

Chapter 8

The Role of Sediment and Sediment Dynamics in the Aquatic Environment



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8.1 Introduction

The dynamic component in hydrology, sedimentology, and, consequently, river morphology serves as a backbone for the entire river environment (Maddock 1999). In addition to water pollution, the hydro-morphological/sedimentological degradation is one of the main pressures on river systems (Ward and Stanford 1995; Dudgeon et al. 2006). The EU Water Framework Directive (WFD, Directive 2000/60/EC) mentions various aspects of hydro-morphological disturbances that must be addressed by management plans to achieve the aims of a good ecological status or a good ecological potential (Article 3/Article 4). However, to reach these goals, the sediment conditions of a river (e.g., sediment continuum) are not part of the evaluation needs. Here, to achieve “good ecological status,” it is assumed that the biotic criteria reflect the hydro-morphological status, while direct assessments of dynamic sedimentological processes are not taken into account (Hauer 2015).

In general, sediments play a decisive role for diversification and composition and, hence, the quality of habitats, especially for the mid- to long-term development of

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habitat features. According to Leopold et al. (1964), there are eight factors forming the morphological traits of a river: channel width, depth, flow velocity, discharge, channel slope, roughness of channel material, sediment load, and sediment size. Disturbances in any of those factors can alter the general habitat composition of the river and consequently the morphological type of a river. Sediments are both habitat forming (e.g., boulders) and part of morphological structures (e.g., gavel at gravel bars) (Hauer et al. 2014).

Concerning possible impacts of sediment disturbances on the aquatic biota, both the time scale and the form of impact (direct or indirect) are decisive. On the one hand, mid- to long-term indirect impacts are evident due to changes of the physical environment (e.g., changes in sedimentology, loss of spawning sites) as well as short-term, direct (highly dynamic) impacts due to physiological stress (e.g., high turbidity for fish) or risk of abrasion (e.g., for macroinvertebrates). Especially, catchment or reach-scale sedimentological and hydro-morphological disturbances may change the channel shape and/or the habitat composition in the mid- to long-term. Disturbances of the sediment regime are always related to deficits or surpluses in sediment supply and sediment transport (e.g., Brooks and Brierley 1997; Sutherland et al. 2002) which are presented in this book chapter.

Specifically, in alpine regions, the impact of sediment deficits is responsible for riverbed incision and related habitat degradation (Habersack and Piégay 2008). At the same time, increase in sediment load and transport is hardly found in alpine regions but is a major problem in regions with soil erosion due to intensive agriculture or forestry (Leitner et al. 2015; Höfler et al. 2016). Man-made reductions in the sediment load due to torrent controls or retention by hydropower use may have two different consequences, sometimes occurring simultaneously in one and the same river. On one hand, depending on the frequency of floods, the coarsening of substrate due to selective transport leads to fluvial armor or pavement layers (Sutherland 1987). On the other hand, in alpine basins with fine material deposits from the tertiary (marine sediments) below the quaternary gravel layer of the riverbed, the risk of a so-called riverbed breakthrough (Habersack and Klösch 2012) may be realized due to a single flood (e.g., the Salzach River in 2002; Hopf 2006). Another increasingly frequent problem connected to sediment retention is the flushing of reservoirs (see also Chap. 6). During flushing, large amounts of retained suspended load are released in a short period of time, mostly in conjunction with flood events resulting in a surplus of sediments in downstream river sections. Consequently, high loads of mostly fine sediments cause high concentrations of turbidity and can be responsible for losses and mortality of aquatic organisms (e.g., Espa et al. 2015).

Consequences of sediment deficits and impacts on the river are (1) decrease in habitat heterogeneity (Kondolf 1997); (2) risk of river bank erosion (Rinaldi and Casagli 1999); (3) risk of damage to infrastructure, e.g., scouring bridge piers (Jäger et al. 2018); (4) lack of spawning habitats for salmonid fish species (Hauer et al. 2013) and depauperate macroinvertebrate fauna (Graf et al. 2016); (5) decrease in sediment turnover rates and river type-specific sediment quality (Kondolf 1997); and (6) risk of channel avulsion during extreme events (Brizga and Finlayson 1990).

Channel avulsion refers to abrupt changes of the river course leading to a new active channel in the former floodplain.

The aim of this book chapter is to give an overview of the role of sediment and sediment dynamics for the aquatic environment with a special focus on alpine rivers and their fish fauna. We describe how sediment dynamics determine river morphology and habitat-forming processes. Moreover, problems of human-induced sediment increase (e.g., reservoir flushings, intensive agricultural and forestry land use leading to intrusion of fine sediments) and deficits (e.g., deposition by torrent controls and hydropower plants) are targeted with respect to the biotic requirements of macroinvertebrates and fish.

8.2 Sediments and River Morphology

Depending on the morphological river type (Montgomery and Buffington 1997), single grain sizes can be hydraulically habitat forming (e.g., cascade or step-pool type) or just components of a morphological feature (e.g., a gravel bar) that determine the hydraulic patterns of a river (e.g., riffle—pool type) (Hauer et al. 2014). As a decisive variable for channel- and habitat-forming processes, the role of sediments is described in the following subchapters according to their importance in morphological classification, sources in and along river corridors considering river scaling aspects.

8.2.1 River Morphology and Substrate Size

The substrate size and variability in substrate resistance according to the stream power are important agents controlling river morphology (according to Leopold et al. 1964). In this chapter, in contrast to the description of the morphological classification presented in Chap. 3, we use the more sediment size-based classification of Montgomery and Buffington (1997). Here, five different river types for alpine rivers can be distinguished with differences in sediment composition, sediment dynamics, and habitat features:

1. The cascade type is characterized by irregular boulders, local pools, and a large range of particle sizes. Energy dissipation is dominated by continuous tumbling and jet-and-wake flow around and over individual, large clasts (Peterson and Mohanty 1960). The large bedforming material of cascade reaches is immobile during typical flows. Large amounts of bedforming material are mobilized in cascade reaches only during infrequent, hydrologically extreme events with recurrence intervals of 50 up to >200 years (Grant et al. 1990; Phillips 2002). Locally stored gravel and finer grains on the lee sides of flow obstructions (e.g., boulders) are typical sedimentological characteristics of cascade reaches (Montgomery and Buffington 1997). Gravel bed spawning grounds are often small and patchy.

2. Step-pool morphology is characterized by downstream alterations of steps (clasts, wood, and/or bedrock) and plunge pools that develop downstream of each step (Chin 1999; Wohl 2013). Step-pool reaches are most commonly situated along river sections where relatively immobile clasts of coarse sediment can additionally trap wood (Wohl 2013). Energy dissipation is distributed stepwise with high levels at the steps and low dissipation at the outlet of the plunge pools. It is often these outlets which offer good spawning hydraulics and sediment conditions for salmonids. According to Whittaker (1987), step-pool channels reflect a sediment supply-limited system. Potential control variables (reach-scale gradient, discharge, sediment supply and size) for step-pool morphologies have been frequently investigated (e.g., Maxwell and Papanicolaou 2001). Here, in alluvial step-pool systems, particle size was found to determine the step height and discharge as the dominant factor determining the step wavelength (Chartrand and Whiting 2000).
3. Plane-bed reaches are characterized by a lack of gravel bars (e.g., point bars or mid-channel bars), which occur due to a low width-to-depth ratio and a large value of relative roughness (i.e., the ratio of the d_{90} percentile to bank-full depth) (Montgomery and Buffington 1997). Plane-bed channels tend to be intermediate between step-pool and pool-riffle channels regarding gradient slope and grain size (e.g., d_{90}) (Wohl and Merritt 2008). Moreover, the characteristics of plane-bed channels typically in combination with an armored bed surface indicate a transport capacity larger than the sediment supply (Montgomery and Buffington 1997). Hence, supply-limited conditions are found for most discharges (Wohl and Merritt 2008) with some exceptions for high flows (e.g., Sidle 1988). Therefore, a lack of upstream bed-load supply (gravel-to-cobble sized sediments) may be responsible for the development of this specific morphological type. Larger gravel bed spawning grounds are rare and patchily distributed.
4. Riffle-pool channels occur at moderate-to-low gradients and are generally unconfined by valley margins or lateral obstructions (Montgomery and Buffington 1997), with a pool spacing of five to seven times the channel width (Keller and Melhorn 1978). In near-natural river systems, riffle-pool channels contain woody debris leading to forced pool formation with irregular distributions of these local depressions (Lisle 1986). Upstream sediment supply and transport rates cause variable changes in the storage capacity and changes in the channel configuration in low gradient riffle-pool channels (Schumm 1977). High-quality spawning sites for salmonid fish (e.g., brown trout) are usually not limited, especially in the transition zone downstream of the pool and upstream of the riffle crest (Hauer et al. 2013).
5. The low gradient dune-ripple type is associated with sand-bed channels (Montgomery and Buffington 1997). One of the main differences from the plane-bed, riffle-pool, step-pool, and cascade morphological types is that dune-ripple channels exhibit wandering bedforms (Henderson 1963) which are mobile during most water stages. For dune-ripple reaches, bed-load transport occurs even under low flow conditions, caused by the low critical mean flow velocity for the initiation of motion of the fine material predominately consisting of

weathered granite and gneiss [according to Hjulström (1935)]. The occurrence of the dune-ripple type, which is classified as transport limited, is shaped by a high intake of fine sediments from tributaries. Such rivers usually provide poor spawning conditions for gravel-spawning fish species.

8.2.2 *Sediment Sources*

The sources of sediment are not addressed in the classification of river types and whether these sources are self-formed or relict. Self-formed and relict-non-fluvial streams can be difficult to distinguish in the field. For relict-non-fluvial stream, the off-river sediment supply is low or sediment input only occurs sporadically (Bunte and Abt 2001). In self-formed rivers, however, sediment sources are related entirely to on-site bed material, bank erosion, and upstream fluvial sediments (Andrews 1984). If the sediment sources are not coupled to hillslopes or other partially non-fluvial sources, streams are classified as uncoupled streams (e.g., Trainor and Church 2003). In contrast, coupled streams are determined by sediment supply from relict-fluvial and non-fluvial sources (e.g., Harvey 2001).

8.2.3 *Scaling of Sediment Dynamics in the River Environment*

Various concepts for scaling river morphology and instream habitats have been developed (e.g., Frisell et al. 1996; Habersack 2000; Maritan et al. 1996; Newson and Newson 2000). From an ecological point of view, the strong dependence of aquatic organisms on abiotic changes in the environment (e.g., sediment turnover, flow fluctuations) has to be emphasized (Hauer 2015). Changes in sediment composition and quantity directly impact aquatic life on various scales. For example, excessive sediment transport rates may change the morphological river type on the reach scale. Consequently, a switch from a riffle-pool morphology to a dune-ripple type can appear due to excessive supply of coarse sand based on impacts of climate change and intensified land use (Hauer 2015). Moreover, the morphological features on the meso-unit scale (decrease in depth variance) as well as the habitat quality at the on-site micro-unit scale can alter. Such local-scale phenomena as, e.g., the loss of interstitial volume and morphological heterogeneity impact macroinvertebrates (Crosa et al. 2010), fish (Pulg et al. 2013; Hauer et al. 2013; Sutherland et al. 2002), and, especially, mussel habitats (Geist and Auerswald 2007). All taxa are strongly influenced by sediment supply at both reach and catchment scales. Therefore, local-scale investigations and research might neglect important aspects of habitat degradation or fail to consider the mid- to long-term evolution and dynamics when mitigation measures are elaborated without considering the driving

sedimentological processes at the reach and catchment scales (e.g., reduced sediment supply due to hydropower) (Hauer 2015).

Changes (natural or anthropogenic) of the sediment dynamics on the catchment scale may lead to large-scale disturbances as, e.g., changes in the “sedimentary-link” concept with far-reaching consequences on the instream sediment quality. The sedimentary link concept describes the form of lateral sediment supply from tributaries and its impact on the longitudinal distribution of grain size (Rice and Church 1998). In alpine landscapes, the concept describes the increase in the amount of bed load combined with an increase in the grain size diameter at tributaries followed by a regular downstream fining (Rice 1998; Rice and Church 1998). Unlike alpine river catchments where sediment input from tributaries leads to an increase in the sediment caliber, the “revised” sedimentary link concept for rivers with high sediment input posits a partial decrease in the sediment caliber at tributaries due to the increased deposition of fines (Hauer 2015).

8.3 Sediment Dynamics and Anthropogenic Alterations of the Sediment Flux: What Aquatic Biota Need and How They React to Alterations

Too Little: The Consequences of Sediment Deficits

Rivers exhibiting naturally (downstream of lakes) or anthropogenically reduced sediment supply are “supply-limited” rivers (Montgomery and Buffington 1997). Limited supply leads to continuous armoring of bed surface sediments, a process occurring during ordinary flood events and without extraordinary floods (Fig. 8.1a). In addition to natural bed armoring, human activities can reduce gravel supply and therefore lead to armors. For instance, dams and weirs are responsible for interruptions of the sediment continuum. Further bank stabilization measures reduce lateral sediment supply. In combination, these man-made structures are likely to reduce

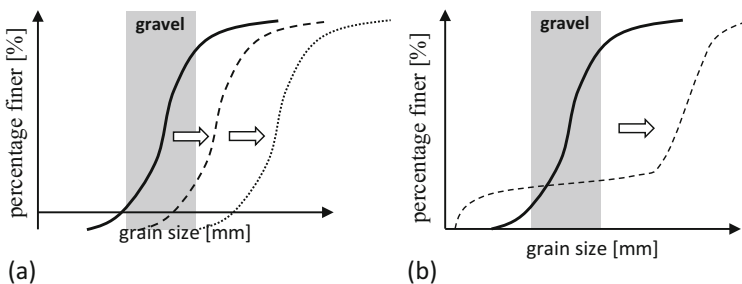


Fig. 8.1 Conceptual schema of mid- and long-term development of spawning gravel in terms of significant (solid line to dashed line) (a) lack of sediment supply from upstream reaches in rivers with low concentration of fines and (b) lack of sediment supply from upstream with high accumulation of fine sediments in the immobile coarse bed surface (clogging)

gravel supply significantly and can thus increase armoring and intensify flushing out heterogeneous sorted sediments. As a consequence of artificially determined, supply-limited conditions, the resultant deficits in bed-load transport may lead to continuous riverbed incision with the risk of channel avulsion and riverbed breakthrough during single flood events (Habersack and Klösch 2012). Continuous riverbed incision is the main driver of decoupling floodplains from the required water stage-dependent dynamics of the main river (see Chap. 3).

Beside problems related to riverbed incision and the coarsening of bed surface, increases in fine sediments are known to change grain size distribution and consequently cause degradation of spawning grounds (Sear and DeVries 2008; Pulg et al. 2013), especially in “supply-limited” rivers (Fig. 8.1b). On the one hand, the armoring of the bed surface reduces or prevents cleaning effects of sediment relocations, which naturally generate suitable spawning habitats in the riverbed.

On the other hand, the increase of fines clogs the pore space and can lead to “sustained clogging” (Fig. 8.1b), since the turnover rate is markedly reduced or prevented even in the case of exceptional high flows. In such situations, washed out soil (e.g., from agricultural land use) or fines (e.g., of a glacier environment) may lead to sedimentation of fines on coarse bed material and/or artificially placed gravel with consequent, negative impacts on embryo survival of gravel-spawning fish through suffocation (Reiser 1998; Greig et al. 2005; Pulg et al. 2013).

Too Much: Consequence of an Increased Fine Sediment Yield

Under natural situations, only extraordinary events (e.g., flooding, torrents) produce “too much” sediment. The “excess” sediments generated in extreme events often raise the issue of fine sediments for analysis and/or management of river ecology. In general, in river morphology (Evans and Wilcox 2014) and fish habitat studies (e.g., Pulg et al. 2013), fine sediments are classified as particles <1 mm. Clogging of interstitial space due to clay intrusion called *siltation* degrades macroinvertebrate habitats (e.g., Buddensiek 1995). However, also coarse sand (>1 mm) may impact habitats of macroinvertebrates (Leitner et al. 2015).

Fine sediment intrusion (FSI) is part of the natural sediment and morphological dynamics in most river systems (Smith and Smith 1980). Land-use properties (e.g., Allan 2004) and geological (e.g., Walling 2005) and hydrological catchment-scale characteristics (flood disturbances, frequency, and magnitude of daily glacier melt-off) (e.g., Smith and Smith 1980; Milner and Petts 1994) have often been identified as drivers for natural FSI or clogging of surface and subsurface layers. Aside from glacial rivers, human (anthropogenic) disturbances have greater impacts on the fine sediment dynamics than natural processes. Man-made changes, however, might increase as well as decrease the amount of (fine) sediment load with mostly negative impacts on aquatic ecology in case of increases. For example, hydropower may cause significant alterations of the (fine) sediment regime based on the storage of water and the capture of sediment by dams which cause profound downstream changes in the natural patterns of the hydrologic variation and sediment transport (Poff and Hart 2002). In particular, fine sediment may be trapped in reservoirs and artificially released during controlled events, which may lead to variable meso-unit

scale deposition patterns and significant alterations of bed-load transport rates downstream (Wohl et al. 2010). Ecological consequences of reservoir flushing are long-term depletions downstream fish stocks (Espa et al. 2015; Buermann et al. 1995) and short-term impacts on macroinvertebrate communities (Rabení et al. 2005; Crosa et al. 2010).

8.3.1 Ecological Adaptations of Macroinvertebrates to Sediment Dynamics

The faunal structure of benthic macroinvertebrates depends on substrate type, diversity, and spatial patch configuration (Beisel et al. 2000). Habitat conditions of macroinvertebrates are to a large extent determined by flow parameters affecting the macroinvertebrates through hydraulic stress near the bottom (Statzner 1981) which is linked to substrate composition (Percival and Whitehead 1929; Beisel et al. 2000). Accordingly, some species prefer the surface of larger substrates where they feed on biofilms in high current, resulting in a flattened body form (Minshall 1967); others that hide in sand and mud are adapted to temporarily low-oxygen concentrations; those who feed on leaves or wood are restricted to organic matter (Schröder et al. 2013). As a consequence, many species are associated to a certain extent to specific habitats, which are composed of either mineral substrate (e.g., sand, gravel stones) or organic matter (e.g., living plants, dead leaves, deadwood) (see examples in Fig. 8.2a). However, habitat preferences frequently change within the life cycle of invertebrate taxa, indicating the importance of mosaic habitat patterns on a micro-scale (Fig. 8.2b).

In general, benthic invertebrates are adapted to sediment dynamics and natural disturbances (erosion). Animals can usually compensate for infrequent extreme events as floods or ice jams that result in destructive sediment transport. Depending

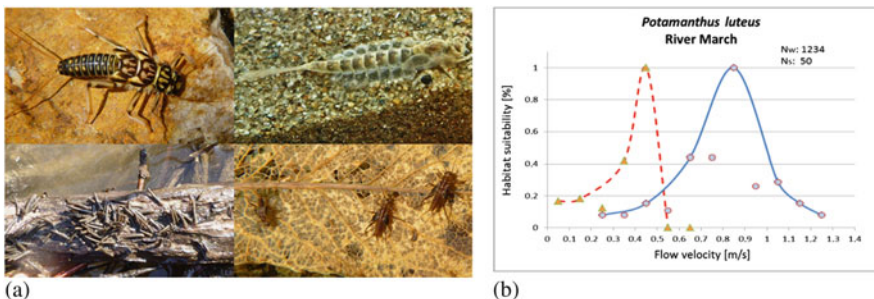


Fig. 8.2 (a) Examples of habitat-specific benthic organisms: *Perla* sp. (macrolithal), *Ametropus fragilis* (psammal), *Nemurella pictetii* (fallen leaves), and *Lepidostoma basale* (deadwood); clockwise from top left; (b) habitat suitability regarding flow velocity of the mayfly *Potamanthus luteus* in summer (red line, nymphs) and winter (blue line, early instars) at the March River (adapted from Büsch 2014)

on their autecological adaptations (anatomy, strategy) and stage of development (egg, different larval stages, and pupal stage), animals hide in the interstice or go into drift in case of disturbances. Drift is a means of recolonizing denuded downstream habitats and structuring benthic invertebrate communities (Tonkin and Death 2013). However, to preserve stable self-sustaining populations in cases of extreme events, successive downstream drifting has to be compensated by upstream migration by larval stages or by compensation flights by adult insects (Williams and Hynes 1977).

However, anthropogenically induced, long-term alteration of the streambed can result in dramatic shifts of the benthic faunal composition. A coarsening of the bed surface in “supply-limited” rivers can lead to a decrease of macroinvertebrate diversity and/or density for those taxa with habitat preferences for fine sediments comprising certain Oligochaeta, Bivalvia, Diptera, or burrowing Ephemeroptera species. Nevertheless, as many studies show that only a low number of taxa indicate a clear preference for fine substrates (e.g., Minshall 1984; Jowett et al. 1991; Leitner et al. 2015; Graf et al. 2016), the more serious effect in supply-limited river stretches is the clogging of the interstices and embedding of coarse substrate by fines. This phenomenon results in a decline in diversity and abundance of interstices inhabiting sprawlers, such as many Plecoptera and Ephemeroptera species (e.g., Weigelhofer and Waringer 2003).

In particular, anthropogenically induced, fine sediment deposition and siltation in streambeds seriously alters benthic fauna composition and, thus, is becoming a considerable stress for rivers throughout the world. Following Wood and Armitage (1997, Fig. 8.3), increased fine sediment yield affects macroinvertebrates (1) in changing substrate suitability for some taxa (Erman and Ligon 1988; Richards and Bacon 1994), (2) in increasing drift due to sedimentation or substrate instability (Culp and Davies 1985; Rosenberg and Wiens 1978), (3) in limiting respiration by deposition of fine sediments on respiration organs (Lemly 1982) or low-oxygen concentrations in the interstices (Eriksen 1966), and (4) in deteriorating feeding conditions due to effects of increased suspended solids on filter feeders (Aldridge et al. 1987) and in the reduction of the food value of the periphyton (Cline et al. 1982; Graham 1990) as well as prey organisms (Broekhuizen et al. 2001; Yamada and Nakamura 2002; Jones et al. 2012).

Consequently, increased input of fine sediments leads to a decrease in diversity, abundance, and biomass of macroinvertebrates as well as to a shift in community structure (Berkman and Rabeni 1987; Wood and Armitage 1997; Angradi 1999; Leitner et al. 2015). For example, Graf et al. (2016) demonstrated that only Chironomidae and Oligochaeta show a habitat preference for sand or are at least more tolerant to this type of substrate, while other taxa belonging to the orders Ephemeroptera, Plecoptera, and Trichoptera (EPT) show preferences for coarser substrate types and are highly sensitive to siltation.

Briefly, increased fine sediment yield has serious effects on benthic macroinvertebrates in lotic systems, emerging as a steady, often unnoticed, process with a high-risk potential for affecting biodiversity leading to critical ecological degradation.

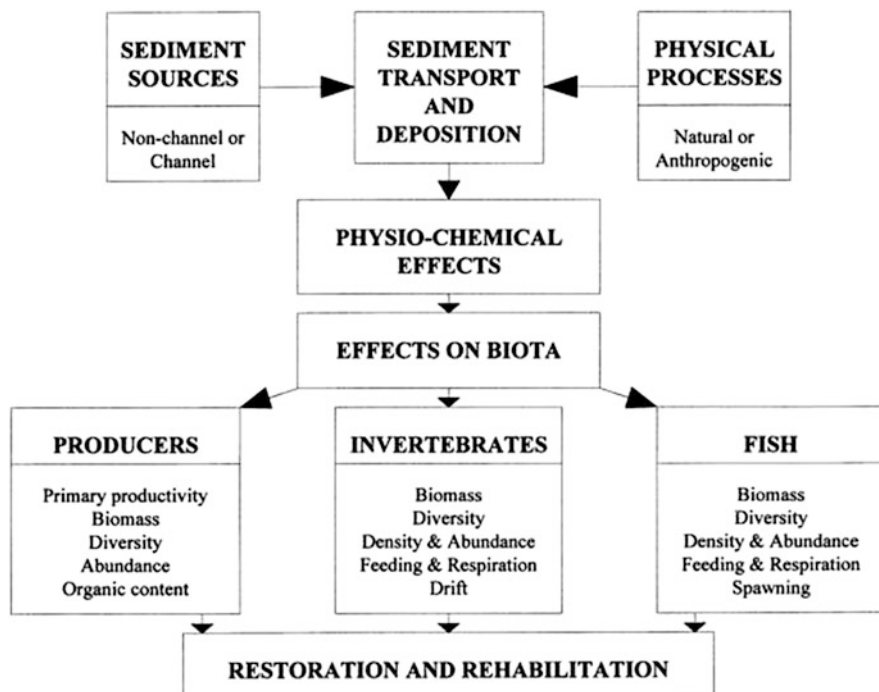


Fig. 8.3 A holistic overview of fine sediment in the lotic ecosystem, after Wood and Armitage (1997) (© Environmental management, Biological effects of fine sediment in the lotic environment, 21(2), 1997, 203–217, Wood, P. J., Armitage, P. D. With permission of Springer)

8.3.2 Ecological Adaptations of Lithophilic Fishes

Sediments play a crucial role in the life cycles of many riverine fish species. This is not surprising since fish fauna had to evolve within the frame of habitat conditions governed by sediment dynamics. Fishes developed strategies or adaptations to cope with dynamic and often stochastically changing sediment conditions. Extensive sediment transport and related relocation are generally destructive events decreasing the survival of incubated egg and juvenile stages of salmonids (e.g., Cattaneo et al. 2002; Lobón-Cerviá and Rincón 2004; Unfer et al. 2011). While the older life stages can actively search for cover, early juvenile stages are exposed to erosive forces that result in high mortality rates. On the other hand, flood events and related sediment relocation reshape the riverbed and refine potential spawning ground for the upcoming spawning period (Poff et al. 1997; Unfer et al. 2011).

For gravel-spawning fish species (lithophilic, most rheophilic species in Europe, such as salmonids and many cyprinids, Fig. 8.4), suitable spawning sediment (bed material composition) and further abiotic components such as water temperature,

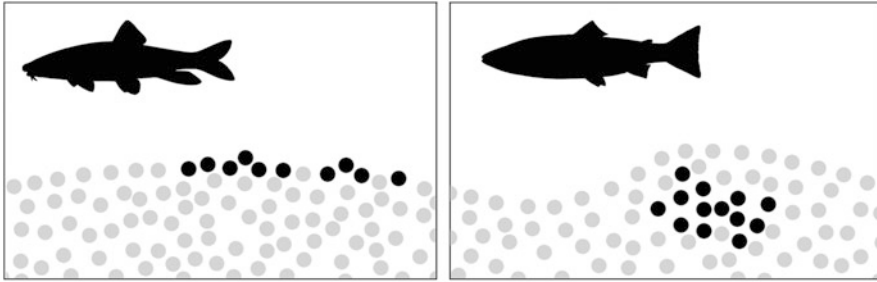


Fig. 8.4 Egg deposition of on-substrate spawners (left, e.g., many cyprinids) and interstitial spawners (e.g., many salmonids)

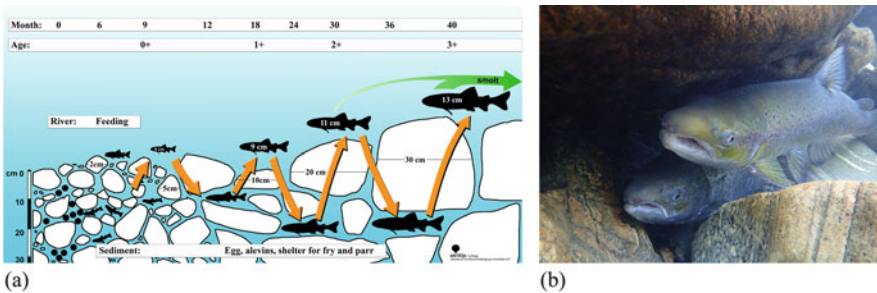


Fig. 8.5 (a) Habitat use of Atlantic Salmon and brown trout juveniles in relation to grain size distribution in Norwegian salmonid rivers (figure adapted from Pulg et al. 2017). (b) Adult Atlantic salmon of approx. 100 cm in length seeking shelter in the river bottom of the boulder-dominated cascade river Nordøla in Western Norway (Photo: Ulrich Pulg).

oxygen concentration, or flow velocity are essential for successful recruitment. Lack of suitable spawning substrate can create bottlenecks for population size and production rates (Pulg et al. 2013). Excessively large grains (large cobble) or armor layers prevent salmonids from redd building (Kondolf 2000), while, on the other hand, high percentages of small grains (fine gravel, sand, silt, clay) do not allow successful reproduction due to reduced permeability and, consequently, insufficient supply of water and oxygen (Sear and DeVries 2008). Besides fines, washout of spawning gravel as well as reduced gravel supply from upstream sources can limit spawning habitats (Barlaup et al. 2008).

Riverine fish depend on substrate also at older life stages (Fig. 8.5). Juveniles of many salmonids spend long periods of their life in the shelter of the sediment, and adults seek shelter on the porous river bottom or behind boulders (Jonsson and Jonsson 2011). Other species (predominately cyprinids) are drifting downstream as larvae and depend on a variable river morphology providing coves, side channels, and oxbows, which are likewise structured by riverbed sediments (Jungwirth et al. 2003).

8.4 Sediment Management Options

Options for sediment management in river catchments are manifold. Basically, they can be divided into (1) structural and (2) nonstructural measures, which can be established on various river scales, including potential consequences (improvements) for downstream river reaches. As an important nonstructural measure, land-use change has to be mentioned. Due to the fact that increased erosion of fines is frequently associated with agricultural land use and intensive forestry (Walling 1990), a reduction of input of erodible soil surfaces provides a management option, especially to prevent clogging of bed sediments (Bakker et al. 2008).

Structural measures on a patch scale (e.g., installation of boulders or deadwood) are useful to create patches of habitats providing the required substratum quality (Hauer 2015). Structural features, such as boulders, have the advantage in that specifically during high (scouring) flows, they provide sheltering habitats in the wake zone accompanied by reduced flow velocities and/or bottom shear stress. Boulder placement or instream use of deadwood can also have effects on the hydraulic conditions and river morphology and, hence, indirectly affect the biota. For example, lateral scour pools with coarse substrate are formed if the flow is vertically or laterally constricted by boulders (Wood-Smith and Buffington 1996).

Examples of structural measures on a larger/local scale are the implementation of river widenings or changes in energy slope (e.g., ramps). Both exhibit local-scale impacts on the sediment transport capacity of rivers. River widenings, in particular, resemble an opportunity to stop riverbed incision, which is often the consequence of a disturbed sediment continuum and channel rectification, specifically in alpine environments. Compared to regulated river sections, local channel widenings increase the hydraulic radius, leading to a decrease in velocity and bottom shear stress (Hauer et al. 2015). In widened river sections, the sediment transport capacity is reduced, which can stop riverbed incision by increasing the aggradation of transported sediments.

Changing the bed (energy) slope is a hydraulic engineering opportunity to influence sediment transport and sediment dynamics when sediment management is required. A large number of artificial transversal obstructions (mainly ramps) are installed to stop ongoing riverbed incision in rectified stretches of alpine gravel bed rivers (DeBene et al. 2016). For this purpose, the bed gradient is reduced between the ramps and the differences in height, and consequently high erosional potential of the flow is controlled by the ramp and the downstream scouring pool (Pagliara 2007). In addition to these technical concepts, by reducing energy slope for channel stability, changes in the bed slope can be explicitly targeted in river restoration (e.g., Habersack et al. 2010) as well as spawning habitat restoration projects (Pulg et al. 2013; Hauer et al. 2015).

Artificial gravel dumping, as an example of structural improvements, is a restoration measure frequently applied below dams (Brown and Pasternack 2008). It affects geomorphic units at meso-scales and thus hydraulic patterns on the microscale (Pasternack 2008). Wheaton et al. (2004) highlight the use of artificial gravel placement as one possible measure to restore or enhance hydro-morphologically suitable spawning habitat conditions for salmonids. For example, in Western Norway, the

restoration of anthropogenically impacted (partially destroyed) spawning habitats of Atlantic salmon (*Salmo salar*) was mainly achieved by artificial gravel dumping (e.g., Barlaup et al. 2008) and the restoration of fluvial processes (Fjeldstad et al. 2012). Other restoration techniques include hydraulic structure placement (e.g., single boulders or groins), mainly to create suitable water depths and flow velocities combined with specific sediment sorting, or an “artificial enhancement” of existing spawning gravels by periodic turnovers of spawning substrate to reduce the amounts of aggregated fine sediments at spawning grounds. The problem inherent with all the above mentioned spawning habitat improvement methods (gravel cleaning, gravel dumping, hydraulic adjustments) is that they were designed to increase the habitat suitability for target species during median or low flow conditions (spawning/incubation period, Wheaton et al. 2004) or to reduce the deposition of fine sediments (Pulg et al. 2013). However, the stability and/or scouring depth of spawning substrate during high flow conditions is typically not assessed in spawning habitat restoration design (short- to mid-term time scale) (e.g., DeVries 2008; Lisle 1989; Buffington et al. 2004).

Concerning sediment management actions in relation to hydropower production, many recent studies focus on sediment management techniques in the reservoir (Schleiss et al. 2010). In this context, very often measures removing sediments from the reservoir, such as mechanical and hydraulic dredging (reservoir flushing), are used (Gaisbauer and Knoblauch 2001). Moreover, sediment bypass systems are frequently investigated and described mitigation measures for sediment management in reservoirs. The diversion of sediments through a tunnel (bypassing) can be seen as a preventive and catchment-scale measure against reservoir sedimentation (Boillat and Pougatsch 2000), as it inhibits the input of bed load and part of the suspended load into the reservoir, ensures sediment continuity during floods (Vischer and Chervet 1996), and thus can improve river ecology and sustainability by preventing riverbed erosion downstream the dam (Schleiss and Boes 2011). Turbidity currents are gravity currents driven by the density contrast between sediment-laden fluid and ambient fluid and are an additional sediment management option (Baas et al. 2005). Moreover, dredging of (fine) sediment material is not only important in alpine hydropower reservoirs but also in run-of-river plants in particular. The dredged material needs to be considered in the morpho-dynamic evolution and sediment balance of the reservoir, while the material dumped downstream of the dam yields an important sediment input on the downstream river reach.

8.5 Conclusions and Outlook

Depending on the morphological river type, sediments can be hydraulically habitat forming or just components of a morphological feature that determines the hydraulic patterns of a river. Aquatic biota (e.g., macroinvertebrates, fish) contain different sediment requirements (e.g., morphological adaption) concerning the sediment quantity and distribution in relation to different life stages. Moreover, different reactions in terms of an increased sediment surplus or sediment deficits by a

disturbed sediment regime are given. Thus, among the most important issues for sustainable river management in the future are studies on processes and consequently an improved process understanding of sediment dynamics on all river scales. Based on this improved process, understanding restoration measures has to be adjusted to cope with, e.g., increased fine sediments, which are now often trapped in reservoirs. Hence, a holistic view of the river systems and driving abiotic processes has to be targeted for future management—including responsible actors in the present sediment management like water management authorities as well as hydropower companies.

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