Chapter 3
River Morphology, Channelization, and Habitat Restoration

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3.1 River Channels as One Piece in the Puzzle

Authorities and planners involved in river restoration projects often tend to focus on the hydromorphological state of a short river reach or certain aquatic habitats where the pending deficits are most evident. Nevertheless, for long-term and sustainable restoration, one should also consider flood dynamics and other interlinked processes at larger spatiotemporal scales, ideally at the catchment scale. Moreover, restoring river morphology also calls for the consideration of the dynamic processes of the whole fluvial system, including the adjacent floodplains, with its diverse interactions between the physical environment (morphology, flow, sediment, etc.) and the riverine coenoses (compare EU Water Framework Directive 2000).

Various concepts in river morphology and ecology address fluvial systems as hierarchical arrangements that integrate typical geomorphic and ecological features over a range of spatial scales. Such well-established schemes are, e.g., the Hierarchical Framework of Stream Habitats (Frissell et al. 1986), the Hydrosystem Approach (Petts and Amoros 1996), the Hierarchical Patch Dynamics Model (Wu and Loucks 1995), the River-Scaling Concept (Habersack 2000), or the Riverine Ecosystem Synthesis (Thorp et al. 2006). They have in common that riverine structures at the local scale are viewed as habitats nested in larger systems at reach scale or catchment scale.

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According to the River Styles Framework, introduced by Brierley et al. (2002), an organism existing in a local habitat is exposed to controls and biophysical fluxes associated with larger spatial entities. These entities exist as a nested hierarchy that builds up from "hydraulic units" as the smallest up to larger "geomorphic units", "river reaches" and "landscape units" and, finally, up to the catchment and ecoregion as the largest spatial scales. These fluvial features can be seen as physical templates that provide the setting in which ecological processes operate and shape riverine coenoses.

Focusing on the ecological functions and the associated biocoenoses of these different spatial entities, aquatic ecologists generally apply the terms micro-, meso-, or macrohabitats. Confusingly, to date, no consistent definition exists that includes both the geomorphological and the ecological perspectives. A microhabitat, roughly corresponding to "hydraulic units," refers to a particular site used by an individual for specific behaviors (e.g., spawning). It can be described by a combination of distinct hydraulic and physical factors such as flow velocity, depth, substrate type, and vegetation cover. Depending on the species (fish, invertebrates, macrophytes, algae, etc.) and the life stage, microhabitats may range from near zero to a few meters. Mesohabitats, typically encountered at the scale of "hydraulic" and "geomorphic units," denote discrete patches of a river channel defined by similar physical characteristics. Such habitats include shallow riffles, deep pools, runs showing high flow velocities, or sediment bars. Depending on the river type, mesohabitats commonly extend over a few square meters but may also cover some hundreds of square meters. While microhabitats refer to sites of individual organisms, mesohabitats can be seen as the area, where aquatic communities and/or specific life stages with similar habitat requirements live (spawning sites, juveniles, adults, etc.). Macrohabitats, spatially best associated with "geomorphic units" or river reaches, typically comprise several mesohabitats shaped by the particular hydromorphological conditions of the respective river reach, branch, or water body (e.g., lotic main channel of an anabranched river, lentic one-side connected backwater, stagnant dead arm). Accordingly, longitudinal continuity and lateral hydrological connectivity and, thus, the distribution and migration possibilities of aquatic organisms are key features for defining macrohabitats.

The different fluvial features—or habitats from the ecological point of view—including those in the adjacent floodplains, undergo permanent hydromorphological and ecological changes owing to influences and fluxes, such as flow and sediments, from the reach or catchment scale. Such adaptive processes of riverine features at a certain spatial scale are also pertinent to specific time scales. The evolution of a new river terrace, for example, usually encompasses longer time spans than the formation of a gravel bar. In many cases, the consequences of physical modifications on the fluvial system are not immediately apparent. Rather, they depend on system-inherent thresholds of response and manifold legacy effects.

Understanding the complex spatiotemporal nature of river landscapes is an essential prerequisite for sustainable and integrative river restoration. However, under daily pressure to balance short-term demands with scarce financial means, the consideration of such complex process-response systems is a challenging task for planners and authorities as well (see Chaps. 15 and 16).

3.2 River Types: Complex Diversity or Confusing Variety?

River systems in the industrialized world today have largely lost their original characteristics. Primarily evident is the disappearance of channel patterns of preindustrial rivers. Such patterns range from deeply incised bedrock channels (gorges) in the headwaters to alluvial anastomosing rivers in the lowlands close to the estuary. Over decades, a confusing number of river classification schemes have been developed to address the various river types from scientific, administrative, or restoration perspectives. In addition, even the terms used to describe specific river types are not applied in a consistent manner in scientific literature. For example, the terms "braiding", "anabranching" or "anastomosing" are sometimes used in a broader sense to describe rivers that show bifurcations in general and in a closer sense in order to explicitly address certain channel styles (Kondolf et al. 2003; Eaton et al. 2010).

Generally, the various classification systems can be distinguished between form-based and process-based schemes. In the first case, rivers are categorized by means of several channel characteristics, such as sinuosity, number of braids, typical forms of cross sections, width-depth ratios, type of substrate, channel slope, etc. (e.g., classification according to Rosgen 1994, 1996). Such descriptive schemes can be used to characterize a channel system in detail; however, it does not provide much information about the underlying fluvial processes, neglects the history of the landscape system, and is of limited value in predicting future channel changes. Accordingly, from the perspective of river management, so-called process-based classification schemes are more useful. They offer a useful framework for assessing potential channel dynamics based on how current forms are shaped by controlling geomorphic processes (e.g., Schumm et al. 1984; Church 1992; Simon et al. 2007). Here, quantitative empirical models provide the best foundation to analyze river forms and to assess the adequacy of management strategies. Based on the early work of Leopold and Wolman (1957), meanwhile, numerous classification systems have emerged that extended our understanding about the relationship between fluvial forms and geomorphic processes. Most schemes are based on critical thresholds with respect to discharge and channel slope (i.e., stream power), sediment volume, and median grain size (see Chap. 8). Other schemes also include bank resistance, the influence of riparian vegetation, and more complex control factors (e.g., Osterkamp 1978; Ferguson 1987; Van den Berg 1995; Yalin and da Silva 2001). The classification of rivers as straight, meandering, and braided originally introduced by Leopold and Wolman (1957) has therefore been substantially expanded.

Today, we understand the complex morphological diversity of rivers as a continuum of fluvial patterns that evolved as a consequence of the given boundary conditions, such as upstream catchment size and its vegetation cover, lateral valley confinement, valley slope, flow regime and sediment type, and transport of material. Channel geometry, patterns, and dimensions reflect the ongoing adjustment to fluctuating flow and sediment yields (bedload/suspended load) and, consequently, the balance of erosional and depositional processes. Here, the concept of stream
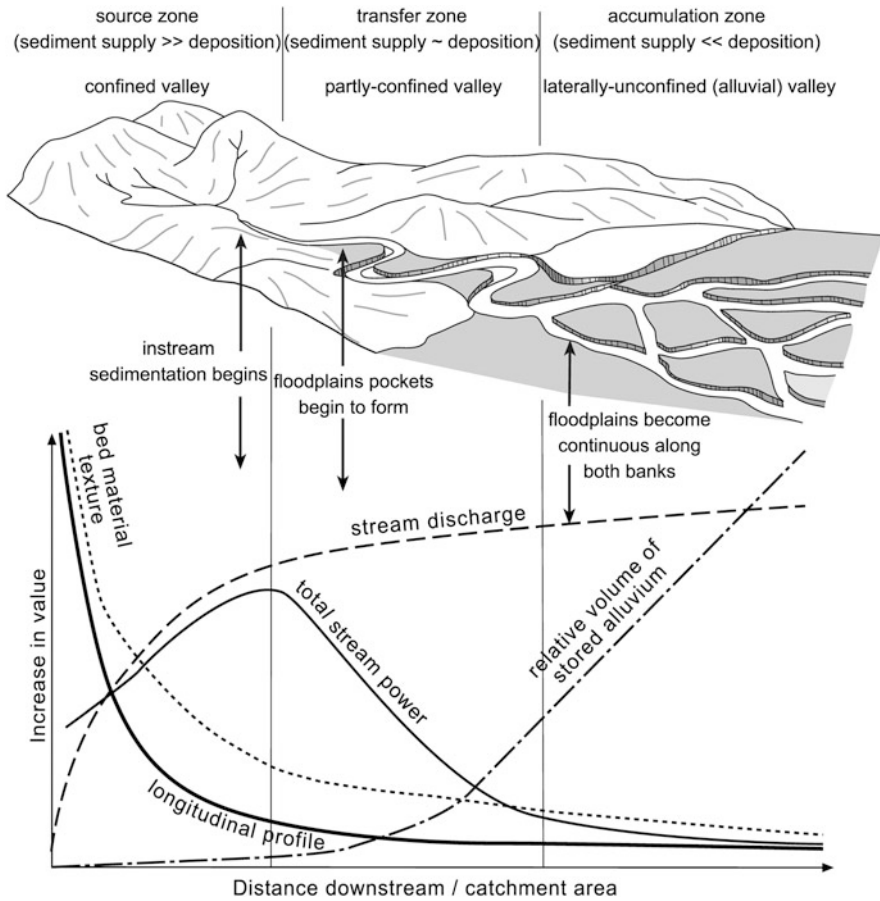
Fig. 3.1 Channel controlling factors and channel characteristics along a schematic river course (source: © 2013 by Kirstie A. Fryirs and Gary J. Brierley; reproduced with the permission of John Wiley & Sons)

power, the product of discharge and channel slope, provides a useful tool to describe the capacity of a river to mobilize and transport material. Comparing stream power and sediment load combined with sediment size helps to identify potential channel adjustments (compare Lane 1954; see Chap. 8).

In an ideal world, the hereinafter described typical sequence of channel patterns (river types) would be identified along a river's course from up- to downstream depending on the abovementioned channel controls (compare Figs. 3.1 and 3.2). In reality, depending on the individual geomorphological setting, rivers may also develop channel forms in mountainous regions that typically would be expected along their lower courses.

In alpine or mountainous headwaters, bedrock-confined rivers that have to follow a narrow and steep valley floor are typical. Stepped-bed profiles with cascades and
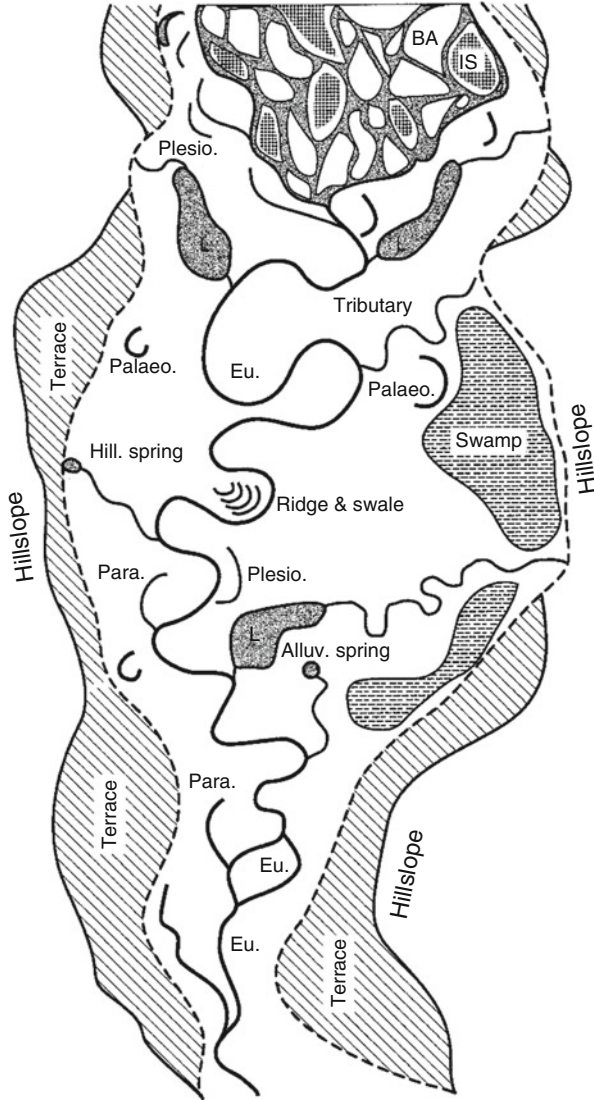
Fig. 3.2 Basic geomorphological features of an idealized river corridor and surface water bodies showing different intensities of hydrological connectivity: *Eu* eupotamal/eurhithral (main channel and lotic side arms), *Para* parapotamal/pararhithral (abandoned braids), *Plesio* plesiopotamal/ plesiorhithral (dead arms close to the main channel), *Palaeo* palaeopotamal/palaeorhithral ("oxbow lakes"—abandoned meander bends remote from the main channel), *L* lateral or riparian lake, *BA* bar, *IS* vegetated island (Based on Amoros et al. 1987; modified according to Ward et al. 2000)

pools in combination with coarse sediment load up to the size of boulders are characteristic elements of such rivers. Denudation processes, gully erosion, and channel incisions prevail, and, accordingly, the steep headwaters can be referred to as the sediment supply zones of river systems. In broader valleys, braided rivers carrying coarse gravel may stretch over the whole valley floor. Flashy flow regimes combined with an excess of bedload provide the pulsing power and material to build such river types. Bar-braided rivers almost devoid of vegetated islands indicate a predominance of turnover processes. In island-braided rivers, fluvial dynamics enable at least the evolution of small, vegetated islands on temporally stable gravel bars. As the valley widens and the valley sides do not yet confine the whole river section, small floodplain pockets begin to form. Because discharge increases progressively with catchment area, total stream power typically peaks along a river course in that section downstream of the headwaters where sufficient flow acts on sufficiently steep slopes (Brierley and Fryirs 2005). Here, the upstream zone, characterized by prevailing sediment supply, commonly passes into the sediment transfer zone, where erosional and depositional processes are approximately balanced. If the transport capacity of the river is sufficient or in case of reduced bedload input, e.g., due to a low relief landscape that is tectonically stable, less braided or even sinuous channels may evolve that oscillate between both sides of the valley. Today, such channel patterns are widespread in alpine valleys. However, in most cases, they are products of channelization programs in the nineteenth or early twentieth century.

Further downstream, where the valley bottom significantly widens or the river course enters spacious alluvial plains, we usually find fluvial forms that probably refer to the most common river type worldwide. These show an extraordinary morphological diversity: anabranching rivers (Huang and Nanson 2007). They range from dynamic high- and medium-energy rivers to low-energy systems dominated by accumulation processes. Such river types can be considered as transition forms between braiding and meandering rivers, because they feature characteristics of both. Wandering gravel-bed rivers, as the high-energy variant of anabranching rivers, are mostly located along the sediment transfer zone and may constitute the beginning of the sediment accumulation zone, where the coarse bedload is deposited (Desloges and Church 1987). They usually exhibit a complex channel network with one or two dominant bar-braided or island-braided arms. Individual branches are separated by larger vegetated islands that may show the same terrain elevation as the adjacent floodplain and, thus, divide the flow up to the bankfull stage. Individual channels show independent patterns and may meander, braid, or remain relatively straight (Nanson and Knighton 1996). Wandering gravel-bed rivers are characterized by intensive lateral and vertical turnover processes, driven by a highly variable flow regime and high loads of coarse bed material. Large woody debris or ice jams that block flow and back water up in individual river arms contribute to the fluvial dynamics. Extreme flows can ram accumulations of such materials through river arms and channels, shaping them as they tear off vegetation and substrate. Channel avulsions, the rapid formation of new river arms by incisions in the floodplain terrain, intersecting larger islands, or reclaiming abandoned arms are typical geomorphic processes.

In downstream sections located already in the sediment accumulation zone, anabranching rivers with mixed loads or sand beds emerge. The substrate of the riverbed and, accordingly, channel patterns are closely interlinked with the geological configuration of the respective reach and the sediment load of large tributaries, especially where they meet, e.g., confluences. Deposition of suspended material starts as channel flow slows with decreasing slope and material accumulated in the current hits critical thresholds. This favors the formation of cohesive riverbanks, which facilitates the development of typical meandering rivers. Such systems show a higher bank resistance, and channels primarily migrate laterally or shift downstream. To distinguish between mildly (sinuous) and sharply curving (meandering) rivers, many authors apply a sinuosity index of more than 1.3 or 1.5 (Schumm 1977; Thorne 1997). The sinuosity index indicates the ratio (quotient) between the length of a river course and that of the valley axis or, sometimes instead of the latter, the linear distance between the upper end and lower end. Once the meander bends become too tortuous and shift close to each other, they are cut off, and a new straighter channel emerges, while the former meander loop remains as a an "oxbow lake" (compare "Palaeopotamon" in Fig. 3.2). Meandering rivers still feature flow velocities, i.e., shear stress, that accommodate the formation of distinct river arms and lateral channel adjustments to instream aggradations. The lower the channel slope, the more instream accretion will occur, and the capability of a river to adapt to these deposition processes will be reduced. Under such conditions, a specific low-energy variant of anabranching channel patterns, so-called anastomosing rivers, with very low gradients and stream power associated with stable cohesive banks, will emerge (Knighton and Nanson 1993). Their individual channels are often sinuous and exhibit almost no lateral migration. However, anastomosing channels have insufficient energy relative to bank strength to allow adjustments to instream deposition of mostly suspended material; hence avulsion is more likely to occur. Flooding overtops riverbanks and builds floodplains by vertical accretion of cohesive fine-grained material. The deposits are typically rich in organic material (Nanson and Knighton 1996). Though anastomosing rivers are typical features of the sediment accumulation zone close to the estuary, they can also emerge further upstream in river sections that are wider and unconfined as a consequence of tectonic depressions where the channel gradient and stream power are significantly reduced (compare Fig. 3.2 at the upper margin).

River deltas or estuaries feature environments very different from the rest of the river system. Transport capacity finally is disrupted, and sediment deposition generally constitutes the principal formative process. Delta areas are transition zones between riverine and maritime environments. They reflect structuring influences from both the ocean, such as waves, tides, and saltwater influx, and the river, such as discharge of freshwater and fluvial sediments. Because sea level provides the ultimate base level of the whole fluvial system, the channel gradient of the upstream river section—and over the long term that of the entire channel network—is directly tied to the elevation of the sea.

The described general framework of morphological river types would be only encountered along an ideal longitudinal profile that shows a concave shape with a

steep upper section close to the source and a progressively decreasing gradient toward the delta. In reality, however, landscapes are heterogeneous mixes, and the evolution of distinct channel patterns along a river's course depends on the regional and local geological basement, tectonic processes, climate conditions, and vegetation cover. In addition, confluences of large tributaries may alter the flow and sediment regime and, accordingly, channel patterns of the main stem. That's why one can encounter typical meandering river sections or even anastomosing reaches upstream of gorges or braided sections. In order to identify the causes for the confusing variety of river types, principles of hydraulic geometry have been used to derive empirical relationships between channel width, depth, slope, sediment size, flow velocity, and external controls such as catchment size and flow (Leopold and Maddock 1953). Generally, rivers on steeper slopes or systems that transport large volumes of coarse bedload with braided channels tend to develop wider and shallower channels than comparable meandering or straight river reaches (Parker 1979). Similarly, rivers with a flashier discharge regime and relatively high peak flows tend to develop wider channels (Brierley and Fryirs 2005). Recent approaches for river classification strive for a basin-wide analysis that also integrates land cover and human modifications. The usage of a hierarchical framework that nests successive scales of physical and biological conditions allows a more holistic understanding of fluvial processes in the whole basin (Buffington and Montgomery 2013).

3.3   A Shifting Balance of Form and Motion

The biodiversity of riverine ecosystems is closely related to habitat composition and habitat development, which are primarily controlled by natural fluvial disturbances (Ward 1998; Tockner et al. 2006). Along the river continuum, patterns of fluvial processes are closely related to the respective morphological river type and may gradually or abruptly change. Bar-braided or island-braided river reaches are subject to permanent turnover processes driven by their flashy regime and abundant sediment influx. Rapid lateral channel adjustments, a tendency toward vertical aggradation, and noncohesive riverbanks that can be easily reworked facilitate the permanent adaptations of existing channels and formation of new braids. Anabranching rivers, i.e., wandering gravel-bed rivers, are also characterized by intensive lateral and vertical turnover processes that boost the formation of new bars and vegetated islands. In contrast to typical braiding rivers, associated floodplains and larger islands feature significant vertical accretions with coarser material at the base and sand or suspended material in the upper soil layer. In such river sections, channel avulsions are typical phenomena (compare Sect. 3.2). The further downstream a river's course one goes, the more the aggradation processes predominate. Meandering and anastomosing channels in lowlands are subject to instream deposition of sediments that often occurs at point bars and to vertical accretion of suspended load in the floodplain. Both river types have in common a fine-grained, cohesive bank material which limits the potential for the balance of flow/deposition to reshape channel. In contrast, sand

channels with insufficient cohesive sediment to form resistant banks are particularly sensitive to flow variability and may easily be reshaped by altered flow conditions or sediment supply (Osterkamp and Hedman 1982).

At the first glance, one may conclude that different forms of channel behavior are bound to certain river types. Instead, morphological river types, i.e., channel patterns, are always products of prevalent fluvial dynamics that also depend on regional differences in climate, lithology, terrain relief, and land cover. In this context, vegetation significantly affects fluvial dynamics and, accordingly, channel patterns in several ways. On the catchment or sectional scale, type and areal extents of the vegetation cover influence the flow regime and local erosion and denudation (areal degradation) processes that, in turn, directly affect sediment availability in the basin (e.g., Allan 2004; Blöschl et al. 2007). On the local scale, riparian vegetation enhances bank resistance and counteracts bank erosion and channel migration but may also boost fluvial dynamics in form of large woody debris (e.g., Gurnell et al. 1995; Corenblit et al. 2007). In the latter case, extreme flows that dislodge vegetation, creates debris masses that can increase the erosive force of a high water event.

Natural river systems never remain in a morphologically static state. Rather they undergo permanent adjustments to internal changes of the system, e.g., when one channel changes in response to alterations in a confluent channel, and to external shifts, such as modified sediment supply or land cover change in the basin. From a temporal perspective, river adjustments reflect cumulative responses to recent events and deferred responses to previous events (Brierley and Fryirs 2005). Thereby, natural channel adjustments are superimposed by human-caused disturbances that additionally boost or curb fluvial dynamics. The geometry of a river channel reflects the balance or unbalance, respectively, of erosional and depositional processes that configure the riverbed and the banks. Generally, rivers seem to "strive" for a state of dynamic equilibrium ("regime status") between the imposed external controls such as valley slope, discharge, and sediment load on the one side and channel responses to those controls, including width, depth, velocity, reach slope, and sediment size, on the other side (Allan and Castillo 2007). While valley slope—from the human perspective—generally remains the same, the flow regime and, in particular, sediment supply are more sensitive and respond to natural or human influences over shorter time frames. This relationship between external controls and channel adjustments is described by "Lane's Law" stating that stream power approximately relates to sediment load (Lane 1954, 1955):

$$Q_S \times D_{50} \sim Q_W \times S$$

Q_S = sediment discharge, D_{50} = median grain size, Q_W = water discharge, S = channel slope; Fig. 3.3.

Stream power, the product of discharge and channel slope, describes the capacity of a river reach to mobilize and transport material. When stream power, i.e., discharge, decreases due to flow regulation or water withdrawal, some of the delivered material can't be transported further downstream, and aggradation processes will transform the channel. The same channel adjustments will occur during unchanged flows, when the sediment supply increases or the material becomes
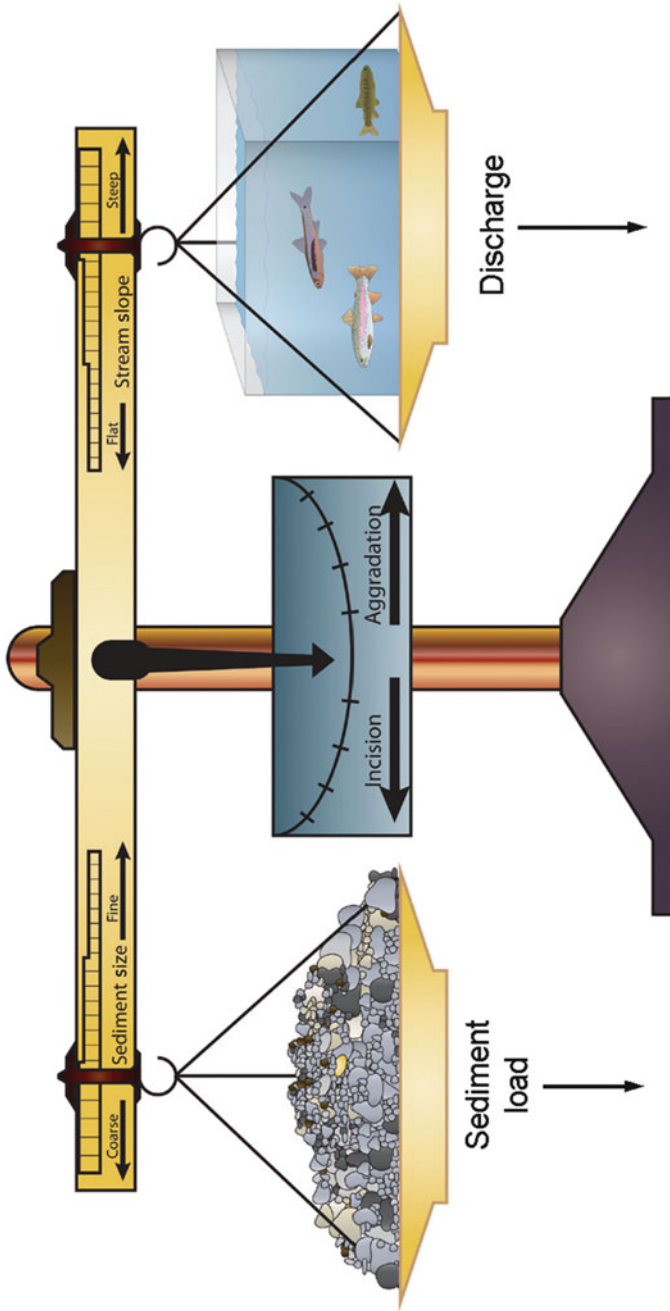
Fig. 3.3 Channel degradation and aggradation as a consequence of the balance between sediment transport (volume and median grain size) and stream power (discharge and channel slope) (Adapted from Pollock et al. 2014; published by Oxford University Press on behalf of the American Institute of Biological Sciences, based on data from Lane 1955)

coarser. On the contrary, dams that retain large shares of bedload generally lead to significantly reduced sediment volumes and smaller sediment sizes in downstream river stretches (see Chap. 6). Lane's Law illustrates that, in this case, stream power is too high for the available sediment load and the river will start to compensate its deficit by eroding the riverbed. Channel degradation downstream of the dam is the consequence. The modification of the channel will last as long as a new balance is not attained and, finally, a new type of channel pattern will emerge. For example, as a consequence of bedload reduction, formerly braiding river reaches may transform to sinuous single-channel rivers (Marti and Bezzola 2004).

Lane's Law and other studies in fluvial morphology assume a kind of equilibrium between external controls and channel geometry or habitat composition (e.g., Mackin 1948; Glova and Duncan 1985; Arscott et al. 2002). Because natural rivers are never totally static, such an equilibrium would be best referred to as a "state of dynamic equilibrium" in which one fluvial process, e.g., erosion, is compensated by a counteracting evolution (in this case aggradation). If fluvial systems did not remain in a kind of equilibrium, they would gradually—or even rapidly if system-inherent thresholds are exceeded—transform to a new morphological state (river type). However, some authors argue that fluvial systems are rarely in dynamic equilibrium, because rivers have to respond to a complex disturbance regime of periodic, episodic, and stochastic events that superimpose themselves on each other. Accordingly, rivers operate in a state of perpetual nonlinear adjustment, rather than oscillating around an equilibrium state (Thorne 1997; Brierley and Fryirs 2005). That way, many rivers show a tendency to develop a recognizable average behavior (Knighton 1998).

Changes in the geomorphological configuration of a river reach can significantly affect its capacity to support the ecological functions and habitat availability of a fluvial system. Likewise, riverine ecosystems, in particular, depend on disturbances that regenerate single parts of the system on a regular basis. Assuming unchanged climate conditions, riverine habitats and their associated biocoenoses undergo ecological successions toward a certain terminal stage that—without further disturbances—would persist (Bravard et al. 1986; Amoros and Roux 1988). Under human undisturbed conditions, periodic and/or stochastic disturbances counteract the general trajectory toward matured terrestrial habitats, rejuvenating the various riverine habitats (Ward 1998; Ward and Tockner 2001). Over the long term, such processes promote morphologically and ecologically differentiated habitat patches, fundamentally determining the competitive interactions at species and community level (Huston 1979, 1994; Hughes 1997). Though an individual habitat may vanish due to disturbances, over lengthier periods and larger areas, in such a "shifting habitat mosaic," the proportions of the differently developed habitat patches are supposed to remain relatively constant as long as the controlling factors do not significantly change (Stanford et al. 2005). Given the hierarchical nature of fluvial systems (compare Sect. 3.1), the "hierarchical patch dynamics" concept emphasizes that higher levels of system organization impose structural and functional constraints on lower levels and its potential ecological processes (Wu and Loucks 1995).

From the landscape perspective of a biocoenosis, e.g., a spatially heterogeneous environment with patches differing in resource quality and quantity, persistence, and

connectivity provides the opportunity for a greater biodiversity than under more uniform and stable conditions (Allan and Castillo 2007). Likewise, riverine species have to adapt to the habitats that shift in space and time and, thus, to the underlying disturbance regime. Because individual species show varying habitat preferences and migration capabilities, they respond to landscape heterogeneity and changes in the habitat mosaic in different ways (Wiens 2002). For example, fish diversity generally peaks in intensely connected habitats, while amphibian diversity is higher in habitats with low connectivity (Tockner et al. 1998). This example shows that a high frequency of disturbance does not necessarily result in a higher riverine biodiversity. Once the disturbance regime significantly exceeds the resilience capacity of riverine species, biodiversity will diminish. According to the "intermediate disturbance hypothesis," a moderate level of disturbance potentially may increase diversity enabling the coexistence of species with divergent recruitments (Connell 1978; Ward and Stanford 1983; Fox 2013). In this context, several studies indicate that island-braided and, in particular, anabranched reaches generally show higher diversities than bar-braided, meandering, or anastomosing river sections (e.g., Stanford et al. 1996; Gurnell and Petts 2002).

3.4 Channelized Rivers

> One can already say that the mighty . . . stream can never be regulated so as the proud human spirit would like to (Wiletal 1897).

Other than remote human impacts, such as land cover changes or mining in the catchment, river channelization measures comprehensively alter the fluvial morphology of a river reach in the most direct form. Dependent on the objectives of a river training program, various types of hydraulic measures are applied, each associated with specific forms of human interference in the physical configuration and ecological functions of fluvial systems. Construction of dams that present a severe local intervention with remote up- and downstream impacts on fluvial systems is often—but not necessarily—accompanied by channelization measures of longer river reaches (see Chap. 6).

River channelization in general pursues two major aims—the improvement of navigability and flood control. Besides that, river straightening was also seen as a means to increase flow speed and to discharge pollutants. In Europe and North America, owing to the advent of steam navigation in the nineteenth century, several river engineering programs aimed at the improvement of the shipping conditions of medium and large rivers (Sedell and Froggatt 1984; Gore and Petts 1989; Alexander et al. 2012; for human impacts on fluvial systems in earlier periods see Chap. 2). Because load drafts of new steam vessels constantly increased, the water depth along navigable waterways had to be adapted simultaneously. In many rivers, deepening of the channel was achieved by a significant constriction of channel width that in most cases was accompanied by a straightening of the whole river section. This was specifically a major concern in braided or anabranching river sections, where flow was

divided into several branches (Wex 1873, 1879). Because they were generally deeper, navigability in sinuous or meandering, single-channel rivers in lowlands was generally easier. However, such systems often had insufficient flood conveyance capacity (N.N. 1853; De Marchis and Napoli 2008). If flood control is the major concern, channelization primarily strives for straightening and/or widening (resectioning) a river reach in order to amplify the conveyance capacity of the channel and to reduce shear stress (Brookes 1988).

Independent from its main purpose, channelization fundamentally modified channel patterns and fluvial dynamics, e.g., when a meandering or braided river section was transformed into a straight, uniform channel. In alluvial reaches, besides the main river arm, the whole riparian ecosystem is affected by channelization's hydraulic measures. Former lotic side arms were cut off and transformed to one-side connected backwaters or were totally separated from the main channel. Accordingly, braided and, in particular, anabranching rivers are subject to the most severe impairments with respect to the channel patterns (Gurnell et al. 2009; Tockner et al. 2010). Specifically, in alluvial reaches, river channelization programs were also designed to prevent lateral erosion of floodplain terrain and to gain new arable land. In order to boost terrestrialization processes in cutoff river arms and in low-lying areas of the floodplain, embankments and closure dams were often designed to function as sediment traps and to facilitate deposition of material even during smaller floods. Applying this technique enabled the reclamation of large areas of new land within a few years to decades (Hohensinner et al. 2011). Because navigability was still constricted during periods of reduced discharge, later in many large rivers, additional groynes and training walls for low flow situations were installed. In the twentieth century, channelization measures were often coupled with the construction of reservoirs and hydropower plants, which guaranteed sufficient channel depths for larger vessels. Though flood protection levees are generally not constructed for purposes of river training, they also severely affect fluvial systems in various respects. Levees that are directly located along riverbanks are often accompanied by massive embankments to prevent undercut erosion. In contrast to flood protection levees in the hinterland, such dykes both morphologically and hydrologically constrain river dynamics.

The history of river channelization highlights that most hydraulic measures were designed to fulfill multiple purposes at once in order to facilitate several forms of human uses in fluvial systems (Winiwarter et al. 2012). It also shows that single hydraulic constructions, e.g., a closure dam to cut off a side arm, may impair a fluvial system in multiple ways. Some river engineering measures that are commonly applied—at least at first glance—only affect the channel itself. Transversal protection structures that are installed perpendicular to the water course, such as ground sills on the channel bottom or higher check dams, are generally applied for stabilizing the riverbed and preventing further channel incision. Both types reduce stream power and, consequently, sediment transport capacity in the upstream river reach. Energy dissipation, the conversion of the kinetic energy of flowing waters into other, less hazardous, forms, such as thermal or acoustical energy, is primarily limited to sites just below the transversal hydraulic structures. On the other hand, dredging

measures aim for lowering the river bottom and are usually conducted to keep waterways navigable or to increase flood conveyance capacity. Though these measures are performed directly in river channels, they potentially also affect larger parts of riparian systems. Water level changes evoked by the transversal structures may significantly influence the groundwater table or surface water bodies in the adjacent floodplain.

During the past two centuries, river regulation measures caused dramatic "regime shifts" for most European braiding, multi-channel, and transitional rivers (Petts 1989; Tockner et al. 2010). In the Alps, channel patterns commonly shifted from formerly braiding to a single-channel river type. As a consequence, the total length of braiding reaches decreased in France and Austria by 70% and 95%, respectively (Muhar et al. 1998; Habersack and Piégay 2008). River engineering measures not only modify the physical configuration of the channelized river section itself; they indirectly also affect the subsequent up- and downstream reaches. Even if only one of the flow-dependent variables (slope, depth, width, and roughness) is affected by the measures, feedback effects will promote adjustments toward a new morphological state (Brookes 1988). In case of channel narrowing, often applied for the purpose of land reclamation, flow velocity and sediment transport capacity increase, eventually causing bed erosion. Nevertheless, the main cause for amplified bed degradation is channel straightening. Particularly in sinuous or meandering rivers, where the new cutoff is much shorter and steeper, stream power significantly increases, and the riverbed may incise by several meters within a year or several years (Knighton 1998; Kesel 2003). Starting from the upper end of a straightened river section, retrograde erosion that progressively encroaches upstream is a typical response process that may affect large parts of a whole river system (Simon 1989). The mobilized material is transported downstream as far as stream power allows, meaning that large volumes will be deposited just downstream of the straightened section. Here, the opposite adjustment process can be observed: aggradation reduces channel slope, channel width may substantially increase, and new channel patterns may emerge (Brookes 1987; Gregory 2006). Well-documented examples from the Danube River and its tributaries in the nineteenth century show that river straightening programs in alpine tributaries led to marked aggradations and bed modifications in the Danube River, even 150 km downstream of the "improved" section (Schmautz et al. 2000). Once an alluvial Danube section was straightened, downstream aggradation and bed transformation causing severe obstacles for navigation forced the regulation authorities to advance channelization continually downstream until the next gorge section of the Danube was reached (Hohensinner 2008; Hohensinner et al. 2014). However, new problems arose in the alluvial reaches downstream of the gorge, and, finally, they were forced to channelize the whole Austrian Danube section (Schmautz et al. 2002).

Today, distinct channel incisions induced by river "training" (channel engineering) in combination with reduced sediment supply from upstream river sections present a major concern in the industrialized world (Gore and Petts 1989; Stanford et al. 1996). Typical consequences for the biota are the reduction of original instream habitat complexity and habitat availability in increasingly uniform riverbeds (e.g., Toth 1996; Lau et al. 2006). Accordingly, pronounced differences in species

composition and abundance can be found compared to more natural sites. Since straightened and constrained river channels generally show higher flow velocities, aquatic communities have to adapt to the altered hydraulic conditions. Fish species and benthic invertebrates preferring moderate or lower flow velocities are largely replaced by rheophilic communities (Jurajda 1995; Jansen et al. 2000). These modifications are referred to as the "rhithralization effect", the shift of a riverine coenoses toward upstream communities (Jungwirth et al. 2000). Higher flow velocities generally result in greater grain sizes of the substrate. Another typical response is riverbed armoring, where the top layer of the bed substrate shows coarser sediment fractions than in the underlying layer. In river sections with negligible bedload transport, such truncated bed dynamics may lead to the clogging of the pore volume of the substrate ("hyporheic interstitial") with silt. Such "colmations" of the riverbed severely impair the exchange processes between the river and the aquifer (Boulton 2007; see Chap. 8).

Apart from the main channel, in alluvial reaches, channelization also affects the hydromorphological configuration and ecological functions of the whole riparian system. Direct forms of impairment include the hydrological separation of the water bodies in the floodplain from the main stem and the promotion of terrestrialization. As already mentioned, the "improvement" of wetlands for better human usage is also an important goal of channelization leading to a drastic reduction of aquatic and semiaquatic habitats. Besides, significantly lowered water levels in the river comprehensively lower downward percolation (infiltration) rates and thereby decrease aquifer recharge in the floodplain. This lowers the resilience of riverine communities to drought. Cutoff side arms and lowered groundwater tables significantly reduce lateral hydrological connectivity, i.e., the various surface and subsurface exchange processes, such as sediments, nutrients, water temperature, or organisms, between the river and the diverse floodplain biotopes (Amoros et al. 1987; Amoros and Bornette 2002).

Accordingly, the stimulating effects of the "flow pulse" at discharges below bankfull and the "flood pulse" at higher stages that in undisturbed condition boost primary production even in remote floodplain areas as a fundamental basis for riverine biodiversity decrease (Junk et al. 1989; Puckridge et al. 1998; Tockner et al. 2000). Moreover, reduced lateral connectivity is reflected by the truncation of the network of potential migration pathways for aquatic organisms. Rheophilic fish species with a preference for lentic conditions in connected backwaters during certain periods in the adult stage, in particular, depend on such lateral migratory pathways between lotic and lentic habitats (e.g., for reproduction, as feeding grounds, or winter refuge; Schiemer and Waidbacher 1992).

Ongoing vertical accretion of sediments during floods further heightens the elevation of the floodplain terrain. As a consequence, besides a lateral decoupling of the floodplain habitats from the river, increasingly a vertical decoupling between the river level (water/groundwater table) and the floodplain terrain is a typical phenomenon (Amoros and Bornette 2002). Historical analyses from Austrian Danube floodplains show that the average depth down to the groundwater table below the terrain surface increased by 63–88% at mean flow situations since the early nineteenth century (Hohensinner et al. 2008). Vertical decoupling of fluvial systems considerably modifies site conditions for riparian vegetation, which is one major cause for the extensive

decline of early successional stages and softwood assemblages in the industrialized world (Egger et al. 2007; Mosner 2012; Reif et al. 2013). Today softwood communities are severely endangered and are specifically protected by the EU Flora-Fauna-Habitat Directive.

The brief discussion of potential consequences of channelization shows that channel adjustment to local or sectional hydraulic constructions most likely affects much longer river sections or may even concern the whole river system. Accordingly, in applying such measures, a much larger spatial and temporal scale has to be considered. However, this also applies in the case of ecologically oriented restoration programs.

Given the diverse forms of hydraulic measures and the general lack of basic data, it is difficult to provide scientifically rigorous information about the worldwide or continental impacts on fluvial systems due to channelization. According to a rough estimate, worldwide, approximately 500,000 km of waterways have been altered for navigation (Tockner and Stanford 2002). Even more speculative are estimates about riverine wetlands that are affected by channelization, because the consequences of local channelization measures and those of wetland reclamation or remote impacts, such as altered flow regime and sediment supply due to the construction of dams or land cover changes in the basin, are superimposed upon each other (see Chap. 15).

3.5   Assessing the Hydromorphological State of Rivers

In several European countries, long traditions exist for assessing the morphological conditions of rivers to provide an overall survey of habitat quality. Formerly, such assessments were particularly related to hydraulic engineering activities and river inventories (e.g., Werth 1987; Raven et al. 1997). These studies focused primarily on morphological conditions of rivers and streams, while at the same time, key elements of the physical environment of fluvial systems, like flow and sediment regime, were not or scarcely addressed. In general, hydromorphological assessment is based on the assumption of a strong relationship between the physical environment and aquatic organisms/biocoenoses of riverine ecosystems (Karr 1981; Muhar and Jungwirth 1998). Thus, those hydromorphological attributes are investigated, mapped, and evaluated, which determine the habitat functions of running waters. The methods of such assessments are diverse, depending on the main aims and objectives, ranging from large-scale surveys at the basin scale to local-scale habitat assessment (see Table 3.1).

Since the EU WFD requires the assessment of hydromorphological quality as an essential part in supporting the ecological status of rivers, numerous methods have been revised and further developed (Boon et al. 2010; Belletti et al. 2014; Poppe et al. 2016). Most of them follow the scheme of the WFD by addressing "hydromorphological quality elements" (EU 2000): (1) hydrological regime (e.g., quantity and dynamics of water flow and connection to groundwater bodies), (2) morphological conditions (e.g., river depth and width variation, structure, and substrate of the river and the riparian zone), and (3) river continuity (regarding

Table 3.1 General aims of hydromorphological assessments

Tasks of large-scale surveys at the basin-wide scale
• Overview of the physical status quo of river systems (e.g., according to the EU WFD), overall identification and documentation of habitat improvement/degradation
• Quantification (intensity of impacts, e.g., river engineering measures, artificial barriers, degree of natural highly impacted river stretches, etc.)
• Basis data for supra-regional planning (e.g., establishment of a large-scale river conservation/restorationnetwork)
• Tool for strategic decisions in early stages of project development
Tasks of local-scale habitat assessment
• Detailed habitat investigation in context with biological studies (auto-/synecological studies)
• Identification and assessment of altered habitat conditions due to anthropogenic impacts and the effects on biota
• Monitoring and evaluation of river restoration

migrating species as well as sediment regime). They mainly focus on (field) investigations, frequently supplemented by analyses of remote sensing data (e.g., orthophotos) at reach scale, describing channel characteristics and mesohabitat conditions. Depending on the specific method, respectively, on national guidelines of the EU member states, they follow a predefined scheme to define investigation units; e.g., in Austria, the hydromorphological status assessment is always related to a 500 m river stretch at all rivers with a catchment area of more than 10 km^2 (BMLFUW 2015). The currently applied assessment methods are basically compliant with the EU CEN standards on hydromorphological assessment comprising also a largely comparable set of assessment categories and parameters (see Table 3.2; CEN 2004; Boon et al. 2010).

Such surveys provide a wealth of useful information, but, with some exceptions, they tend to focus on forms rather than processes, typically evaluating hydromorphological degradation on how the characteristics of a river reach differ from "reference" conditions, based on "pristine" sites located elsewhere or how the reach looked at some time during the past. Recently developed studies aimed to go beyond this scheme, to enhance the survey methods to better integrate physical processes as driving forces for the occurrence and reshaping of river channels and instream habitats.

Summarizing, hydromorphological assessment is a key foundation for river basin management and should build on the growing understanding of geomorphological processes (Montgomery and Buffington 1998; Kondolf et al. 2003; Brierley and Fryirs 2005) and integrate biological knowledge with regard to habitat requirements of aquatic species at different spatial scales. In particular, the following issues are crucial:

- To choose methods, harmonized with the specific aims, objectives, and thus spatial scale.
- To identify adequate assessment attributes and evaluation algorithms.

Table 3.2 Assessment categories, features, and attributes comprising a standard hydromorphological assessment according to EN 14614 (From Boon et al. 2010)

Assessment categories	Generic features	Examples of attributes assessed
Channel		
Channel geometry	Planform	Braiding, sinuosity
		Modification to natural planform
	Longitudinal section	Gradient, long-section profiles
	Cross section	Variations in cross section shown by depth, width, bank profiles, etc.
Substrates	Artificial	Concrete, bed-fixing
	Natural substrate types	Embedded (boulders, bedrock, etc.)
		Large (boulders and cobbles)
		Coarse (pebble and gravel)
		Fine (sand)
		Cohesive (silt and clay)
		Organic (peat, etc.)
	Management/catchment impacts	Degree of siltation, compaction
Channel vegetation and organic debris	Structural form of macrophytes	Emergent, free-floating, broad-leaved submerged, bryophytes, macro-algae
	Leafy and woody debris	Type and size of feature/material
		Weed cutting
Erosion/deposition character	Features in channel and at base of bank	Point bars, side bars, mid-channel bars and islands (vegetated or bare)
		Stable or eroding cliffs, slumped or terraced banks
Flow	Flow patterns	Free-flow, rippled, smooth
		Effect of artificial structures (groynes, deflectors)
	Flow features	Pools, riffles, glides, runs
	Discharge regime	Off-takes, augmentation points, water transfers, releases from hydropower dams
Longitudinal continuity as affected by artificial structures	Artificial barriers affecting continuity of flow, sediment transport, and migration for biota	Weirs, dams, sluices across beds, culverts
Riverbanks/riparian zone		
Bank structure and modifications	Bank materials	Gravel, sand, clay, artificial
	Types of revetment/bank protection	Sheet piling, stone walls, gabions, rip-rap
Vegetation type/structure on banks and adjacent land	Structure of vegetation	Vegetation types, stratification, continuity
	Vegetation management	Bank mowing, tree felling
	Types of land use, extent, and types of development	Agriculture, urban development

(continued)

Table 3.2 (continued)

Assessment categories	Generic features	Examples of attributes assessed
Floodplain		
Adjacent land use and associated features	Types of land use, extent, and types of development	Floodplain forest, agriculture, urban development
	Types of open water/wetland features	Ancient fluvial/floodplain features (cutoff meanders, remnant channels, bog)
		Artificial water features (irrigation channels, fish ponds, gravel pits)
Degree of (a) lateral connectivity of river and floodplain (b) lateral movement of river channel	Degree of constraint to potential mobility of river channel and water flow across floodplain Continuity of floodplain	Embankments and levees (integrated with banks or set back from river), flood walls, and other constraining features Any major artificial structures partitioning the floodplain

- To enhance the methodological approach by comprehensively including the adjacent floodplains/wetlands in assessing the physical environment of river landscapes.
- Far more consideration has to be given to physical processes to better understand the current conditions and the causes of alterations (human uses, restoration measures, etc.) and responding effects (Belletti et al. 2014).

3.6 Conclusion

Addressing the hydromorphological state of riverine ecosystems with profound understanding requires consideration of larger spatial scales. Channel geometry and fluvial dynamics are not solely determined by local geomorphological framework conditions. Rather they are the product of influxes from the upstream catchment. Over the long term, both sediment transport and discharge, on the one side, and the local/sectional setting (e.g., geology, topography), on the other side, lead to the formation of certain channel patterns. However, the typical sequence of morphological river types along a river's course from constrained upstream gorges over braided, anabranched, and meandering rivers to, finally, anastomosing lowland rivers can be rarely found in nature. Tectonic barriers or depressions and large tributaries may interrupt that typical sequence and foster channel patterns that would normally not be expected at a respective site. Changes in upstream sediment delivery and altered discharge regimes trigger local channel adjustments. Even downstream hydromorphological changes may affect channel geometry in upstream sections due to retrograde soil erosion.

Accordingly, channelization measures do not only affect the physical configuration and dynamic fluvial processes at a respective river reach. Rather they influence much longer river sections or even the whole river system, including the tributaries. Human interventions into riverine environments always call for consideration of unintended side effects and potential long-term legacies that may cause new problems at upstream or downstream sections. What seems to be clear for river channelization does also apply to restoration measures. Locally implemented river restoration projects may also influence the up- and downstream fluvial processes and, thus, the habitat availability and the ecological state of longer river sections.

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