Biological Effects of Fine Sediment in the Lotic Environment

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ABSTRACT / Although sedimentation is a naturally occurring phenomenon in rivers, land-use changes have resulted in an increase in anthropogenically induced fine sediment deposition. Poorly managed agricultural practices, mineral extraction, and construction can result in an increase in suspended solids and sedimentation in rivers and streams, leading to a decline in habitat quality. The nature and origins of fine sediments in the lotic environment are reviewed in relation to channel and nonchannel sources and the impact of human activity. Fine sediment transport and deposition are outlined in relation to variations in streamflow and particle size characteristics. A holistic approach to the problems associated with fine sediment is outlined to aid in the identification of sediment sources, transport, and deposition processes in the river catchment. The multiple causes and deleterious impacts associated with fine sediments on riverine habitats, primary producers, macroinvertebrates, and fisheries are identified and reviewed to provide river managers with a guide to source material. The restoration of rivers with fine sediment problems are discussed in relation to a holistic management framework to aid in the planning and undertaking of mitigation measures within both the river channel and surrounding catchment area.

The deleterious effects of high suspended solid loads and sedimentation on riverine habitats have been well documented (Berkman and Rabeni 1987, Carling and McCahon 1987). The terms fine sediment and sedimentation used herein describe sediments less than 2 mm in size, thus encompassing sand (<2000 to >62 μm), silt (<62 to >4 μm) and clay (<4 μm) (Chang 1988, Church and others 1987). Fine sediments in the water column increase turbidity, limit light penetration, and potentially reduce primary productivity with resultant impacts on the rest of the food chain (Davies-Colley and others 1992, Van Nieuwenhuyse and LaPerriere 1986). Sedimentation modifies the substrate by altering its surface conditions (Graham 1990) and the volume of fine sediment within the hyporheos (Richards and Bacon 1994). In extreme cases, fine sediments smother the entire riverbed, changing channel morphology (Doeg and Koehn 1994, Nuttall 1972, Wright and Berrie 1987), killing aquatic flora (Brookes 1986, Edwards 1969), clogging the interstices between substrate clasts, increasing invertebrate drift, and reducing the available habitat for benthic organisms (Petts 1984a, Richards and Bacon 1994, Schälchi 1992).

KEY WORDS: Sedimentation; Fine sediment; Holistic approach; Ecological impact; River restoration

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This review aims to provide information on the causes and extent of sedimentation in the lotic environment and in particular the impact on riverine ecology. We aim to examine the whole range of sizes and types of sediment (inorganic and organic) that have been referred to as fine sediments or implicated in sedimentation studies. We recognize that the effects of different types of fine sediment and sedimentation will vary, and where possible distinctions will be made between them. By considering the river holistically (Figure 1) the generation and passage of fine sediment to the stream and its transport, deposition, and storage in the channel can be elucidated. This is important in terms of both natural and anthropogenically induced processes because the extent of sedimentation varies spatially and temporally. Individual rivers respond in different ways to both natural and human impacts according to their catchment characteristics, although the latter tends to accelerate natural processes. There is a need to recognize and identify the physiochemical effects of sedimentation and their impact on riverine biota before mitigation measures are implemented (Figure 1).

Nature and Origins of Fine Sediment

The characteristics of fine sediment in rivers at a global scale are highly variable, reflecting variations in climate, catchment geology, basin scale, and sediment

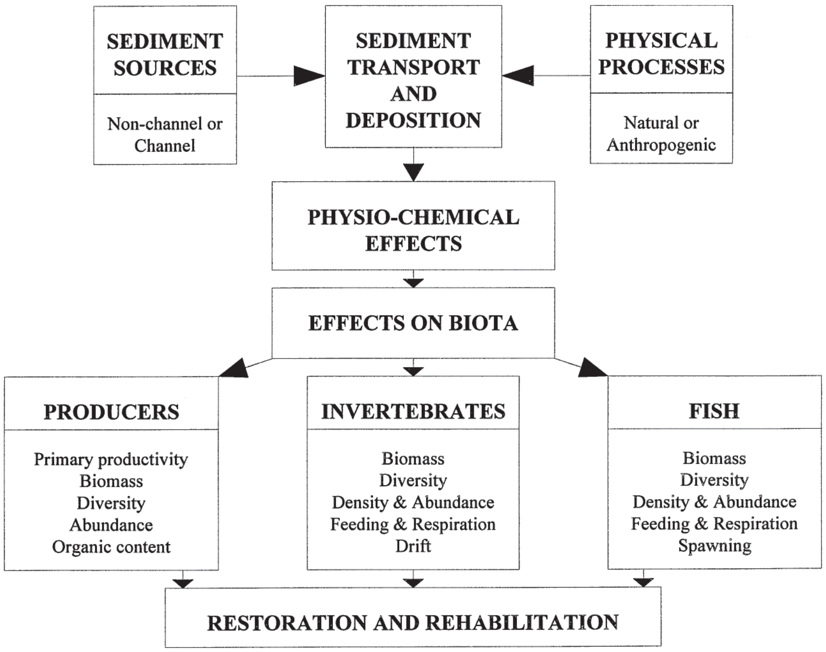

Figure 1. A holistic overview of fine sediment in the lotic ecosystem.

erosion and delivery process (Walling and Moorehead 1989). Frequently the terms "fines" and "sedimentation" are used in their broadest sense by many freshwater scientists. For examples, Pinder and others (1987) refer to "soft sediments" to characterize the entire range of fine particles in riverine deposits. Wright and others (1983) adopt an even broader definition, which encompasses sand and silt (as determined by physical size) as well as fine and coarse organic material such as leaves.

The term sedimentation has similarly been widely applied to the deposition of a whole range of fine sediments. In laboratory flumes the term has been used to describe the deposition of inorganic sediments, ranging from coarse sand to clay (Beschta and Jackson 1979, Carling 1984, Einstein 1968, Jopling and Forbes 1979, Schälchli 1992, 1995). Studies in natural streams and rivers have also examined this wide range of sediment sizes with a varying level of attention given to organic material (Graham 1990, Petts 1988, Sear 1993). The organic matter component of fine sediments has often been ignored, despite the fact it is increasingly being considered a major descriptor of benthic sediments (Gagnier and Bailey 1994) and communities (Boulton and Lake 1992, Culp and Davies 1985). The organic fraction of silt deposits is biodegradable and may be selectively resuspended as flow velocity increases (Carling and McCahon 1987). As a result, the impact of this material may vary seasonally depending on the river in question.

It is widely recognized that sediments less than 63 µm in size are the most important fraction for contaminant adsorption and transport, due to their relatively large surface area and geochemical composition (Stone and Droppo 1994). Silt and clay are particularly important in heavy-metal transport and their storage within fluvial sediments (Thoms 1987). However, the association of toxic materials with fine sediments is beyond the scope of this current review.

At its most basic level, sedimentation is controlled by natural variations in river flow. It is possible to identify two main sources of sediment available to the river: (1) channel sources, which are principally derived from the bed and banks of the stream and its tributaries; and (2) nonchannel sources within the catchment, such as bare soils that are susceptible to erosion (Grimshaw and Lewin 1980). The supply of sediment from channel sources is strongly related to stream discharge and the stability of the channelbed and banks. In marked contrast, the supply of sediment from nonchannel sources may be highly variable depending on its mode of production and transport into the stream. The principle sources of fine particles available to a stream from channel sources are: (1) river banks subject to erosion due to high shear, long exposure to water, and location (e.g., on a meander bend); (2) mid-channel and point bars subject to erosion; (3) fine bed material stored within the interstices or from surficial deposits; (4) natural backwaters where sediment may accumulate during base flow conditions; (5) fine particles trapped within aquatic macrophyte stands or associated with the seasonal growth and decline of aquatic vegetation; and

(6) other biotic particles including phytoplankton and zooplankton. In some instances there may be some on-site generation of fine particles due to the decay of aquatic macrophytes, bioflims and invertebrate material. Benthic invertebrate fecal material has been shown to constitute a significant source of fine particulate matter (Ladle and Griffiths 1980, Ward and others 1994).

However, much of this material would initially be derived from nonchannel sources and may only be stored within the channel temporarily. The main nonchannel sources of fine sediment supplied to a stream are: (1) exposed soils subject to erosion—this material is transported to the channel via gullies, rills, and other features associated with runoff erosion; (2) mass failures within the catchment, such as landslides and soil creep; (3) urban areas, which markedly increase sediment delivery by increasing both the volume and timing of runoff; (4) anthropogenic activities; (5) litter fall, principally leaf material from vegetation adjacent to the channel; and (6) atmospheric deposition, due to aeolian processes and precipitation.

The processes involved are controlled by a number of factors such as land use, soil type, and ground/vegetation cover (Table 1). The influence of these factors may vary depending on the time of year and the nature of individual runoff events. The dynamics of the catchment sediment budget may thus provide important insights into the downstream impact of changing rates of erosion, conveyance, or storage within the river channel (Walling and Quine 1993).

Humans can increase the mobilization of large volumes of sediment into streams and rivers by activities such as agriculture (Richards and others 1993, Walling 1990), mining (Davies-Colley and others 1992), forestry operations (Scrivener and Brownlee 1989), construction of roads (Extence 1978) and reservoirs (Boon 1988, Marchant 1989), and flow regulation (Hellawell 1988, Petts 1988) (see Table 2 for more detail). However, the nature of the river and the environment around it strongly influence the volume of sediment transported to the river, the degree of sedimentation, and its impact on both fauna and flora. Anthropogenic activities have important hydrological, geomorphological, and ecological implications, altering the physical environment of the stream by increasing runoff and affecting both the volume and timing of sediment delivery to the stream.

The most widespread impacts of sedimentation are associated with the fines eroded from agricultural land (Walling 1990). Typically, the deleterious impact of fines associated with forestry activities are less than those in agricultural areas. However, when poorly managed on steep slopes, forestry operations potentially mobilize large volumes of sediment from freshly exposed soils, landslides, surface scour from roads, and sediment stored in the bed and banks of the river (Murphy and Milner 1996). This is primarily the result of a decrease in slope stability as a result of the removal of trees and the decomposition of roots, which help protect the soil and bind it together (Scrivener and Brownlee 1989).

The effect of river regulation via impoundment on benthic substrate is complex and largely depends on the purpose of the dam. A dam used for hydroelectric

Table 1. Factors controlling volume of fine sediment reaching channel from nonchannel sources[a]

Factor	Level of impact	Comment
Topography	Variable	High on steep slopes, low on gentle slopes
Soil type	Variable	Dependent on erodability of soil and ground cover
Ground cover	Variable	Impact decreases with increasing ground cover
Sediment delivery	High	No buffer zone or if disturbance adjacent to watercourse
	Moderate	Some form of buffer zone or impact not adjacent to watercourse
	Low	Extensive control measures/buffer zones or impact some distance away from watercourse
Landuse		
Agriculture	High	>50% arable or poorly managed land
	Moderate	<25% arable or pasture
	Low	Fallow, orchards or effective soil conservation
Forestry	High	Clear cut, bare soil and/or no buffer zone adjacent to watercourse
	Moderate	Clear cut but with some soil conservation and buffer zones
	Low	Well-managed harvesting and effective soil conservation and/or buffer zones
Urban	Variable	Increases both the volume and speed of runoff to the channel
Disturbance (i.e., surface mines and construction activities)	Variable	Highly variable depending on the extent, timing and location of disturbance in relation to watercourse and implementation of preventative measures

[a]Adapted from Coleman and Scatena (1986).

Table 2. Conditions of flow, physical impact, and cause of increase in suspended sediment and sedimentation in rivers and streams

Flow	Location	Impact	Cause	Author
Flume	Washington (USA)	Development of fine sediment clog	Induced	Beschta and Jackson (1979)
Flume	Cumbria (UK)	Infiltration of fine sediment to base of substrate	Induced	Carling (1984)
Flume	California (USA)	Infiltration of fine sediment to base of substrate	Induced	Einstein (1968)
Flume	Washington (USA)	Development of fine sediment clog	Induced	Jackson and Beschta (1984)
Flume	Idaho (USA)	Clogging of the surface of substrate	Induced	McClelland and Brusven (1980)
Flume	Zurich (Switzerland)	Development of fine sediment clog	Induced	Schälchli (1992)
Flume	Zurich (Switzerland)	Development of fine sediment clog	Induced	Schälchli (1995)
Compensation	UK rivers	Thin surficial deposits of silt	Impoundment	Armitage (1987)
Compensation	South Island (N. Zealand)	Siltation of stone surface biofilm/periphyton community	Impoundment	Graham (1990)
Compensation	2 rivers (UK)	Infiltration of fines (<2 mm) into gravel bed	Impoundment	Petts (1988)
Compensation	Northumberland (UK)	Infiltration of fines (<2 mm) into gravel bed	Impoundment	Sear (1993)
0.2–0.6 m/s	3 streams Missouri (USA)	Increase in the proportion of fines within the substrate	Agriculture	Berkman and Rabeni (1987)
0.05–0.38 m/s	British Columbia (Canada)	Experimental sediment deposition and transport (0.5–2 mm)	Induced	Culp and others (1985)
0.15–0.85 m/s	Virginia (USA)	Storage of fine sediment in channel and at margins	Natural	Miller and Shoemaker (1986)
0.86–1.18 m/s	2 streams (USA)	Siltation of experimental cages	Natural	Peckarsky (1984)
0.2–0.4 m/s	Hess (Germany)	Artificial smothering of bed by sand	Induced	Wagner (1984)
0.2–0.4 m/s	Hess (Germany)	Artificial smothering of bed by sand	Induced	Wagner (1989)
Variable	South African rivers	Silt and sand suspension and deposition	Natural/induced	Chutter (1969)
Variable	Colorado (USA)	Fine sediment infiltration into substrate	Road construction	Cline and others (1982)
Variable	California (USA)	Inorganic sediment suspension and deposition	Natural, human impact	Cordone and Kelly (1961)
Variable	Michigan (USA)	Assessment of silted and clean substrates	Induced	Cummins and Lauff (1969)
Variable	South Island (N. Zealand)	Fine sediment suspension and deposition	Placer gold mining	Davies-Colley and others (1992)
Variable	Dorset (UK)	Siltation within macrophyte stands	Natural	Dawson (1978)
Variable	South African streams	Siltation on and within macrophytes	Natural, human impact	Edwards (1969)
Variable	USA rivers	Erosion silt suspension and deposition	Natural, human impact	Ellis (1936)
Variable	Essex (UK)	Smothering of substrate by sand and silt	Road construction	Extence (1978)
Variable	London (UK)	Development of fine sediment clog	Natural	Frostick and others (1984)

Table 2. (Continued)

Flow	Location	Impact	Cause	Author
Variable	Wyoming (USA)	Sediment in suspension and deposition at margins of river	Reservoir release	Gray and Ward (1982)
Variable	N. Carolina (USA)	Filling of substrate interstices and surficial silts	Logging and enrichment	Lemly (1982)
Variable	California (USA)	Infiltration of fines in to gravel bed	Natural	Lisle (1989)
Variable	California (USA)	Filling of pools with fine sediment	Regulation and logging	Lisle and Hilton (1992)
Variable	Cornwall (UK)	Sediment suspension and deposition of sand	China clay extraction	Nuttall (1972)
Variable	Cornwall (UK)	Sediment suspension and deposition of sand and silt	China clay extraction	Nuttall and Bielby (1973)
Variable	South Island (N. Zealand)	Fine sediment suspension and deposition	Placer gold mining	Quinn and others (1992)
Variable	New Zealand streams	Fine sediment suspension and deposition	Natural, human impact	Ryan (1991)
Variable	Birmingham (UK)	Infiltration of fines into gravel bed	Urbanisation	Thoms (1987)
Variable	Shropshire (UK)	Deposition and resuspension in a natural backwater/dead zone	Natural	Tipping and others (1993)
Variable	Wales (UK)	Infiltration of fines into gravel bed	Coal mining	Turnpenny and Williams (1980)
Variable	Alaska (USA)	Fine sediment suspension and deposition	Placer gold mining	Van Nieuwenhuyse and LaPerriere (1986)
Variable	Dorset (UK)	Deposits at margins of river and within macrophytes	Natural	Welton (1980)
Base Flow	Ontario (Canada)	Deposition of up to 0.61 g dry weight/cm/day	Road construction	Barton (1977)
Base Flow	Alaska (USA)	Fine sediment suspension and surficial deposition	Placer gold mining	Bjerklie and La Perriere (1985)
Base Flow	4 rivers (UK)	Sediment suspension and varying degrees of siltation	Channelisation	Brookes (1986)
Base Flow	Durham (UK)	Infiltration of fines into gravel bed	Natural	Carling and McCahon (1987)
Base Flow	3 upland streams (UK)	Surficial fine particle deposition	Natural	Carling and Reader (1982)
Base Flow	Victoria (Australia)	Sand and silt deposition up to 2 km downstream of weir	Desilting operations	Doeg and Koehn (1994)
Base Flow	Ontario (Canada)	Surficial fine particle deposition	Natural	Droppo and Stone (1994)
Base Flow	Devon (UK)	Surficial fine particle deposition	Natural	Lambert and Walling (1988)
Base Flow	California (USA)	Storage of fines (<210 μm) in gravel bed	Natural, Logged	Mahoney and Erman (1984)
Base Flow	Idaho (USA)	Infiltration of sand (>150 μm) into gravel bed	Natural, Human impact	Richards and Bacon (1994)
Base Flow	Alaska (USA)	Infiltration of sand into gravel bed	Induced	Shapley and Bishop (1965)
Base Flow	Kent (UK)	Extensive siltation of river bed and margins	Drought and abstraction	Wood and Petts (1994)
Base Flow	Berkshire (UK)	Extensive siltation of river bed and margins	Drought and abstraction	Wright and Berrie (1987)

power generation will have a highly variable discharge, whereas one used for the storage of water for a public water supply will vary moderately. The general effect of a dam is to reduce pre-regulation peak discharge and to increase low flows (Petts 1984b). Almost all sediment transported by the river upstream of the impoundment will be deposited within the reservoir, and this reduction in sediment load downstream can lead to significant main channel degradation and armoring of substrates where the river retains its erosive power (Donnely 1993). However, downstream of non-regulated tributaries, sedimentation has been widely recognized as a consequence of the elimination or reduction in the magnitude and frequency of mainstream floods that would naturally act as flushing flows for these sediments (Petts 1984b, 1988). In their absence, sedimentation may occur on both the surface and within the substrate, leading to the development of a finer gravel matrix infill than in comparable unregulated tributaries and rivers (Armitage 1987, Petts 1988, Sear 1993).

Suspension and Deposition

Artificial or experimental manipulations of fine sediment have been more widely reported than natural increases in deposition as a result of low flows, primarily because in most cases they are easier to monitor. It is generally difficult to predict natural events that will result in fine sediment deposition due to the relatively infrequent nature of droughts and low flows.

The initiation of particle motion from the bed and banks of a river occurs when a threshold flow intensity is exceeded. The critical flow intensity controlling the initiation of particle movement is measured by shear stress, velocity, or stream power, and this critical flow has the minimum intensity capable of initiating the movement of a sediment grain (Richards 1982, Schälchli 1992). Well-sorted sand grains (0.2–0.5 mm) have the lowest threshold velocity and critical bed shear. Greater velocities and shear stress values are required to transport larger particles and also smaller particles that are protected by submergence within the laminar sublayer. However, many fine sediments are cohesive and are normally eroded as floccules rather than individual particles, further discouraging their detachment (Richards 1982). Two types of fine sediment transport can be identified: (1) along the surface of the substrate as bedload by rolling, sliding, or saltating; and (2) as turbulence increases, the weight of the particle may be upheld as suspended load by a succession of eddy currents (Petts and Foster 1985).

The deposition of fine sediments occurs when tractive forces are less than the settling velocity (gravitational forces) exerted upon the grain, as expressed by Stokes's Law (Richards 1982). However, this only holds for silts and clays. For particles larger than 0.1 mm, the relationship between grain diameter and fall velocity is nonlinear due to the influence of inertial forces. Several other factors such as particle shape, water temperature, flocculation of particles, and the turbulent nature of flow in rivers also influences particle deposition (Carling 1992, Norwell and Jumars 1984). The assumption that fine sediment deposition only occurs in areas of slow flowing water is a common misunderstanding. During spates, an increase in the volume of suspended sediment and fine bedload occurs. Some of this material is carried into interstitial spaces reducing substrate porosity and hydrostatic permeability, leading to a decline in the volume of water within the substratum and reduced concentrations of dissolved oxygen (Crisp 1989, Moring 1982, Turnpenny and Williams 1980).

Experimental studies, principally in flumes, have identified many of the physical effects of sedimentation, although the outcome largely depends on the nature of the fines and the substrate. Froude numbers have been used to help characterize the flow conditions that influence the intrusion of fines into the bed (Beschta and Jackson 1979, Carling 1984). This dimensionless variable represents the ratio of inertial to gravitational forces in fluid flow (Chow 1959). At low Froude values, 0.5-mm sand grains have been observed to develop a seal or clog in the uppermost layer of previously clean gravels, thus preventing the infiltration of fines deeper in to the substrate. At higher values, associated with greater velocity and turbulence, the seal has been observed to develop at greater depth within the substrate (Beschta and Jackson 1979, Schälchli 1992). This process can be divided into three phases. In phase 1, coarser particles effectively bridge and close interstitial pores and crevices. During phase 2, the pores are filled by medium-sized particles, and in the final phase, the accumulation of fine particles leads to the development of an almost impermeable layer between the surface and subsurface layers of the substrate (Schälchli 1995). However, in flume studies of finer (<0.5-mm) sediments, the development of clogs has not been recorded. These sediments, through a combination of turbulent pulses and gravitational settling, have been observed to fill interstitial spaces from the base of the substrate upwards (Carling 1984, Einstein 1968).

Sedimentation occurs under a number of flow conditions and in different areas of the channel, resulting in distinct types of sedimentation and characteristic deposits (Table 2). A reduction in flow velocity, particularly during low flow conditions during the summer months, can lead to large volumes of fines and decaying organic matter being deposited onto the riverbed (Giles and others 1991). This problem is particularly acute in groundwater-fed streams, which rely on precipitation for aquifer recharge (Wright and Berrie 1987).

During baseflow conditions, the development of ephemeral surficial fine particle deposits up to 20 mm thick have been reported (Carling and Reader 1982, Droppo and Stone 1994, Lambert and Walling 1988). The influence of these predominantly inorganic deposits have been difficult to gauge due to their temporary nature, although they do not appear to consolidate into a compact layer and are easily disturbed and resuspended when flow increases. It has been noted, however, that almost all of these sediments have a grain size <1 mm and are similar to the substrate matrix material. Some of these sediments may therefore infiltrate into the bed and constitute an important source of particles for replacing matrix material winnowed from the interstices of the substrate during high flows.

Even under normal flow conditions, natural sedimentation occurs in backwaters or dead zones, such as clearly defined pools, regions of retarded flow close to the bank, the water within macrophyte beds, and sheltered areas behind individual cobbles and boulders. Anthropogenic structures, such as the lee behind a groin, may also be considered to be dead zones. Large volumes of sediment accumulate in these areas due to reduced resuspension and enhanced deposition, except at high discharge when turbulent flow mobilizes these sediments (Tipping and others 1993). An experimental reduction in flow from 0.5 m/s to <0.01 m/s in an artificial dead zone resulted in complete coverage of a gravel substrate by fine organic material within two days (Armitage unpublished data).

Effects on Biota

The causes and deleterious effects of fine sediment suspension and deposition on the ecology of running waters have been widely reported (Table 3), with the most marked impact on primary productivity, faunal diversity, and abundance. The influence of fine sediment on fisheries has historically been particularly well documented (Cordone and Kelly 1961, Shapley and Bishop 1965) as have the effects on benthic invertebrates (Chutter 1969, Cordone and Kelly 1961, Cummins and Lauff 1969), although there have been relatively few studies on the effects of sedimentation on aquatic macrophytes (Edwards 1969).

Primary Producers

The impact of sedimentation on producers in streams and rivers has far reaching consequences since periphyton and aquatic macrophytes form the base of the food chain and any deleterious impacts will probably also be manifested in the invertebrate and fish communities. Fine sediment suspension and deposition affects producers in four main ways: (1) by reducing the penetration of light and, as a result, reducing photosynthesis and primary productivity within the stream (Van Nieuwenhuyse and LaPerriere 1986); (2) by reducing the organic content of periphyton cells (Cline and others 1982, Graham 1990); (3) by damaging macrophyte leaves and stems due to abrasion (Lewis 1973a,b); and (4) by preventing attachment to the substrate of algal cells, and by smothering and eliminating periphyton and aquatic macrophytes in extreme instances (Brookes 1986).

Aquatic macrophyte growth has important implications for the hydraulic conditions within a stream. Seasonal growth of both marginal and instream macrophytes influences flow velocity and secondary flow patterns, creating areas of slow and fast flowing water, increasing channel roughness (Manning's *n*) and water depth (Hearne and Armitage 1993, Watson 1987), and increasing habitat diversity (Armitage 1995). Macrophyte stands can therefore enhance the deposition and accumulation of fine sediments (Carpenter and Lodge 1986, Dawson 1978, Welton 1980) and effectively act as sieves, trapping sediment particles that settle out and are deposited beneath them.

In extreme instances, high suspended solid concentrations or sediment deposition may exclude periphyton and rooted macrophytes from reaches where they historically occurred or would naturally be expected (Nuttall and Bielby 1973, Van Nieuwenhuyse and LaPerriere 1986). Lewis (1973a) found that suspended coal particles seriously damaged the aquatic moss, *Eurhynchium riparioides*. Deleterious abrasion of the plants' leaves was evident within three weeks at a sediment concentration of 100 mg/liter and the development of new side shoots only occurred at concentrations below 500 mg/liter. As the volume of suspended coal particles increased to 5000 mg/liter germination of spores was reduced by 42% (Lewis 1973b).

Brookes (1986, 1988) examined the effects of channelization, involving the straightening, widening, or deepening of the channel, on the macrophytes in four rivers in southern England. Twenty-four hours after operations ceased in Wallop Brook, Hampshire (UK), the deposition of sediment reached a maximum of 130 cm in pools and 5 cm in riffles. Stands of *Ranunculus penicillatus* var. *calcareus* (Butcher), were smothered and eliminated in pools since the plant is unable to vary its rooting level. In contrast *Nasturtium officinale* only declined by 60%, reflecting its ability to adjust its

Table 3. Ecological impact and cause of an increase in suspended sediment and sedimentation in rivers and streams

Impact	S/D[a]	Cause	Author
Primary producers			
Elimination of macrophytes—no effect	D	Channelisation	Brookes (1986)
Reduced species diversity and organic content	S & D	Road construction	Cline and others (1982)
Reduced productivity, biomass, and organic content	S & D	Placer gold mining	Davies-Colley and others (1992)
Reduced organic content	D	Impoundment	Graham (1990)
Reduced primary productivity	S & D	Placer gold mining	Van Nieuwenhuyse and LaPerriere (1986)
Macroinvertebrates			
Impaired filter-feeding and reduced metabolic rate of mussels	S	Induced	Aldridge and others (1987)
Reduced density, abundance, and diversity	S & D	Road construction	Cline and others (1982)
Reduced density (>50%) and increased drift	S & D	Induced	Culp and others (1985)
Reduced abundance and diversity	S & D	Desilting operations	Doeg and Koehn (1994)
Reduced density and diversity	D	Water filtration facility	Erman and Ligon (1988)
Change in community structure	D	Road construction	Extence (1978)
Change in community structure	S & D	Reservoir release	Gray and Ward (1982)
Reduced diversity and biomass	D	Logging and nutrient enrichment	Lemly (1982)
Reduced diversity	D	China clay extraction	Nuttall (1972)
Reduced diversity and relative abundance of taxa	D	China clay extraction	Nuttall and Bielby (1973)
Reduced density and effect of predation	D	Natural	Peckarsky (1984)
Reduced density and diversity	S & D	Placer gold mining	Quinn and others (1992)
Change in community structure	S & D	Agriculture	Richards and others (1993)
Change in community structure and an increase in drift	S & D	Induced	Rosenberg and Wiens (1978)
Decline in abundance of emerging taxa	D	Induced	Wagner (1984)
Decline in abundance of emerging Ephemeroptera	D	Induced	Wagner (1989)
Change in community structure	D	Induced	Walentowicz and McLachlan (1980)
Reduced abundance	D	Drought—Abstraction	Wood and Petts (1994)
Reduced abundance and diversity	D	Drought—Abstraction	Wright and Berrie (1987)
Fish			
Reduced standing crop	S & D	Road construction	Barton (1977)
Reduced abundance of benthic insectivores, herbivores, and lithophilous spawners	D	Agriculture	Berkman and Rabeni (1987)
Decline in quality of salmonid spawning habitat	D	Natural	Carling and McCahon (1987)
Reduced abundance	D & S	Desilting operations	Doeg and Koehn (1994)
Reduced survival of salmonid eggs	D	Water filtration facility	Erman and Ligon (1988)
Decline in quality of salmonid spawning habitat	D	Natural	Lisle (1989)
Decline in quality of salmonid spawning habitat	D	Impoundment	Sear (1993)
Decline in quality of salmonid spawning habitat	D	Induced	Shapley and Bishop (1965)
Decline in quality of salmonid spawning habitat and reduced survival of eggs	D	Coal mining	Turnpenny and Williams (1980)

[a]S = suspended sediment, D = deposition of sediment.

rooting level. In Ober Water, Hampshire, and the River Cale, Somerset, surficial deposits were never more than 10 cm thick. In the River Wylye, Wiltshire, sediment deposition was negligible because operations coincided with a period of high water flow, resulting in most of the sediment remaining in suspension; because construction took place before the start of the growing season, there was no damage to riverine macrophytes. In all of the river's post-operation deposits were short-lived and were removed during the next spate. This demonstrates that the timing of channel management activities is vitally important in the management of fine sediments.

Benthic Macroinvertebrates

The natural variability of river flow, from the extremes of flood to low flows, results in variations in the concentration of suspended solids and their deposition. Therefore, benthic faunal communities should be able to withstand short-term increases in suspended and benthic sediments. Additions of fine particulate material due to human disturbance over a short duration may also result in a rapid recovery. However, continuous high levels of sediment input, generally associated with agriculture and surface mining activity, may completely change the natural faunal assemblage.

Fine sediment suspension and deposition affects benthic invertebrates in four ways: (1) by altering substrate composition and changing the suitability of the substrate for some taxa (Erman and Ligon 1988, Richards and Bacon 1994); (2) by increasing drift due to sediment deposition or substrate instability (Culp and others 1985, Rosenberg and Wiens 1978); (3) by affecting respiration due to the deposition of silt on respiration structures (Lemly 1982) or low oxygen concentrations associated with silt deposits (Eriksen 1966); and (4) by affecting feeding activities by impeding filter feeding due to an increase in suspended sediment concentrations (Aldridge and others 1987), reducing the food value of periphyton (Cline and others 1982, Graham 1990) and reducing the density of prey items (Peckarsky 1984).

An increase in the volume of fine sediments clearly favors some benthic invertebrates at the expense of others. Some taxa, such as Chironomidae, utilize fine sediments in the construction of cases and tubes (Dudgeon 1994), and Oligochaeta and Sphaeriidae are frequently associated with fine sediment (Armitage 1995). However, there have been relatively few studies on the effects of fine sediment deposition on individual taxa. Eriksen (1963, 1966) examined the oxygen consumption of two burrowing mayfly larvae in different sized substrates. *Ephemera simulans* displayed a preference for coarse substrates since its gills are inefficient at the low O_2 concentrations found in silt deposits. *Hexagenia limbata,* in contrast, is more common in silt deposits, into which it burrows. Both taxa display morphological and physiological adaptations for the preferred environment, emphasizing the need to understand specific faunal habitat requirements and their response to fine sediment deposition.

The most serious and obvious ecological and physical effects of sedimentation occur as a result of human activity close to river channels. Placer gold-mining on the West Coast of the South Island of New Zealand resulted in a deterioration of the optical properties of the water and the deposition of fine onto and within the riverbed (Davies-Colley and others 1992). The resulting low densities of benthic flora and macroinvertebrates were attributed to the high level of suspended solids and associated turbidity (Quinn and others 1992). Similar results were recorded in streams in Alaska subject to placer gold mining (Bjerkli and LaPerriere 1985) and several streams in Cornwall, England, subject to china clay wastes (Nuttall 1972, Nuttall and Bielby 1973).

The deposition of sand is a particular problem highlighted in many studies (see Tables 1 and 3). Leudtke and Brusven (1976) suggested that its deposition indirectly affects benthic fauna by impeding their upstream migration, even at low current velocities. Sand is an inherently unstable substrate (ASCE 1992) with most benthic taxa being found in the uppermost layers of the substrate (Strommer and Smock 1989) and some small taxa reach very high densities (Soluk 1985). It has also been recognized that the timing of sand deposition, peaking during base flow conditions, coincides with the period of dispersion and colonization by young benthic macroinvertebrates (Extence 1978).

Fish

The effects of fine particle suspension and deposition on fish are better documented than for other organisms. There are several reasons for this; fish are economically important both commercially and recreationally. Other organisms do not offer such tangible benefits, although in some countries, such as the UK, there is government legislation that requires river authorities to protect the flora and fauna in the waters under their control (Armitage and Petts 1992). It has also been suggested that the effects of anthropogenic activity will ultimately be reflected in the fish community, due to direct impacts and/or food-chain-related events (Ryan 1991).

At least five ways in which high concentrations of fine sediment adversely affect lotic fisheries have been identified. (1) by adversely acting on the fish swimming in the water and either reducing their rate of growth, reducing their tolerance to disease or killing them; lethal concentrations primarily kill by clogging gill rakers and gill filaments (Bruton 1985); (2) by reducing the suitability of spawning habitat and hindering the development of fish eggs, larvae and juveniles; all of these stages appear to be more susceptible to suspended solids than adult fish (Chapman 1988, Moring 1982); (3) by modifying the natural migration patterns of fish (Alabaster and Lloyd 1982); (4) by reducing the abundance of food available to fish due to a reduction in light penetration and as a result photosynthesis, primary production, and a reduction of habitat available for insectivore prey items (Bruton 1985, Doeg and Koehn 1994, Gray and Ward 1982); and (5) by affecting the efficiency of hunting, particularly in the case of visual feeders (Bruton 1985, Ryan 1991).

Salmonids deposit their eggs in a shallow pit or redd excavated by the female at the head of a riffle and then bury them under 10–40 cm of bed material. The location and construction of the redd winnows out fine sediments, thus increasing gravel permeability and intergravel flow to oxygenate the eggs (Kondolf and others 1993, Milner and others 1981, Sear 1993). However, incubation requires between two and six months and during this period the redds are vulnerable to the deposition of fine sediments (Chapman 1988, Lisle 1989). Experimental studies have shown that the concentration of fines is a critical factor in the embryonic development of salmonids. A significant increase in the volume of fines can result in reduced egg survival, an increase in the number of premature alevins, and an increase in the likelihood of predation (Olsson and Petersen 1986, Reiser and White 1990). Lisle (1989) found that the infiltration of fine bedload material (0.25–2 mm) into salmonid spawning gravels accounted for 70%–78% of the total sediment deposited within experimental gravels, implanted in a river in California. In extreme cases, when the surface layers of the substrate become clogged, developing eggs and fry may be entombed (Kondolf and others 1993, Moring 1982, Petts 1988).

Sedimentation of salmonid spawning gravels as a result of coal industry effluent on the Ebbw Fawr, an industrial river in South Wales, seriously suppressed reproductive success and the natural recovery of trout (*Salmo trutta* L.) populations (Turnpenny and Williams 1980). In reaches affected by mining waste, a decline in dissolved oxygen and gravel permeability occurred. During incubation in seriously affected reaches 98%–100% of eyed salmonid eggs died compared to 9% at a nearby control site. A survival threshold for dissolved oxygen of 16 μg/cm^2/h was calculated with a medium lethal supply rate of 50 μg/cm^2/h. Even if dissolved oxygen levels are above this critical threshold, however, the removal of metabolic wastes may not occur from within the substrate, leading to a fatal increase in carbon dioxide and ammonia levels.

The negative effects of sedimentation on fisheries are not confined to salmonids. The deposition of fines on the bed of a river in northeast Missouri (USA) resulted in identifiable impacts on both fish feeding and reproductive guilds (Berkman and Rabeni 1987). As the percentage of fine substrate increased, the difference between fish assemblages in riffles, runs, and pools decreased, largely due to a decline in the abundance of riffle taxa. Benthic insectivores and herbivores declined, as did lithophilous/gravel spawners, as the volume of <62.5-μm sediment increased within the bed. The results of this study suggested an overall degradation of fish habitat, due to sedimentation, as a result of erosion from adjacent agricultural land.

Discussion

The causes and negative effects of increased suspended sediment and sedimentation on the physical environment and the flora and fauna in streams and rivers around the world are highly variable (Tables 2 and 3). This reflects the different sediment sources, types of sediment, and the factors influencing its transport and deposition into and within the channel (Table 1). Human activities have greatly increased the natural sedimentation processes. In some instances this has been difficult to quantify, particularly in the case of agriculture. This is largely due to the lack of information relating to natural baseline conditions and the cumulative effect of fine sediments from headwaters on downstream areas.

The recovery of flora and fauna after an impact associated with fine sediments is controlled by the nature of the impact and the survival of organisms in refugia from which recolonization can take place (Sedell and others 1990); as a result recovery times vary greatly (Niemi and others 1990). Natural recovery processes may operate quickly following short-duration pulse disturbances: 21 days as a result of sediment released due to reservoir cleaning operations (Gray and Ward 1982), 45 days as a result of desilting a weir (Doeg and Koehn 1994). It is important to distinguish between different types and magnitudes of disturbance (Gore and Milner 1990). When an impact is extended over several months or years, as in the case of mineral extraction, impoundment, urbanization, and agricultural practice, the morphology and ecology of the

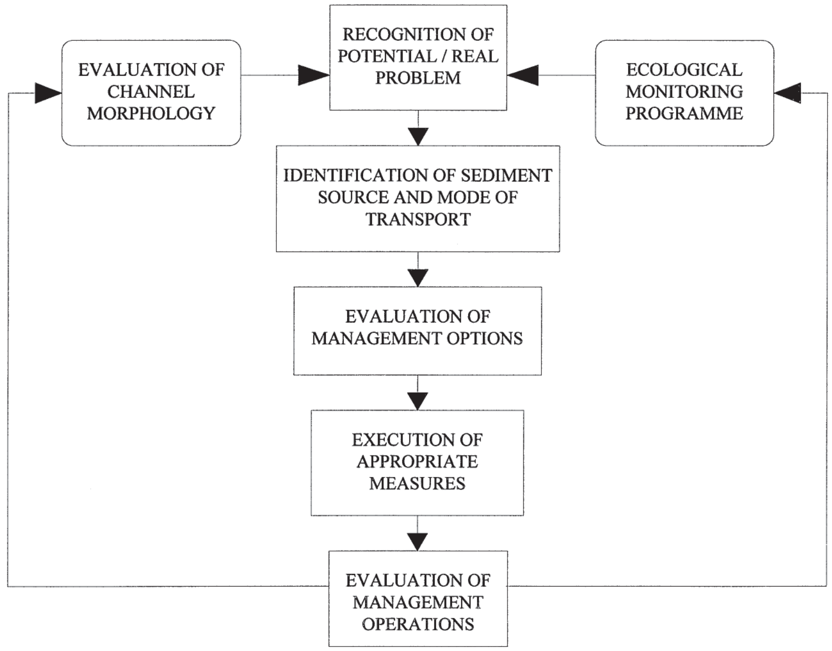

Figure 2. A holistic management framework for fine sediment in streams and rivers.

channel may be completely altered. Press disturbances such as these may require many months or years for the morphology and ecology of the channel to recover and may require human intervention to restore the system to a natural state.

Recognition of the need for river restoration has been widely accepted (Brookes 1988, Gardiner 1991), and there are an ever increasing number of terms used to describe restoration activities, including rehabilitation, revitalization, renaturation, reconversion, and restructuring (Muhar and others 1995). These terms encompass a wide range of activities at different scales, from the creation of an individual pool or riffle to the long-term management of entire river systems. However, there is a need to undertake such operations within a holistic framework. Figure 2 shows a pathway through which the monitoring of riverine ecology and channel characteristics can be utilized by river managers to aid in the identification of potential and existing problems within the catchment associated with fine sediment. This in turn can be used to evaluate different management options, undertake appropriate mitigation measures, and form the basis of an ongoing ecological and physically based monitoring program.

Many measures exist to control sediment deposition and transport in streams. In catchments with high sediment loads it may be necessary to install sediment traps, stabilize river banks, and introduce instream devices such as groins and willow posts (Brookes 1988, Jungwirth and others 1995, Sear and others 1994, Shields and others 1995). These measures reduce sediment input into the channel and/or help remove fine sediment accumulations from key locations at the margin and within the bed of the river. The main aim of such projects is usually to increase instream morphological diversity and ecological value, primarily directed at fish habitat, while at the same time maintaining flood defense properties. Results have been promising, with several projects reporting improvements in the physical environment and an increase in the number of fish taxa present as well as an increase in density and biomass (Jungwirth and others 1995, Shields and others 1995). However, in the case of some of the most degraded rivers, short- and medium-term management options may not offer any perceptible benefit, despite substantial economic expenditure. In such situations it may be necessary to accept the dereliction of a river so that resources can be directed to rivers where restoration projects have a chance to succeed (Boon 1992). This emphasizes the need for further research and long-term studies to assess the temporal and spatial variability of sedimentation.

Probably the most desirable, although often impractical, aim of restoration activities involves the prevention of fine sediment influx to the stream. The primary aim of such a project is to address the causal factors at their source within the catchment rather than cure the symptoms within the stream. Reforestation or the establishment of riparian vegetation is increasingly common (Jungwirth and others 1995) despite the time lag of up to 30 years between its establishment and observable recovery (Bryant 1995). Other options involve the careful development of best management practices for human activities such as agriculture, construction, and forestry to minimize erosion and sediment delivery to the channel. The proposed holistic approach to the management of fine sediments within river catchments (Figures 1 and 2) should enable river managers, hydrologists, geographers, and ecologists alike to identify sediment sources, the impact of sedimentation, and an increase in suspended sediments in both the physical environment and the flora and fauna within the channel. Through the identification and consideration of these factors the deleterious impact of sedimentation may be mitigated allowing the river to recover.

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