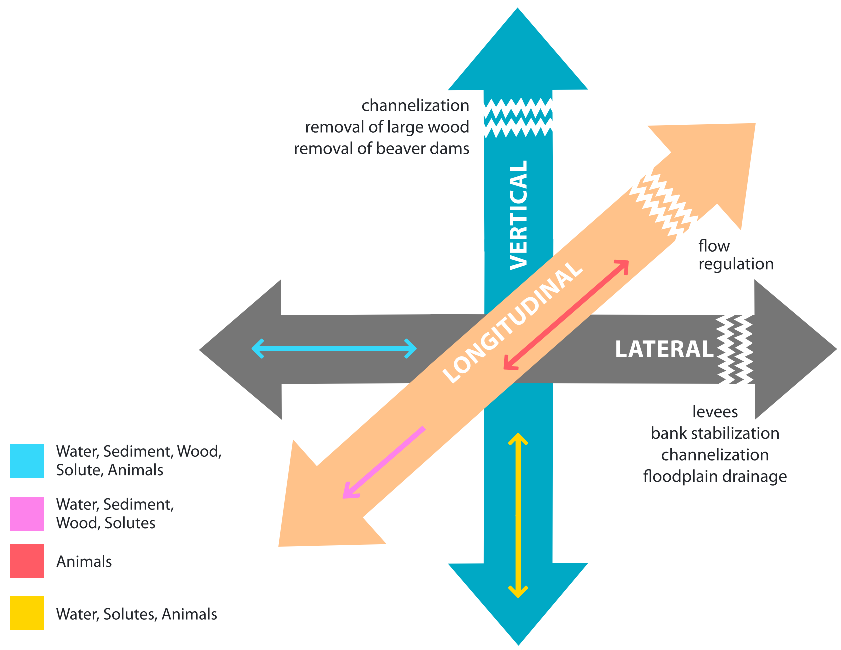

Figure 3. Schematic illustration of how human alterations (italicized font) of river corridors alter longitudinal, lateral, and vertical connectivity. Arrows on interior lines indicate directions of movement (e.g., organisms move up and downstream within a river network whereas water moves downstream). Arrows on wide bands are intended to emphasize the existence of at least some form of bidirectional movement in each of the major dimensions of connectivity.

et al., 2014; Meybeck, 2003). In much of the world, human alterations begin with changes in land cover outside the river corridor. Changing land cover alters water, sediment, and large wood yields to the river corridor, which commonly causes associated changes in river corridor process and form. A typical scenario is that increased sediment yield following clearing of native land cover causes river planform to change, as recorded in the stratigraphic records of river valleys from 7,000 years ago in China (Rosen, 2008) and southeastern Europe (Dotterweich, 2013; Lang & Bork, 2006) to circa 600 years ago in Poland (Latocha & Migon, 2006) and less than 200 years ago in parts of the United States (e.g., Trimble, 2013). Sometimes a subtler change, such as from one type of crop to another, also results in sufficiently large changes in water and sediment yield to transform river planform (Klimek, 1987). Reforestation following cessation of agriculture can reduce sediment yields and result in channel incision (Keesstra et al., 2005). Other common scenarios of human activities outside of the river corridor that alter inputs to the river include urbanization (e.g., Elmore & Kaushal, 2008; Meyer et al., 2005), altered topography (e.g., Bierman et al., 2005; Hooke & Martin-Duque, 2012), and, indirectly, climate change (Goode et al., 2012; Immerzeel et al., 2010; Kingsford, 2011).

Within the river corridor, humans fundamentally alter the fluxes and retention of water, sediment, and large wood by changing longitudinal, lateral, and vertical connectivity (Figure 3). Flow regulation by dams and diversions (Graf, 1999; Nilsson, Reidy, et al., 2005) decreases downstream (longitudinal) movement of water, sediment, and wood, whereas removal of stationary and mobile large wood from the channel and floodplain (e.g., Montgomery et al., 2003; Sedell & Froggatt, 1984; Wohl, 2014) and river corridor engineering facilitates downstream movements and limits retention within the river corridor (e.g., Fryirs, 2013; Kondolf et al., 2014). Bank stabilization, channelization, levee construction, and floodplain drainage reduce lateral connectivity between the channel and floodplain (e.g., Blanton & Marcus, 2009; Kondolf et al., 2006; Thoms, 2003) and limit the ability of the river corridor to adjust to fluctuating inputs (Graf, 2001). Instream obstructions such as large wood and beaver dams create pressure gradients that drive hyporheic exchange flows (Briggs et al., 2013; Sawyer et al., 2011). Channelization and removal of instream obstructions reduce vertical connectivity between surface environments and the hyporheic zone (Boulton, 2007).

At least four salient points arise from considering human alterations of process and form in river corridors. First, these alterations are nearly ubiquitous. Human-induced climate change affects every watershed on

Earth (e.g., Gosling & Arnell, 2016). More direct alterations such as flow regulation affect nearly every river basin in the temperate-zone latitudes (Nilsson, Reidy, et al., 2005), and the global effect of dams appears in significant alterations of water residence time within river basins (Vörösmarty et al., 1997) and the fluxes of sediment from rivers to the ocean (Syvitski & Kettner, 2011).

Second, human alterations of watersheds and river corridors have a very long history in some regions. Land clearing has affected water and sediment yields for 7,000 years in parts of Europe and Asia. The earliest known dam was built in Egypt circa 2800 BCE (Smith, 1971). Construction of artificial levees dates back 3,500 years in China (Clark, 1982) and 300 years in the eastern United States (Watson & Biedenharn, 2000). Channelization has been practiced in Europe since circa CE 1750 (Petts, 1989). Even in regions with a relatively short history of intensive human alterations of river corridors, these alterations have been of sufficient duration and intensity to fundamentally alter river corridor process and form (e.g., Brierley et al., 2005; Brooks et al., 2003; Collins et al., 2012; Walter & Merritts, 2008).

The third key aspect of human alterations of river corridors is the occurrence of multiple forms of human activities simultaneously or overlapping in time and space. Upland deforestation and mining during the latter half of the nineteenth century in the Southern Rockies of Colorado, for example, occurred synchronously with removal of large wood and beavers from river corridors, flow regulation, and alteration of floodplains via construction of roads and railroads (Wohl, 2001). Removal of wood and beaver from channels in the southeastern United States was essentially simultaneous with upland deforestation that caused aggradation in channels, burying mill dams and ponds along those channels and exacerbating overbank flooding. In some cases, the aggradation triggered valley incision; at other sites, people channelized the rivers in order to increase downstream conveyance of flood waters. All of these changes occurred within a timespan of less than a century (Ferguson, 1999; Jackson et al., 2005; Magilligan & Stamp, 1997; Sutter, 2015).

Finally, the effects of historical human alterations have in some cases been forgotten if the activity that triggered the alteration is no longer occurring (e.g., Phillips, 1997). Forgotten in this context refers to society as a whole. Most individuals born long after these human alterations never knew of the existence of the alterations, so these individuals cannot be said to have forgotten something. Undoubtedly, the most striking example from the past decade of societies forgetting their historical actions is the recognition of the legacy from thousands of mill dams in the U.S. Mid-Atlantic Piedmont region. As initially documented by Walter and Merritts (2008), many of the streams in the Piedmont were wide, shallow, marshy valleys with multiple shallow channels. As people of European descent began to use the landscape for agriculture starting in the late seventeenth century, they cleared upland vegetation, which increased sediment yields to river corridors. Settlers also channelized and dammed streams for water power. Tens of thousands of dams built on rivers throughout the region continued in operation until power began to be supplied by steam engines in the late nineteenth century. As mill ponds filled with legacy sediment from upland erosion, the original valley bottom was buried. In parts of the southeastern United States, some of the mill dams themselves may be buried by meters of sediment (Ferguson, 1997).

The presence of the mill dams was forgotten by society and unrecognized by river scientists, even though the eventual breaching of abandoned dams led to the formation of headcuts in the legacy sediment. The thick sequences of relatively fine legacy sediment overlying basal gravel and cobbles were interpreted as floodplain vertical accretion deposits (Wolman & Leopold, 1957). When increased sediment and nutrient yields to nearshore environments such as Chesapeake Bay were subsequently recognized as detrimental, restoration efforts initially focused on reducing sediment yields from uplands (e.g., Hassett et al., 2005). Increasing recognition of bank erosion of legacy sediment (e.g., Merritts et al., 2013; Pizzuto & O'Neal, 2009) was associated with changes in restoration practice, still ongoing, including efforts to remove millpond sediment in order to restore wetland valley bottoms (Forshay & Mayer, 2012; Hartranft et al., 2011; Merritts et al., 2011). Restoration of wetland valley bottoms has also been applied elsewhere (Booth et al., 2009). Documentation of the presence and continuing legacy of mill dams represents a fundamental shift in how river scientists and resource managers conceptualize landscapes and river corridors in the Mid-Atlantic Piedmont and other river networks in which mill dams were formerly abundant.

A similar scenario occurred in the Pacific Northwest region of North America starting in the late 1970s as river scientists gradually recognized how much more abundant large wood had been in river corridors prior to intensive deforestation and river engineering starting approximately 150 years ago (e.g., Collins et al., 2002, 2003, 2012; Keller & Swanson, 1979; Sedell & Froggatt, 1984). Deforestation removed trees from the uplands and the river corridor, resulting in reduced potential for continuing recruitment of large wood to the river corridor via natural processes of individual treefall, mass mortality, and hillslope failure (Maser & Sedell, 1994). Downed large wood within channels was also commonly removed as part of *stream cleaning* during and after timber harvest (Sedell et al., 1991). Where log floating was used to transport timber to sawmills, the river corridor was modified to facilitate more efficient downstream transport of wood. Modifications included construction of splash dams that were dynamited to send a concentrated and highly erosive pulse of water and timber downstream (Miller, 2010). Along some river segments, the entrance to secondary channels or overbank areas was blocked to increase efficiency of downstream transport of cut logs (Sedell et al., 1991) and naturally occurring obstructions such as large boulders and stable wood were removed from channels (Sedell et al., 1991). Similar modifications of the river corridor associated with timber harvest and log floating have been described for other forested regions, including parts of Sweden (Nilsson, Lepori, et al., 2005; Tornlund & Ostlund, 2002) and the Great Lake States (Wohl, 2014), Appalachians (Coy et al., 1992), and Rocky Mountains (Ruffing et al., 2015; Young et al., 1994) in the United States.

Documentation of the effects of wood removal created a context for understanding how formerly anastomosing or braided rivers with spatially heterogeneous floodplains had transformed to single-channel planforms with less lateral connectivity and more homogeneous floodplains (Collins et al., 2002, 2012). Analogous examples of river metamorphosis as a result of changes in riparian vegetation, large wood, and channelization come from Australia (Brierley et al., 2005), central Europe (Pišút, 2002), and the southeastern United States (Phillips & Park, 2009; Triska, 1984). As understanding has grown of the integral role of large wood in forested river corridors, river management and restoration increasingly emphasize protecting and actively restoring downed wood in channels and on floodplains (USBR and ERDC (Bureau of Reclamation and U.S. Army Engineer Research and Development Center), 2016). As with mill dam legacy sediment, this represents a fundamental shift in thinking about large wood after centuries of aggressively removing wood.

In each of these regional examples, recognition of the continuing effects of a historical human alteration came as something of a revelation to river scientists, changing the way in which scientists conceptualize river process and form in the region or in a particular type of river corridor. There is no reason to assume that analogous revelations will not occur in future.

4. Watershed- to Global-Scale Implications of Human Alterations

At the most general level, human activities have significantly changed watershed- to global-scale retention of water, sediment, and large wood in uplands and fluxes of these materials *to* river corridors. By altering river corridor form and regulating fluxes *within* river networks, human activities have also significantly changed retention and fluxes within river corridors. Associated with these alterations have been reductions in spatial heterogeneity within river corridors (Peipoch et al., 2015) and lateral mobility of river channels that promotes heterogeneity and lateral connectivity (Florsheim et al., 2008). Temporal and spatial fluctuations in water, sediment, and large wood fluxes have been reduced (Poff et al., 2007; Wohl et al., 2015), and longitudinal, lateral, and vertical connectivity within river corridors have commonly declined (Kondolf et al., 2006; Ward & Stanford, 1995). These changes have simplified and homogenized river corridors, with a loss of habitat abundance and diversity (Peipoch et al., 2015), decreasing water quality (Erisman et al., 2013), and rates of extinction for freshwater organisms that are much higher than rates for terrestrial organisms (Ricciardi & Rasmussen, 1999).

The ubiquity and long history of human alterations can be conceptualized as a cascade of legacies (Figure 4). At the watershed scale, we have predominantly increased water fluxes and decreased water retention—apart from reservoir storage—by decreasing infiltration and disconnecting, draining, or filling wetlands, including floodplain wetlands (e.g., Sterling et al., 2012; Vileisis, 1999). Altered land cover and topography have significantly increased sediment fluxes to river corridors (Syvitski et al., 2005). Sediment retention within naturally occurring depositional sites in river corridors (floodplains, alluvial fans, and deltas) has been reduced via channelization and dams, but sediment retention within reservoirs has dramatically increased, creating a net increase in sediment retention within river corridors (Syvitski et al., 2005; Wohl et al., 2015). Deforestation and hillslope stabilization have decreased fluxes of large wood to river corridors, and flow

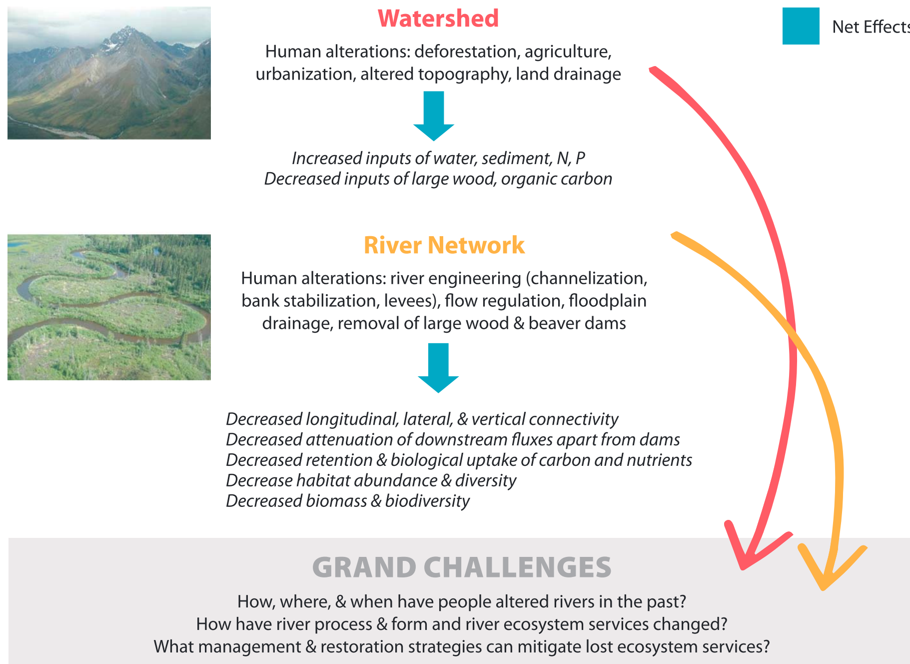

Figure 4. The cascade of human legacy effects on river corridors, starting with alterations outside of the river corridor that affect inputs to the river and continuing with alterations within the river corridor that affect process and form. These alterations give rise to the grand challenges listed at the bottom of the figure.

regulation, river engineering, and active wood removal have decreased fluxes and retention of wood within river corridors (Montgomery et al., 2003; Wohl, 2014). Along with these changes to the primary drivers of river corridor process and form have come increased nutrient (N, P) and carbon fluxes to rivers and decreased retention and biological uptake within river corridors because of lower spatial heterogeneity and associated natural attenuation of downstream fluxes of solutes (Battin et al., 2008; Ranalli & Macalady, 2010). Organic carbon fluxes to river corridors have likely decreased, but retention and biological uptake within river corridors, apart from reservoir storage, have likely decreased even more, creating increased gaseous emissions and riverine transport of organic carbon to the oceans (Bauer et al., 2013; Butman et al., 2015; Raymond et al., 2008; Wohl et al., 2017).

Although several high-profile papers have promoted recognition of the cumulative global effects of human alterations (e.g., Foley et al., 2005; Steffen et al., 2015), individual investigators have arguably not fully integrated the implications of human alterations into their thinking when conceptualizing research designs for specific watersheds. The default assumption is still commonly that, outside of urban areas or obviously altered river corridors such as channelized reaches or those with regulated flow, conditions are relatively natural or at least reflect predominantly natural processes. I have seen this in proposals to examine downstream changes in grain size and channel geometry in rivers with extensive flow regulation and roads within laterally confined river corridors. In these river corridors, flow regulation changes available flow energy and transport capacity, and roads change river corridor geometry and substrate erosional resistance, so that downstream trends are likely to be strongly influenced by human alterations. Analogously, I have reviewed proposals to quantify downstream changes in wood load in river corridors with historic riparian timber harvest and removal of wood from the channel. Even though the forest has regrown and wood has not been actively removed for a few decades, the lag time for the river corridor to return to the natural range of variability is likely at least two centuries (Bragg, 2000; Stout et al., 2018). Of particular importance, contemporary measurements and numerical simulations of processes such as nitrogen dynamics at the watershed scale or river network scale are commonly based on scaling up from reach-scale measurements. This approach can result in misleading interpretations of the role of differently sized rivers if the measurements come from locations where decades to centuries of human alteration have significantly reduced spatial heterogeneity, connectivity, and retention in rivers (e.g., Helton et al., 2011; Wollheim et al., 2015).

Ignoring the presence and continuing effects of historical and contemporary human alterations of watersheds can lead to fundamental misinterpretations of river process and form, analogous to the interpretation of mill dam legacy sediments as floodplain vertical accretion deposits. If we start with a misperception of the dynamic character or natural form of a river, we underestimate the potential of that river and may develop less effective management targets (such as emphasizing stabilization of upland rather than stream-bank sediment sources in the Mid-Atlantic Piedmont example).

5. Grand Challenges

The grand challenges resulting from historical human alterations of river corridors are fourfold. The first challenge is to recognize the presence of a legacy in the form of historical human alteration(s) that continues to influence the river corridor. The second challenge is to understand the source of the legacy in terms of the chronology of changes, the type of human alteration, and the extent and intensity of alterations. The third challenge is to understand the implications of the legacy: How have process and form changed within the river corridor and how has this affected river functionality or ecosystem services? Is the legacy continuing to alter form and process? The fourth grand challenge is to design management or restoration strategies that can mitigate the loss of river functionality or ecosystem services.

Understanding the source and implications of a legacy can be extremely difficult in a region in which all watersheds have experienced centuries of human influences. Reference sites, defined as watersheds or reaches of a river corridor with minimal human alteration, become invaluable in this context. Although existing resource use and population density may make it impossible to completely restore reference conditions at an altered site, knowledge of reference conditions and the natural range of variability from historical (Pastore et al., 2010) and geological (Rathburn et al., 2013; Willis & Birks, 2006) archives provides critical insight for river management. Natural range of variability here refers to the conditions of a natural system prior to intensive human alteration of that system (e.g., Fryirs et al., 2012; Morgan et al., 1994; Richter et al., 1997). For example, knowledge of reference conditions and trajectories of change through time can be used to constrain effective management options (Brierley & Fryirs, 2016). A well-documented example of failure to use such knowledge comes from a river restoration project at Uvas Creek in California (Kondolf et al., 2001). A meandering channel form fixed in place with bank stabilization was completed at the site in November 1995. In February 1996 a flood with an estimated 5- to 6-year recurrence interval completely reconfigured the channel to a braided planform. Analysis of historical maps and aerial photographs indicates that Uvas Creek repeatedly alternates between braided and meandering planforms over timescales of a few decades, a nonlinear behavior common to rivers in drylands (e.g., Friedman & Lee, 2002; Graf, 1983; Tooth, 2000). The ability to forecast likely trajectories of response for river process and form in response to natural disturbance or human alterations is greatly strengthened by understanding the inputs, history, and valley context of the river corridor (e.g., Brierley & Fryirs, 2005, 2016).

Ruddiman (2012) argues that physical and biological scientists need to incorporate the knowledge of past human activities developed by disciplines such as history and archeology. I also argue that all scientific disciplines could be more effective at communicating their understanding of past and contemporary landscapes and river corridors to society as a whole, including those members of society—from individual citizens and nongovernmental organizations advocating and practicing river restoration to regulatory agencies—influencing policy that affects rivers.

River corridor process and form are most appropriately characterized as exhibiting nonlinear behavior, in which outputs are not proportional to inputs across the entire range of the inputs (Phillips, 2003). Evidence of nonlinearities come from documented patterns of hysteresis in suspended and bedload sediment (Lenzi & Marchi, 2000; Mao et al., 2014; Moog & Whiting, 1998) and large wood (Kramer & Wohl, 2017; MacVicar & Piégay, 2012) transport, as well as changes in water-sediment and water-wood discharge relations with time since the last large flood (Kramer et al., 2017). Thresholds govern changes in channel cross-sectional geometry (e.g., Howard & Kerby, 1983) and planform (Schumm, 1985), as well as inputs of water (Tromp-van Meerveld & McDonnell, 2006), sediment (e.g., Korup et al., 2004), and large wood (Wohl & Ogden, 2013) to the river corridor at timescales of a single storm to decades. Alternative states characterize river corridors at timescales of decades to centuries (Collins et al., 2012; Heffernan, 2008; Livers et al., 2018). These nonlinear behaviors can be observed in highly managed river corridors, but insight into the controls on thresholds and nonlinearities may be most effectively obtained based on reference conditions, as in the three studies cited earlier in the context of alternative states. Each of these studies relied on historical information on river corridor process and form prior to intensive human alteration to demonstrate that contemporary river corridors had functioned very differently in the historical past.

Another example of the type of insight that can be gained from knowledge of reference conditions is the physical context that sustains native biota. Aquatic and riparian species can reach threatened or endangered status for numerous reasons, including competition from introduced species, loss of food resources, and contamination, but a key stressor for many at-risk species is loss of habitat abundance and diversity because of altered process and form in river corridors (Hoagstrom, 2015). Ecologists typically cannot predict the habitat, food, and dispersal requirements of each species at all life stages of an organism without actually studying the species in a natural environment. Insights into habitat requirements gained from such studies under reference conditions can help river management target critical components of habitat that must be protected or restored in altered river corridors, such as a minimum duration of overbank flooding for successful fish spawning and rearing (Galat et al., 1998) or a threshold magnitude and frequency of flow to distribute plant propagules downstream and create new germination sites along the channel banks (Merritt et al., 2010; Nilsson & Berggren, 2000). Although native species are adaptable to some degree, native biota have usually adapted to the natural range of variability within a river corridor and deviating too far from this range can lead to extinction (e.g., Bisson et al., 2009; Perkin et al., 2015). Consequently, it remains important to not *forget natural* (Dufour & Piégay, 2009), but rather to use knowledge of natural range of variability, as indicated by reference conditions, to understand present and potential future river process and form.

The fourth grand challenge is how to incorporate knowledge of natural conditions and human alterations into river management. One approach is to quantify response curves that describe how water discharge, for example, interacts with valley geometry to create spatial and temporal patterns of flow depth, velocity, and shear stress that govern habitat availability for fish (King & Brown, 2010). The underlying assumption is that valley geometry is essentially static and is, along with water supply, the primary driver of habitat. In reality, of course, water supply and valley geometry fluctuate with time, and other variables such as sediment supply and the abundance and distribution of large wood and living vegetation may exert critical influences on habitat. Although multiple response curves can be combined using Decision Support Software to generate first-order, watershed-scale predictions of how habitat might change in response to changes in discharge (King et al., 2003), this remains a broad-brush technique.

Another approach to river management is to maintain or restore characteristics of the river corridor that create a desired process. This underlies the restoration of riparian vegetation as a buffer to retain upland inputs to the river corridor of nitrogen, phosphorus, and fine sediment, or the development of environmental flows to restore physical variability such as erosion and deposition through time, or lateral connectivity by inundating floodplains. One of the key uncertainties in this approach is how much and how long? How spatially extensive must the riparian buffers be to effectively mitigate significantly increased upland inputs (e.g., Bernhardt & Palmer, 2011)? How large and of what duration must peak flow be to adequately inundate the floodplain? Response curves can help to answer the question of how much, but we need to improve our ability to integrate bivariate response curves in order to better simulate the reality of multivariate river corridors.

A third approach to river management is to create a template of river corridor form that will facilitate desired processes. Examples include the emplacement of engineered logjams (Gallisdorfer et al., 2014; Roni et al., 2014) or beaver dam analogs (Bouwes et al., 2016), which are structures designed to mimic the form and function of natural features. This type of river corridor engineering can extend to setting back or notching levees in order to restore channel-floodplain connectivity (Florsheim & Mount, 2002), reconfiguring the river planform to enhance habitat (Murphy et al., 2004; Theiling et al., 2015), or removing artificial barriers in order to allow high flows to return to abandoned channels or cutoff meanders (Anderson, 2014; Nilsson, Lepori, et al., 2005). As with the other approaches to river management, understanding of river process and form prior to human alteration can inform decisions about the nature of the template being created.

Each of these examples of river management designed to restore process and form has advantages and limitations, but all of them rely on insight into how human activities have modified the river corridor and how management can mitigate some of the negative consequences of past modifications. Undoubtedly, the

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Figure 5. Slabcamp Creek, Daniel Boone National Forest, Kentucky, USA, before (upper photo) and after restoration. Photographs courtesy of Arthur Parola.

greatest challenge occurs when we mistake human altered for natural and thus cannot begin to think about alternative management strategies that can restore some aspects of natural river process and form.

6. Legacies and Perceptions

Matilde Welber (University of Trento, personal communication, 2018) described to me an outreach exercise in which sixth- to eighth-grade children from different locations in northern Italy were given access to a stream table after a short lesson about river habitat and channel changes during floods. Welber and her colleague Walter Bertoldi created an initial straight or sinuous trapezoidal channel and let the channel evolve into a braided planform over the next few minutes. The children were then asked what they could see, where they wanted to live (the children were given model houses to place in the stream table), and where they expected plants to grow (the children were given plastic shrubs). Children who lived near the field protocol for the exercise (the Tagliamento River) were very familiar with a braided planform and placed vegetation on the emerging portions of bars as well as the margins of the braid plain, in a manner that mimicked actual vegetation establishment. When the exercise was repeated at a science fair in the city of Trento, where piedmont rivers are regulated and bound by artificial levees and small mountain streams have numerous check dams, the children were unfamiliar with the braided planform and planted shrubs exclusively on the floodplain.

This anecdote emphasizes the critical importance of perception and experience in governing our understanding of the natural world. What we see is what we understand to be normal and therefore what we expect to see. In this context, fully natural river corridors can strike some people as dangerous, unnatural, and in need of restoration and management, as illustrated by studies of public perceptions of large wood (Chin et al., 2008; Piégay et al., 2005) and braided rivers (le Lay et al., 2013). Analogously, a river corridor that has been heavily modified by humans may be perceived as natural and fully functional with respect to ecosystem services such as habitat. We are unlikely to recognize something we do not think to look for, and this is the greatest obstacle to understanding forgotten legacies of human alterations in river corridors.

Another example of the importance of perception is illustrated by challenges to some forms of river restoration in parts of the U.S. Appalachians. Arthur Parola of the University of Louisville (personal communication, 2019) has implemented restorations that removed legacy sediments from mountainous stream valleys, uncovering an organic-rich soil layer and a seedbank of highly diverse wetland plants but no signs of large trees (Figure 5). This stratigraphic and botanical evidence suggests that prior to nineteenth century deforestation, these valley bottoms were likely a complex of multichannel systems through wetlands and beaver ponds, highly retentive of organic carbon, sediment, and water. Parola's use of this conceptual reference as a basis for river restoration, however, has met with resistance. Even regulators who are enthusiastic about restoring these systems are constrained by policies created to protect existing habitat. These policies measure the quality and value of existing resources with assessment tools that do not account for legacy effects. Streams are considered to be natural and high functioning if they have a forested riparian zone, moderately stable banks and substrate, good water quality, and high macroinvertebrate indices. Therefore, restoration designs are expected to have physical characteristics similar to those of these reference streams. For example, trees must shade the channel and provide a forested riparian corridor. The stream channel geometry must be single thread and remain very similar to its constructed configuration. The stream should inundate its floodplain about every 1.5 years and not be obstructed by beaver dams, and it should transport organic matter and sediment supply to downstream waters rather than retaining them. Because these and other regulatory concepts of natural functions were developed based on contemporary streams rather than those that existed prior to intensive disturbance by humans, they limit the possibility for restoration of many lost ecosystem functions and they leave little room for restoration of marshy systems with multiple shallow channels and beaver.

This example illustrates how the existence of forgotten legacies poses scientific challenges for river scientists and also poses challenges to the application of scientific understanding in regulatory and societal contexts. Scientific understanding of rivers as dynamic, spatially heterogeneous, nonlinear ecosystems—messy, changeable places—is commonly fundamentally different than societal expectations for, or perceptions of, rivers. This difference is reflected in calls to *clean up the river* and *put the river back in its place* following major floods, and in river restoration projects that tend to emphasize esthetically pleasing river forms rather than processes that sustain river ecosystems (Bernhardt et al., 2005).

Reviewing flow restoration and protection in Australian rivers, Arthington and Pusey (2003) asked the basic questions of *How much water does a river need? and How can this water be clawed back from other users?* (p. 378). As global human population continues to grow and becomes ever more urbanized, these questions can be broadened to, How much space and how much water, sediment, and wood does a river need? and How can this space and these inputs be reclaimed from human users? Phrased differently, at what point in the downward spiral of river engineering, damage from natural hazards such as floods, and loss of ecosystem services do we completely re-envision possibilities and move people and infrastructure out of the river corridor (e.g., Perry & Lindell, 1997)? Effectively addressing any of these questions requires that we understand how past human activities have modified river corridor process and form, as well as how those past alterations constrain river science and management going forward.

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