

FINE-GRAINED SEDIMENT IN RIVER SYSTEMS: ENVIRONMENTAL SIGNIFICANCE AND MANAGEMENT ISSUES

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ABSTRACT

Fine-grained sediment is a natural and essential component of river systems and plays a major role in the hydrological, geomorphological and ecological functioning of rivers. In many areas of the world, the level of anthropogenic activity is such that fine-grained sediment fluxes have been, or are being, modified at a magnitude and rate that cause profound, and sometimes irreversible, changes in the way that river systems function. This paper examines how anthropogenic activity has caused significant changes in the quantity and quality of fine-grained sediment within river systems, using examples of: land use change in New Zealand; the effects of reservoir construction and management in different countries; the interaction between sediment dynamics and fish habitats in British Columbia, Canada; and the management of contaminated sediment in USA rivers. The paper also evaluates present programmes and initiatives for the management of fine sediment in river systems and suggests changes that are needed if management strategies are to be effective and sustainable. Copyright © 2005 John Wiley & Sons, Ltd.

KEY WORDS: fine-grained sediment; river basins; sediment management; land use change; reservoirs; fish habitats; contaminated sediment; sustainable management

INTRODUCTION

Fine-grained sediment in river systems

Viewed at the simplest level, material is transported in rivers in two forms, as solid material and in solution (with the latter usually being defined as material $<0.45\ \mu\text{m}$), and within each of these two forms there are organic and inorganic components. The solid load is usually divided into bedload and suspended load. Whether material is bedload or suspended load is usually determined by the relationship between flow conditions and the structure, density and size of the material, with the suspended load being composed of finer and/or less dense material. In many river systems, most of the suspended sediment load is $<2\ \text{mm}$ (i.e. sand-sized or less) in size, with much of this being $<63\ \mu\text{m}$ (i.e. silt- and clay-sized material), although there are exceptions (Walling and Moorehead,

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1989; Walling *et al.*, 2000). In addition, the $<63 \mu\text{m}$ fraction of the suspended load has increased importance in biogeochemical fluxes within river systems because this is the chemically active component of the solid load and thus many contaminants and nutrients (including polychlorinated biphenyls (PCBs), dioxins, radionuclides, heavy and trace metals, and phosphorus) are transported (and stored) in association with the $<63 \mu\text{m}$ fraction (Salomons and Forstner, 1984; Horowitz *et al.*, 1993, 1995; Foster and Charlesworth, 1996; Owens *et al.*, 2001). It is important to recognize, however, that much of the fine-grained suspended load is cohesive and, thus, is not transported as individual discrete particles but rather as flocculated or aggregated particles (Droppo and Ongley, 1994; Petticrew and Droppo, 2000; Droppo, 2001).

For the reasons described above, this paper considers fine-grained sediment as material likely to be transported within the river channel in suspension and thus focuses on material $<2 \text{ mm}$ in diameter, with emphasis on the $<63 \mu\text{m}$ fraction. This paper does not (except from the perspective of sediment production, when the two modes of transport are difficult to separate) consider coarse-grained sediment because the transport processes and management issues generally differ from those that relate to fine-grained sediment and are considered in other publications in this special issue.

Fine-grained sediment: quantity and quality issues

The delivery of suspended sediment to the global ocean has been estimated to be of the order of $15\text{--}20 \times 10^9 \text{ t year}^{-1}$, with a disproportional amount being discharged by rivers in mountainous areas (Milliman and Syvitski, 1992; Farnsworth and Milliman, 2003; Syvitski, 2003). Increasingly, research based on long-term monitoring (i.e. decades) of suspended sediment fluxes, sediment budget studies and reconstructed sediment yields from depositional environments (such as lakes and reservoirs) is showing that fine-grained sediment fluxes (especially fine sediment delivery to rivers and sediment transport in rivers) are generally increasing throughout the world in catchments that are impacted by human activities, such as deforestation, agriculture, construction and mining activities (Wolman and Schick, 1967; Trimble, 1983; Dearing *et al.*, 1987; Soutar, 1989; Dedkov and Mozhherin, 1992; Walling, 1995; Foster and Lees, 1999; Walling and Fang, 2003; Owens, 2005a). Human activity may be directly or indirectly responsible for 80–90% of the fluvial sediment delivered to the coastal oceans (Farnsworth and Milliman, 2003). In many upland and mountain environments, however, the link between human activity and sediment yields is less clear, at least on a regional scale, and other factors such as climate and tectonic activity appear to dominate observed trends and patterns (Caine, 2004). In cases where trends in estimated fine-grained sediment fluxes (transport or deposition rates) have been compared to climate records and anthropogenic activities (such as land use and management) (cf. Foster and Lees, 1999; Owens and Walling, 2002a; Olley and Wasson, 2003), the latter often provide the best match and explain the observed patterns in sediment fluxes. On the other hand, in some regions decadal or shorter variations in fine sediment fluxes can be linked to climatic fluctuations caused by phenomena such as El Niño/Southern Oscillation (Syvitski, 2003; Gomez *et al.*, 2004). There are, however, important temporal and spatial scaling effects, magnitude–frequency considerations, hillslope–channel coupling issues, and floodplain and channel storage effects that need to be considered when disentangling the effects of climate and anthropogenic activities on sediment fluxes (Phillips, 1992, 1997; G. C. Foster *et al.*, 2003; I.D.L. Foster *et al.*, 1996, 2000; Métivier and Gaudemer, 1999; Trustrum *et al.*, 1999; Lang *et al.*, 2003).

Although human activity has generally resulted in increased fine-grained sediment delivery to rivers and increased sediment transport in rivers, it must be recognized that this is not always translated to increased sediment yields in downstream reaches. In some instances downstream sediment yields have remained broadly constant, for example due to changes in sediment storage, or have decreased over time due to the construction of impoundments, dams and reservoirs (Trimble, 1983; Vörösmarty *et al.*, 2003; Walling and Fang, 2003). Vörösmarty *et al.* (2003), for example, estimate that reservoirs trap about 25–30% of the global sediment flux to the oceans.

In studies that have been able to determine the sources of the fine-grained sediment being actively transported in rivers (by direct monitoring or fingerprinting techniques), these sources are often dominated by topsoil from agricultural fields, especially arable and overgrazed grassland (Collins *et al.*, 1997; Walling *et al.*, 1999; Owens *et al.*, 2000) or parts of the catchment disturbed by forestry (Mohta *et al.*, 2003), construction or mining activities (Figure 1). In ‘mature’ urban systems, although sediment yields are generally lower than yields during the initial phases of construction (cf. Wolman and Schick, 1967), studies have demonstrated that a significant proportion (up to 40%) of the

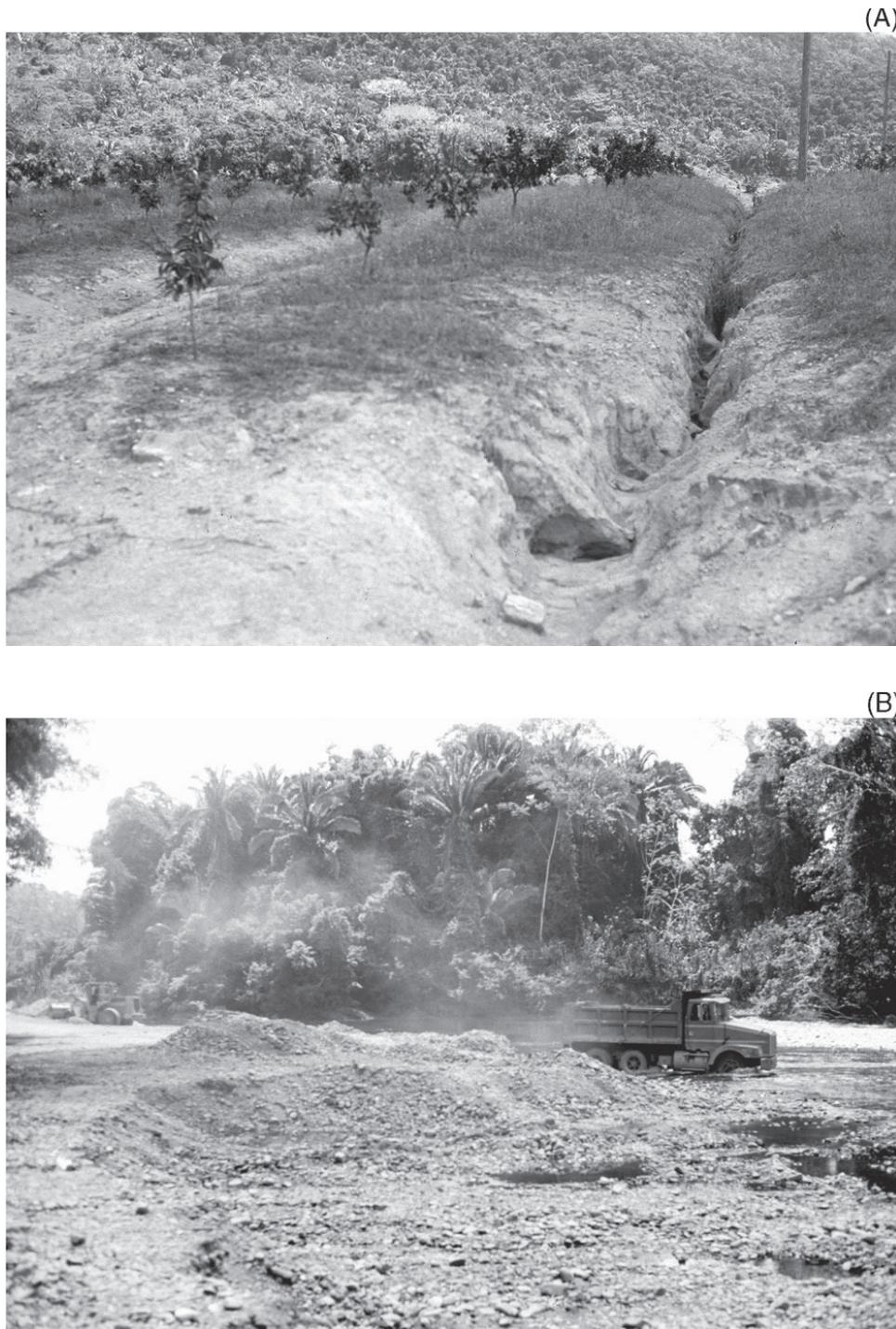


Figure 1. Sources of fine-grained sediment in rivers draining to the barrier reef in Belize: (A) soil erosion on a citrus plantation; and (B) sediment extraction from the channel bed and banks of the Sittee River (photos by P.N. Owens)

fine-grained sediment flux is derived from urban sources such as solids from sewage treatment works and road dust (Carter *et al.*, 2003; Robertson *et al.*, 2003), which often contain elevated levels of contaminants and nutrients.

Fine-grained sediment exerts a fundamental control on the hydrological and geomorphological behaviour of a river, and contributes to biological functioning by contributing to habitat quality and quantity (for example, composite particles as habitats themselves, creation of mud flats etc.). Excessive changes in fine-grained sediment inputs to river systems can, however, have a variety of detrimental effects. These effects can be divided into two main

types: quantity and quality. Excessive sediment inputs to rivers due to increased erosion (e.g. due to deforestation, agriculture) or disturbance of the land surface (e.g. from forestry operations, mining and construction) can cause physical problems of turbidity in the water column and sedimentation in channels, reservoirs, estuaries, harbours and the near-coastal zone. In turn, this sedimentation may affect channel morphology and behaviour, and navigation. With many of these changes there are often detrimental effects on habitats, such as salmonid spawning gravel (Sear, 1993; Armstrong *et al.*, 2003) and barrier reefs (McCulloch *et al.*, 2003; Nunny *et al.*, in press). In the case of sediment quantity, it is important to recognize that too little sediment (both coarse- and fine-grained) can be as detrimental to the geomorphological and ecological functioning of a river as can too much sediment. Too little sediment can result in 'hungry water' where sediment-starved water can lead to channel incision, erosion of channel banks, a change in the particle size composition of the channel bed, a modification of riverine habitats (e.g. reduced supply of fine-grained sediment downstream of dammed rivers can result in decreased turbidity and thus competitive advantages for non-native, sight-feeding fish) and the undermining of bridges and other structures (Kondolf, 1997).

From a sediment quality perspective, the fine-grained sediment loads (especially the <63 µm fraction) being transported by many rivers are showing evidence of increasing concentrations of contaminants and nutrients, and these concentrations are often approaching or above available sediment quality guidelines (Owens and Walling, 2002b; Blake *et al.*, 2003). In turn, this has implications for river ecology (such as eutrophication) and human health (i.e. excessive levels of pathogens and radionuclides). For example, a study of 129 lakes in England and Wales has found that 69% have total phosphorus concentrations that indicate that they have been affected by phosphorus pollution (Foy and Bailey-Watt, 1998). Furthermore, the US Environmental Protection Agency (EPA) (cited in Power, 2002) estimates that 10% of lakes, rivers and bays of the USA have sediment contaminated with toxic chemicals that can kill resident fish or impair the health of people and wildlife that eat contaminated fish.

To illustrate the magnitude and global nature of the concern associated with sediment quantity and quality issues in rivers, Table I presents an assessment of the main anthropogenic drivers and pressures in river basins in some of the worst affected continents. This information was compiled as part of the IGBP-LOICZ Basins programme, the

Table I. List of the main drivers, pressures and changes of land-based sources (and in particular catchments) on the coastal zones of different areas of the world based on the LOICZ Basins research programme. Most of these pressures relate to sediment quantity (e.g. erosion/sedimentation) or sediment quality (e.g. eutrophication, pollution) issues (Salomons, 2004)

Region	Ranking	Anthropogenic drivers	Major state changes and coastal impacts	Present pressure status	Trend expected
South America	1	Urbanization	Eutrophication	Major	Increasing
	2	Damming/diversion	Erosion/sedimentation	Major	Increasing
	3	Industrialization	Pollution	Medium	Increasing
	4	Agriculture	Eutrophication/pollution	Medium	Increasing
	5	Deforestation	Erosion/sedimentation	Medium	Increasing
Africa	1	Damming/diversion	Erosion/sedimentation	Major	Increasing
			Salinization	Local	
			Nutrient depletion	Local	
	2	Various drivers	Biodiversity loss	Major	Increasing
	3	Deforestation	Erosion/sedimentation	Medium	Increasing
East Asia	4	Agriculture	Eutrophication/pollution	Medium	Increasing
	5	Urbanization	Eutrophication/pollution	Medium	Increasing
	1	Urbanization	Eutrophication/water abstraction	Major	Increasing
	2	Agriculture	Eutrophication/pollution/reclamation/disease	Major	Increasing
	3	Damming/diversion	Erosion/sedimentation/nutrient depletion	Major	Increasing
Russian Arctic	4	Industrialization	Pollution	Minor	Increasing
	5	Deforestation	Erosion/sedimentation	Major	Increasing
	1	Industrialization	Pollution	Major	Increasing
	2	Navigation	Erosion/sedimentation	Medium	Increasing
	3	Damming	Erosion	Medium	Decreasing
	4	Agriculture	Nutrient/water/sediment	Minor	Stable
	5	Urbanization	Nutrient/water abstraction	Minor	Stable

main objective of which was to assess and rank the main impacts of land-based sources (and in particular catchments) on coastal systems (Salomons, 2004; Salomons *et al.*, 2005). It is clear from Table I that erosion and associated sedimentation issues rank highly in most regions and are identified as major causes of concern. In Africa, for example, erosion/sedimentation associated with damming and diversion is ranked joint first and is identified as a major driver of change. Damming also ranks highly in Asia and South America, and erosion/sedimentation features as an important issue in all of the regions listed in Table I, although the driver varies between regions. Similarly, in Table II it is clear that increased sediment fluxes in rivers is a major pressure in river catchments in Oceania and has detrimental impacts on the coastal zone including siltation and associated eutrophication and pollution effects.

Having identified the magnitude of the issue (Tables I and II), Table III lists in more detail some of the main detrimental effects associated with the quantity and quality of fine-grained sediment in river systems, and gives examples to illustrate these. In order to examine some of these sediment quantity and quality issues in further detail, and in particular to illustrate the complexity of managing fine-grained sediment in river systems, the following sections describe four examples where the recent (i.e. last 200 years or so) activities of society have influenced the quantity and quality of fine-grained sediment. Due to limitations in space, the focus is on examples from the so-called developed world, particularly because there are existing and forthcoming sediment management policies, programmes and guidelines available for these countries (and these are discussed later), although examples have been chosen to illustrate some of the main concerns identified in Tables I and II. The examples are: land use

Table II. Matrix characterizing major catchment-based drivers and pressures and a qualitative ranking of related state changes impacting the coastal zone in Oceania (based on Kjerfve *et al.*, 2002)

Driver	Pressure	State change*	Impact on coastal system	Time [†]
Climate	Increased sediment transport	3	Siltation Erosion	p
Agriculture	Nutrient effluent	1	Eutrophication	p
	Land clearing and reclamation	3	Pollution (heavy metals)	
	Water extraction increase	3	Siltation	
	Increased sediment transport	3	Biodiversity loss	
	Changes to water balance	3	Erosion of stream banks and increased sedimentation	
Deforestation	Increased agriculture along coast	3	Siltation of coral reefs	p
	Increased sediment loads	3	Sediment accretion	
	Alteration to water balance	2	Erosion	
	Changes to water regime	3	Biodiversity loss	
	Siltation	3		
Mining	Ecological damage	3		p
	Increased sediment loads	3	Pollution (heavy metals)	
	Changes to hydrological cycle	3	Siltation Eutrophication Sediment accretion Erosion Contamination Biodiversity loss	
Urbanization (point source effluents)	Pollution discharge	3	Pollution	p
	Population growth	3	Eutrophication	
	Increased sediment runoff	3	Contamination	
	Water extraction	2	Biodiversity loss	
Nuclear test	Radioactive residues	3	Pollution	d
			Contamination	
			Biodiversity	

*State change: 3 = major; 2 = moderate; 1 = minor.

[†]Timescale: p = progressive (continuous); d = direct (spontaneous).

Table III. Examples of some of the detrimental effects caused by anthropogenic-induced changes in the quantity and quality of fine-grained sediment in river systems

Sediment quantity or quality issue	Change in fine-grained sediment delivery	Effects	Examples
Quantity	Too little sediment	Channel incision	Piave River, Italy (Surian, 1999); Lower Ebro River, Spain (Vericat and Batalla, 2005)
		Undermining of engineering structures, causing a hazard and associated costs for reconstruction	Undermining bridges (Kaoping River, Taiwan; Kondolf, 1997) and bridge collapse (Duero River, Portugal; Batalla, 2003)
		Changes in channel morphology (such as channel width, sinuosity, braiding index etc.)	Piave River, Italy (Surian, 1999); River Drôme, France (DAVD, 2000)
		Reduced supply of sediment to coastal zones and possible increase in coastal erosion	Californian coast, USA (Inman, 1985, in Kondolf, 1997)
		Possible loss of valuable sediment-based habitats such as floodplains, mud flats and deltas	Ebro delta, Spain (Batalla, 2003); Nile delta, Egypt (Saito <i>et al.</i> , 1994; Batalla, 2003)
		Threat to salmonids by changing particle size of spawning gravel	Upper Sacramento River, California, USA (Kondolf, 1997)
		Threat to estuarine and coastal fish stocks	Baja, California, USA (Saito <i>et al.</i> , 1994); Sea of Bohai, China (Syvitski, 2003)
	Too much sediment	Sedimentation in lakes and reservoirs reducing life-span, and affecting operation efficiency and costs	66 small dams in Zambia (Sichingabula, 1997); nine lakes/reservoirs in England and Scotland (Foster and Lees, 1999)
		Sedimentation of salmonid spawning gravel and altering other sensitive habitats, reducing or changing biodiversity	England and Wales (Theurer <i>et al.</i> , 1998); New Zealand (Ryan, 1991); worldwide review (Newcombe and McDonald, 1991); Lake Øyeren, Norway (Bogen and Bønsnes, 2002); Mosel River, Germany (Vogt and Symader, 2002)
		Sedimentation on floodplains affecting habitats, land use	Russian Plain (Sidorchuk and Golosov, 2003)
		Sedimentation on river channels/aggradation causing changes in river morphology and behaviour	Russian Plain (Sidorchuk and Golosov, 2003)
		Sedimentation of harbours and estuaries and associated costs of dredging	$50 \times 10^6 \text{ t year}^{-1}$ of sediment is dredged from coastal areas of UK (Fletcher 2001 in Power, 2002); $4\text{--}5 \times 10^6 \text{ m}^3 \text{ year}^{-1}$ of fine sediment and sand is dredged from Hamburg harbour and River Elbe, Germany (Netzband <i>et al.</i> , 2002; Port of Hamburg, 2003)
		Sedimentation of coastal zone, including barrier reefs	Belize barrier reef (Nunny <i>et al.</i> , in press); Great Barrier Reef, Australia (McCulloch <i>et al.</i> , 2003), Caribbean and Oceania reefs (Kjerfve <i>et al.</i> , 2002)

Continues

Table III. Continued

Sediment quantity or quality issue	Change in fine-grained sediment delivery	Effects	Examples
Quality	Increase in delivery of sediment-associated nutrients (especially phosphorus) and contaminants	Eutrophication and potential impacts on aquatic life	Slapton Ley, UK (Johnes and O'Sullivan, 1989); rivers in UK (DEFRA, 2003); River Aire, UK (Owens and Walling, 2002b); for global review see Correll (1998)
		Toxicity effects on aquatic organisms	Tisa and Danube Rivers (Macklin <i>et al.</i> , 2003); see Warren <i>et al.</i> (2003) for review of micro-organic contaminants
		Detrimental effects to human health	Such as due to failures of mine tailings dams (Diehl, 2001, in Macklin <i>et al.</i> , 2003) and redistribution of radioactive Chernobyl fallout (Van der Perk <i>et al.</i> , 1999)
		Dealing with contaminated dredged sediment	500 × 10 ⁶ euros spent since 1980s on treatment and disposal of contaminated dredged material, Hamburg port, Germany (Netzband <i>et al.</i> , 2002; Port of Hamburg, 2003); 23 to 47 × 10 ⁶ t of contaminated sediment are managed annually in the USA (NRC, 1997, in Power, 2002)
		Deposition and long-term storage on floodplains resulting in 'chemical time bomb'	Humber basin, UK (Hudson-Edwards <i>et al.</i> , 1999; Walling and Owens, 2002); Tisa and Danube Rivers, Europe (Macklin <i>et al.</i> , 2003)

changes and sediment fluxes in New Zealand (deforestation/agriculture–erosion/sedimentation); the effects of reservoir construction on sediment fluxes and management using examples from a variety of different countries (damming–erosion/sedimentation); the interaction between sediment dynamics and fish habitats in British Columbia, Canada (deforestation–habitats/biodiversity); and the management of contaminated sediment in USA rivers (industrialization/urbanization–contamination/pollution). The latter sections of the paper review a selection of the existing programmes and initiatives developed to manage fine-grained sediment (in terms of both quantity and quality) and its impact on river systems, and focus on Canada, Europe, New Zealand and the USA. The last section makes recommendations for integrated basin-scale sediment management in river systems in light of the case studies presented.

CASE STUDIES OF FINE-GRAINED SEDIMENT MANAGEMENT ISSUES

Land use change and the production of fine-grained sediment: the case of the Waipaoa River Basin, New Zealand

In most parts of the world, especially developing countries and countries with low population and levels of urbanization, erosion and sediment problems associated with deforestation and agriculture represent important and pressing concerns for river basins (Tables I and II). Located in the east coast region of the North Island, New Zealand (Figure 2A), the Waipaoa River drains the eastern flanks of the Raukumara Range. The 2200 km² basin is underlain by overthrust Cretaceous mudstone, argillite and greywacke of the East Coast Allochthon and a cover sequence of poorly consolidated Neogene marine sedimentary rocks (Mazengarb and

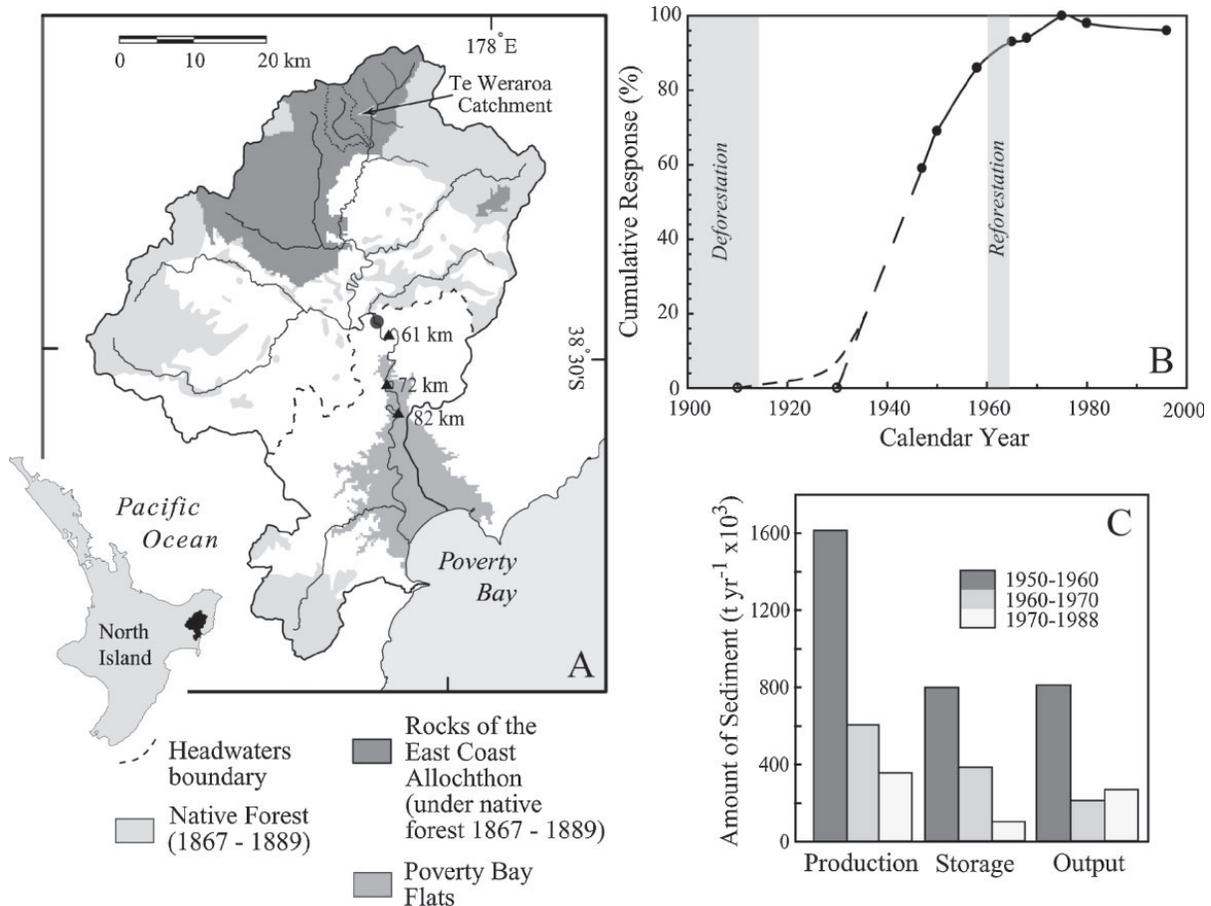


Figure 2. (A) Location map showing the remnants of native forest in the headwaters (after Murton, 1968), and outcrops of rocks of the East Coast Allochthon that are prone to gully erosion (after Mazengarb and Speden, 2000). Solid circle indicates the location of the main gauging station at Kakanania, and kilometre markers (solid triangles) indicate the location of drill core sites on the Poverty Bay Flats. (B) Response of Te Weraroa Stream catchment (see (A) for location) to deforestation and reforestation indexed by the rate of aggradation in the stream channel (after Gomez *et al.*, 2003b). (C) Sediment production, storage and yield from Te Weraroa Stream catchment prior to (1950–1960) and after reforestation (after Gomez *et al.*, 2003b)

Speden, 2000). Polynesian settlers (Maori) disturbed the lowland forests (Wilmshurst *et al.*, 1999), but the activities of European colonists impacted the entire basin (Page *et al.*, 2000). Wholesale clearance of the indigenous forest began in the late 1820s, and much of the lowland had been deforested by 1875 (Murton, 1968). Clearances in the headwaters continued until 1920, and today only 2.5% of the basin remains under native forest.

Deforestation destabilized the landscape and, following the most intensive period (1890–1910) of land use change in the headwaters, extensive, shallow landsliding was first observed in the hill country during the winters of 1893 and 1894. The incidence of shallow landsliding increased during the first decade of the twentieth century, and by the end of the second decade it had become a pervasive erosional process throughout the headwaters (Henderson and Ongley, 1920). Numerous gullies also developed in the headwaters after the native beech, podocarp and mixed hardwood forest was replaced by pasture. Gully erosion is associated with *c.* 10% of the terrain in the Waipaoa River basin, most of which is underlain by sheared and crushed rocks of the East Coast Allochthon (Figure 2A; Gage and Black, 1979), and 420 gullies currently are active (Marden *et al.*, 2005). Most gullies vary in size from <0.01 to *c.* 0.2 km^2 , and the drainage basins that support them range from a few thousand square metres to 0.5 km^2 in area. Small linear gullies occupy topographically convergent areas in otherwise unchannelled zero-order basins, but the larger, amphitheatre-like gully complexes have absorbed virtually their entire drainage basin (De Rose *et al.*, 1998).

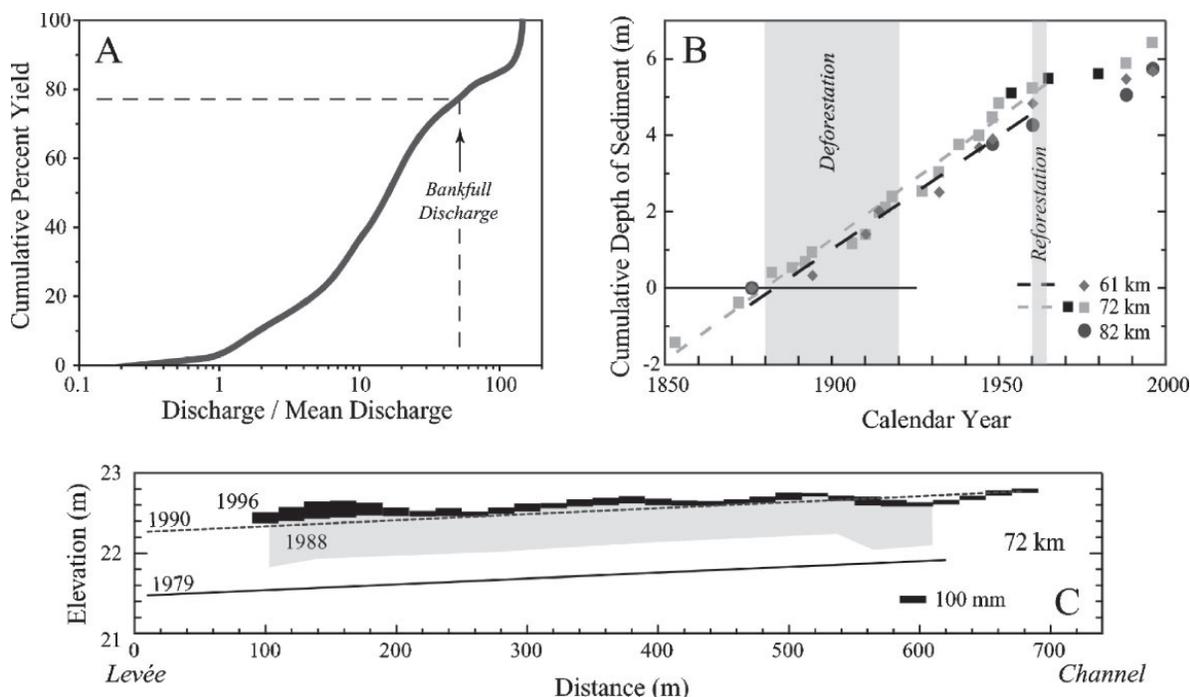


Figure 3. (A) Cumulative distribution of the suspended sediment load of the Waipaoa River at Kanakanaia transported at discharges less than the indicated value (after Gomez *et al.*, 2003a). (B) Sediment accumulation curves (zeroed at 1876) for cores obtained on the Poverty Bay Flats at 61, 72 and 82 km downstream (after Gomez *et al.*, 1999). The reduction in the accumulation rate in the period after reforestation likely is a product of a decrease in the incidence of flooding, rather than a reduction in the availability of fine sediment. (C) Profiles across the active floodplain and thickness of flood deposits, Waipaoa River, at 72 km downstream (after Gomez *et al.*, 1998). Lines are profiles surveyed in 1979 and 1990, smoothed by linear regression. Shading scales thickness of deposits from floods in 1988 (grey) and 1996 (black)

Gully erosion supplemented by shallow landsliding during intense rainstorms (when event rainfall exceeds *c.* 200 mm in <72 hours) generates large quantities of fine-grained sediment (Trustrum *et al.*, 1999), and the Waipaoa River annually delivers *c.* 15×10^6 t (standard deviation of annual yield is 6.7×10^6 t) of suspended sediment to the Pacific Ocean (Hicks *et al.*, 2000). For comparison, the coarse sediment (bedload) yield amounts to only *c.* 1% of the suspended sediment yield. While the shallow landslides typically generate 10 to 20% of the Waipaoa River's annual suspended sediment yield overall, they supply as much as 60% of the suspended sediment transported during high flow events (Page *et al.*, 1999; Reid and Page, 2002). Flows associated with overbank events transport 24% of the mean annual suspended sediment load (Figure 3A), and frequent runoff events are relatively more important than large floods to both the long-term suspended sediment and particulate organic carbon yields (Gomez *et al.*, 1999, 2003a; Hicks *et al.*, 2000). Suspended sediment concentrations in flood flows are very high ($>30 \text{ g l}^{-1}$) and, although most floods only last for a few tens of hours, sediment accumulates rapidly on the floodplain. The average post-1850 rate of vertical accretion is *c.* 60 mm year^{-1} (Figure 3B), and contemporary rates of vertical accretion on the floodplain are 14 to 18 mm h^{-1} (Gomez *et al.*, 1998, 1999).

Directed management initiatives in the Waipaoa River basin have attempted to reduce erosion in the headwaters and prevent damage to land and property on the Poverty Bay Flats. Attempts to control erosion in the headwaters using fascines and check dams were largely ineffective, but many gullies eventually were stabilized after a programme of reforestation with exotic tree species was implemented in 1960 (Allsop, 1973; Marden *et al.*, 2005). The exotic forest (i.e. *Pinus radiata*, *Pseudotsuga menziesii* and *Pinus nigra*) was opened to commercial timber harvesting in 1990.

Changes in sediment production due to deforestation and reforestation can be assessed on the basis of information available for a small (29 km²) headwater catchment, Te Weraroa Stream (Figure 2A). Here the conversion to pasture was completed by 1914, and 80% of the catchment was reforested between 1962 and 1965. After the inception of gully erosion in the early decades of the twentieth century, the catchment response can be gauged with reference to the rate of aggradation in the stream channel (Figure 2B), which was assessed from

stream cross-section and seismic surveys (Gomez *et al.*, 2003b). From *c.* 1935 until 1960 gully erosion continued unabated. In the ensuing decade, the amount of sediment contributed from gullies declined dramatically (by >60%) as the exotic forest became established (Figure 2C; Marden *et al.*, 2005), and currently two gully complexes (in which erosion was too far advanced to be mitigated by afforestation) generate almost all of the sediment. The calibre of this material is much finer than the sediment that formerly was produced by the more numerous linear gullies, much of which (48%) went into storage along the Te Weraroa stream (Gomez *et al.*, 2003b), and today these two (and four other) large, active gully complexes in the headwaters each generate (from areas of <1 km²) between 1% and 3% of the Waipaoa River's annual suspended sediment load (cf. De Rose *et al.*, 1998; Marden *et al.*, 2005). In summary, although gravel production as indexed by the rate of channel aggradation waned after 1960 (Figure 2B), reforestation had little or no effect on the amount of fine-grained sediment produced by the gully complexes.

The increase in fine-grained sediment production following deforestation likely impacted native fish communities (cf. Rowe *et al.*, 2000; Richardson and Jowett, 2002), and also led to an increase in the rate at which alluvium accumulated on the Poverty Bay Flats (Pullar, 1962; Pullar and Penhale, 1970). Following large floods in 1944 and 1948, the lower reaches of the Waipaoa River were straightened, reducing the channel length by *c.* 8 km, and flood control levées were constructed, reducing the area of the high-value agricultural land and settlements on the Poverty Bay Flats that was susceptible to inundation by *c.* 70%. However, overbank deposition periodically continues to increase the elevation of the active floodplain and reduce the standard of flood protection, particularly in the upper reaches of the Waipaoa River flood control scheme (Figure 3C; Peacock, 1991). Thus, on the basis of current rates of overbank sedimentation and a standard of protection based on a flood with a recurrence interval of 100 years, proposed upgrades to the upstream end of the scheme that are due to be implemented in the first decade of the twenty-first century will offer protection for only *c.* 50 years. This off-site impact recently refocused attention on the benefits of on-site management strategies and conservation measures for reducing the supply of fine sediment from the headwaters. For example, by virtue of the effect that vegetation has on soil moisture conditions and the addition of root strength, reforestation modulates the threshold for shallow landsliding (that generates additional sediment) during large-magnitude events that cause overbank flooding. Thus Reid and Page (2002) found that prioritizing land for reforestation according to landslide susceptibility could have a significant impact on fine sediment yields. With prioritization, a 40% reduction in landslide-derived sediment could be achieved through reforestation of 8% of the Waipaoa River basin, whereas 25% of the land would need to be reforested to achieve the same effect through random selection. This suggests that targeted management in headwater areas could reduce the delivery of fine-grained sediment and potentially reduce some of the associated problems in the downstream reaches of the Waipaoa River.

Reservoir sedimentation and management strategies: a global perspective

The flow of sediment through a river basin is a natural phenomenon. If dams are located within river basins, as the flow of water is interrupted, the downstream movement of sediment may also be prevented. While coarse-grained sediment such as boulders and gravel (i.e. the bedload fraction) is almost certain to be deposited within a reservoir, in most situations the majority of the suspended sediment load is also deposited, and fine-grained sediment will often represent a significant (if not the dominant) amount of the sediment deposited in a reservoir.

Although reservoir sedimentation is a worldwide problem (Vörösmarty *et al.*, 2003; Table I), it is particularly evident in areas with high sediment yields and a high degree of impoundment, such as the Mediterranean climatic regions (Batalla, 2003) (Figure 4A). In such areas, water availability and demand do not coincide, thus the degree of river impoundment tends to be higher than in more humid regions (Batalla *et al.*, 2004). The sediment trapped in dams can have both beneficial (clearer, less turbid water downstream, reducing excessive delivery to coastal zones) and detrimental (progressive reduction of dam impoundment capacity, impairment of basic reservoir operation, 'hungry waters') effects. Thus, annual replacement costs in the USA are estimated at US \$6 billion (Fan and Springer, 1993).

There are a variety of strategies for managing sedimentation in reservoirs, ranging from prevention of sediment entry into the reservoir to sediment removal techniques. Illustrated by examples, a number of sediment management strategies are reviewed briefly below.

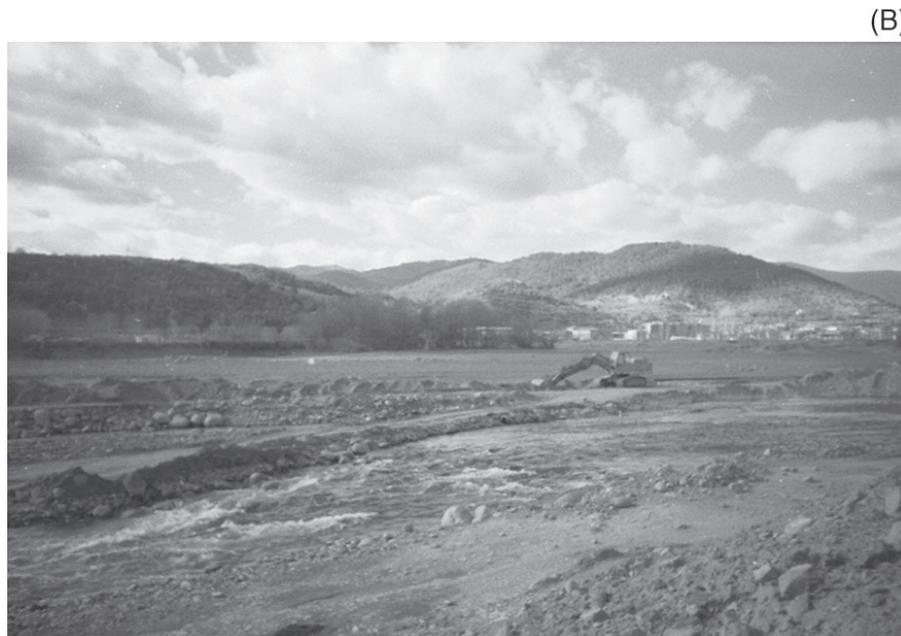


Figure 4. (A) Sedimentation (content: silt 76%, clay 19%, coarse fractions 5%) in the Barasona reservoir (Ésera River, Ebro basin, Spain), which has been in operation since 1932. (B) Mechanical extraction of sediments in the delta of the Talam Reservoir (Noguera Pallaresa River, Ebro basin, Spain). This has been practised since 1990 (photo (A) by R. J. Batalla (June 2001) and photo (B) by J. Caba (June 2002)). The photo in (A) is reproduced with kind permission of the Spanish Society of Geomorphology and the Spanish Quaternary Association)

Prevention of sediment entering the reservoir probably represents the most sustainable management option. Identification and subsequent control of the main sediment sources (such as the erosion of soil, mass movement events and channel bank erosion) in the contributing catchment will reduce the delivery of sediment to the reservoir. It will, however, be necessary to evaluate the effects of the reduction in sediment delivery on the sustainable functioning of other parts of the river system, as described above (see also Table III).

Another option to prevent sediment from entering the reservoir is sediment routing methods, which can be used to hydraulically transport sediments beyond the dam. Sediment routing can be used to prevent sediment deposition

in a reservoir, such as, for example, when the reservoir is drawn down during sediment inflow events, or where sediment underflows occur by opening gates or diversions to allow the sediment to pass through or by the dam. For example, sediment by-pass using a diversion tunnel or off-stream reservoirs has been used in Switzerland, France, South Africa and Taiwan (Morris, 1993).

Mechanical extraction or dredging of the sediment once in the reservoir can be applied to restore capacity. Cost is the most important constraint, and published values range from US \$0.3 m⁻³ for Lake Springfield in Illinois (Morris, 1993) to US \$15–50 m⁻³ for Feather River in California (Kondolf, 1995). Once extracted, the sediment from reservoirs or debris-control basins has been utilized to enhance fish habitats (Buer, 1994) and to protect river infrastructures (Kuhl, 1992). The sediment (usually the coarse-grained fraction) can also be mined as construction aggregate, as is done in virtually all dams in Taiwan. In the Talam Reservoir in the Noguera Pallaresa River in Spain (Central Pyrenees), >0.6 × 10⁶ m³ of sediment has been removed for aggregate within the last 10 years (Figure 4B). Generally, the fine-grained sediment fraction has limited beneficial use, but the Shikma Reservoir in Israel is mined in its upper section to produce sand and gravel for construction and the fine-grained sediment in its lower section is mined to produce clay for use in cement and bricks (Laronne, 1995). However, these practices are not without their limitations, with the increased turbidity in the water column (and associated effects on reservoir flora and fauna), noise, dust and the NO_x and other emissions caused by heavy machinery amongst potential environmental impacts.

Sediment can be hydraulically flushed from a reservoir (pass-through) by opening low-level outlets and permitting the reservoir to be drawn down sufficiently to resuspend fine-grained sediment and move bedload. If it is done frequently at high flows the reservoir behaves essentially as a reach of river, passing inflowing sediments through the dam outlets. Successful attempts are reported for the old Aswan Dam on the Nile River and for the Bhagaruk Reservoir on the Yeluard River in India (Stevens, 1936), and for the River Inn in Austria and Germany (Hack, 1986). In contrast, if sediment is released during baseflow, the river's transport capacity is generally inadequate to move the surplus load and severe effects are likely to occur. The abrupt increase in sediment load and decrease in dissolved oxygen level may alter both the substrate and aquatic habitat conditions downstream of the dam.

Examples of the harmful effects of sluicing can be found in California (e.g. the Kern River downstream of the Democrat Dam, and the Carmel River below the Los Padres Dam; Kondolf, 1995) and in Spain (e.g. the Noguera Ribagorzana downstream of the Santa Anna Dam, and the Ésera River downstream of the Barasona Dam; Palau, 1995). Sediment pass-through during floods offers the most environmentally sensitive option, but it is costly due to the high value of water stored in reservoirs. In addition, the use of flow-based methods on a regular basis is prevented by climatic variability and the need for a minimum pool on each reservoir for the effective protection of valves.

Reservoirs in series also provide opportunities for sediment management (Zhang *et al.*, 1976), in that it is possible to design flow releases so as to use clear water from upstream reservoirs to flush the sediment from the beds of reservoirs downstream. The release of water to scour sediments might be feasible in flood-control basins and reservoirs in temperate climate areas, but would be more difficult to apply in large water conservation structures under highly variable climates, as in the Mediterranean.

In conclusion, at present only a few places, such as Israel, California and Taiwan, have undertaken official sediment management pilot programmes as a basis of future management strategies. Since reservoirs are designed to provide renewable sources of water supply, sediment management must be an integral part of the functioning system of both existing and future dams. If the sediment is not managed, reservoirs are likely to fill progressively, affecting dam operation and exacerbating downstream environmental impacts.

Fine-grained sediment and fish spawning habitats, with reference to rivers in British Columbia, Canada

There is much concern associated with the effects of increased sediment loads to rivers and issues of habitat and biodiversity loss (Tables I and II). The management of terrestrial sediment delivery to streams is an important factor in maintaining habitat quality in rivers, as primary producers such as invertebrates and fish can be negatively affected by increases in fine sediment loads (Waters, 1995) (see also Table III). Stream biota can be affected by sediment being carried in the water column or when it is stored in or on the stream bed. Increases in suspended inorganic sediment concentrations have been found to be deleterious to filter-feeding invertebrates and to fish,

which exhibit avoidance behaviour and negative physiological responses (Anderson *et al.*, 1996). While the alteration of the gravel bed morphology associated with high-magnitude discharges can drastically modify the quality and quantity of habitat, the changes caused by fine sediments in the channel can be more insidious as they occur more frequently and at lower flow regimes. The settling and infiltration of fine particles into gravel beds has been identified as a factor regulating fish egg and larval mortality by many researchers (McNeil and Ahnell, 1964; Adams and Beschta, 1980; Scrivener and Brownlee, 1989) and in most of these cases the change in bed sediment quality was associated with a change in land use (including forest harvesting, and road and bridge construction) and a concomitant increase in the delivery of fine-grained sediment to the stream.

The settling and infiltration of fine sediment (silt and clay as well as sand and fine gravel) into gravel interstices acts to impede inter-gravel water flow and reduce oxygen levels, vital to benthic organisms (Chapman, 1988; Baxter and Hauer, 2000). The reduction of inter-gravel flows can result from the surface gravel becoming capped by sand, which forms an impermeable layer inhibiting the penetration and/or emergence of water (Sear, 1993), thereby restricting the supply of oxygenated water. Alternatively, the accumulation of fine particles through the depth of the gravel bed reduces inter-gravel pore space, thereby diminishing flow volume, providing less oxygen per unit time to the organisms. While both the sand-sized and the silt- and clay-sized inorganic particles physically restrict the movement of water and therefore reduce the supply of oxygen through the gravel, another important, but less well-researched, factor is the gravel-stored organic matter.

The physical presence of small organic particles, like inorganic particles, is expected to decrease inter-gravel flows and oxygen by capping or blocking. However, gravel-stored fine particulate organics can also decrease inter-gravel oxygen levels through consumption. That is, bacterial communities on the surface of these organic fine sediments require oxygen, therefore they exert a biological oxygen demand (BOD) while decomposing the organic material (Bjornn and Reiser, 1991).

McNeil and Ahnell (1964) and Chamberlain *et al.* (1991) point out that increased forest harvesting is associated with increased organic matter proportions in gravel-stored sediments. Intuitively, this could be explained by an increase in both eroded soil organic matter and plant detrital material being delivered to the stream channel. These are two large pools of available organic material that are naturally found in the riparian zone. In pristine rivers of the west coast of North America, including those in British Columbia, Canada, spawning Pacific salmon are another prominent source of organic matter as well as an agent of geomorphic change (Petticrew and Arocena, 2003). Post-spawning salmon carcasses that escape terrestrial scavengers will release particulate and dissolved organic matter within the stream (Helfield and Naiman, 2001), enhancing stream bacterial and algal growth (Richie *et al.*, 1975; Wold and Hershey, 1999).

While organic matter is usually less dense than water and thus it might be expected to float and be transported out of the system, flocculation can facilitate the settling and storage of these fine particles (Kranck *et al.*, 1993; Droppo and Ongley, 1994; Petticrew and Biickert, 1998). A study in O'Neil Creek, a highly productive sockeye salmon stream in the northern interior of British Columbia (Petticrew and Droppo, 2000), found that the flocculated suspended sediment sizes changed over the season as the organic matter sources to the stream changed. Using stable isotopes of C and N, it was found that the organic component of the largest floc size, noted following the major salmon die-off, was composed predominantly of nutrients associated with salmon carcasses (McConnachie, 2003). A concurrent study found the size and density of the gravel-stored flocs (Figure 5) was related to the presence of the fish detrital material (Petticrew and Arocena, 2003). Flocs collected during the period of active spawn were smaller and denser, while sediment stored in the gravel during salmon die-off were larger and less dense, presumably due to changes in the organic matter structure. A follow-up study in this same stream has characterized a decrease in inter-gravel oxygen associated with die-off of the fish (Petticrew and Rex, pers. comm.).

Of importance here from a management perspective is that this stream, which has experienced minimal recent disturbance (a forest access road and bridge built in 1980), has a very low sediment yield and yet the transfer of the organic matter to the gravel environment results in a significant oxygen reduction. If abundant inorganic fine sediment were delivered to the stream during this period of fish die-off (i.e. due to land use changes such as deforestation, road construction or river mining activities) such that flocculation and settling were enhanced, the resulting storage of both types of fines would increase and the resultant impact on oxygen conditions would be expected to be much more extreme.

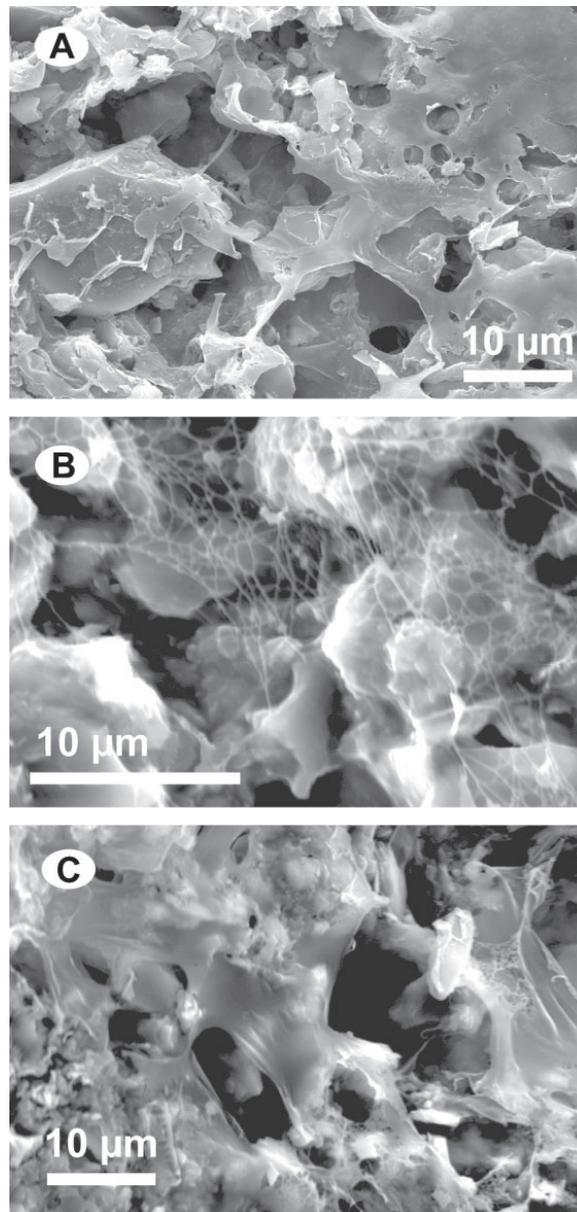


Figure 5. Electron micrographs of (A) pre-spawn, (B) mid-spawn and (C) post-spawn samples of fine sediment collected from interstitial waters of a gravel-bed river, O'Ne-eil Creek, British Columbia. The spider-web-like organic matter (at mid-spawn) was associated with smaller, denser particles while the more extensive glue-like layer of organic matter (at post-spawn) coating inorganic particles created larger flocs (from Petticrew and Arocena, 2003: reproduced with kind permission of Kluwer Academic Publishers)

While organic matter in natural systems provides a food source to the benthic organisms, disturbances such as forest harvesting have been found to alter the biomass of the macroinvertebrate communities (Fuchs *et al.*, 2003). These changes could be associated with alterations in food quality and quantity as well as changes in habitat quality. Increased delivery of both organic and inorganic sediment to the gravel due to flocculation could not only modify the benthic habitat but also change the size and delivery rate of suitable food supplies. Thus, sediment delivery and storage effects could be experienced at a number of trophic levels in the system. Clearly, for fish habitats to be maintained at optimum conditions there is a need to monitor and manage both the fine-grained inorganic and organic sediment fluxes within river basins such as those in British Columbia and other similar environments.

Management issues associated with heavily contaminated fine-grained sediments: the case of Lake Coeur d'Alene and the Coeur d'Alene and Spokane river basins, Idaho and Washington, USA

In urbanized and industrialized areas, pollution of surface waters (including eutrophication) is a major concern (Table I). As such, contaminated fine-grained sediment represents an important component of river basin management in countries like the USA. Much of the Coeur d'Alene (CDA) River basin, USA, as well as about two-thirds of Lake CDA, lie downstream from the CDA mining district (Figure 6). Furthermore, the Spokane River basin, which begins at the northern outlet of Lake CDA and extends to the Columbia River, also lies downstream of the mining district. The mining district has been in operation since the 1880s and was one of the major sources of Ag, Pb and Zn in the USA (e.g. Bender, 1991). Until 1968, when tailings ponds were established to limit downstream sediment transport, most of the mining and ore-processing wastes were discharged directly into the South Fork of the CDA River (Reece *et al.*, 1978; Figure 6). It has been estimated that during the course of mining, processing and smelting operations in the area, some 115×10^6 t of mine tailings were produced, and that over 70×10^6 t of these tailings currently have been deposited on the floodplains and bed of the CDA River (Javorka, 1991; Bookstrom *et al.*, 2001). The tailings are highly enriched in Ag, As, Cd, Cu, Fe, Mn, Pb, Sb and Zn (Rabe and Bauer, 1977; Bender, 1991). In 1983, as a result of the elevated trace element concentrations of the mining and processing wastes, the US Environmental Protection Agency (EPA) established the Bunker Hill Superfund Site that encompasses a 54 km^2 box in the Kellogg and Smelterville Flats area (e.g. Bender, 1991; Figure 6).

Subsequent studies, performed between 1990 and 2001, have indicated that there are some 70×10^6 t of trace-element-rich fine-grained sediments in Lake CDA, and that additional quantities of trace-element-rich sediments have entered the Spokane River system, over 200 km downstream from the Bunker Hill Superfund Site (Horowitz *et al.*, 1993, 1995; Bookstrom *et al.*, 2001; Grosbois *et al.*, 2001; Figure 6). Horowitz *et al.* (1993, 1995) have estimated that the chemical composition of the trace-element-rich sediments on or in the lakebed can be formed from a mixture of 10% mine tailings combined with 90% background material. Kuwabara *et al.* (2000) have shown that as a result of reducing conditions in the Lake CDA sediment column, a number of trace elements (notably Cd,

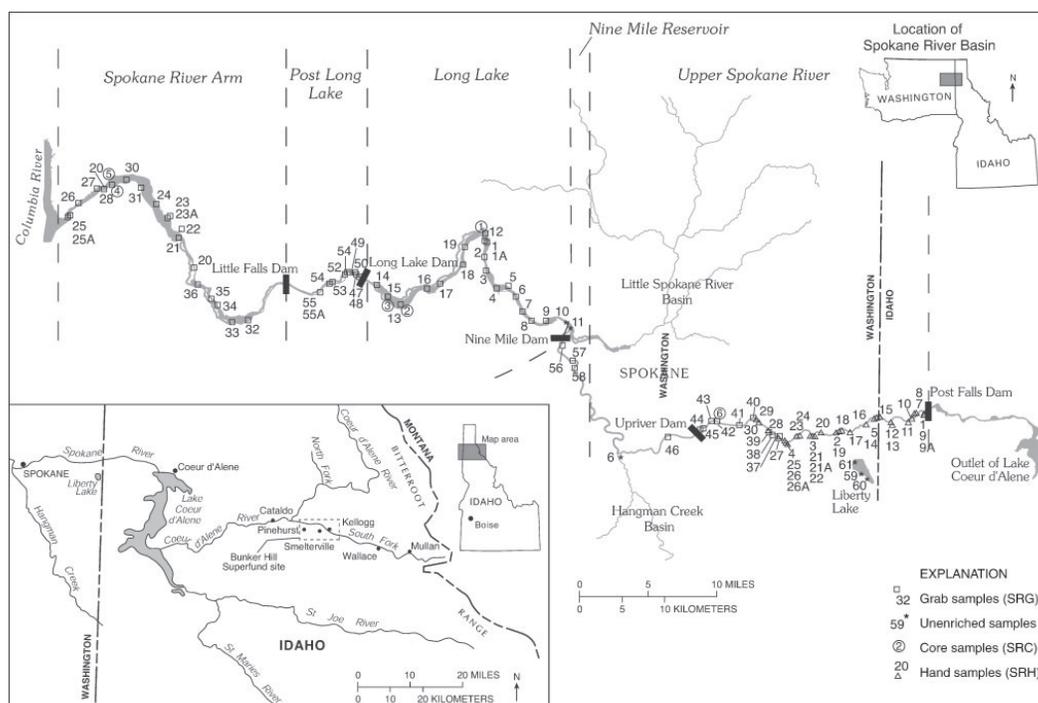


Figure 6. Maps of the Coeur d'Alene River, Lake Coeur d'Alene, and the Spokane River Basin. The Spokane River Basin begins at the northern outlet of Lake Coeur d'Alene, and ends at the Columbia River. The insert details the Coeur d'Alene Basin; the area outlined by the dashed lines demarks the 54 km^2 Bunker Hill Superfund Site

Fe and Zn) are being released into the overlying water as a result of post-depositional remobilization. Fluxes from the bed sediments for some dissolved trace elements can be on a par with those entering the lake from the CDA River. Some of these remobilized trace elements remain in solution whereas others precipitate in association with iron oxides (Horowitz *et al.*, 1993; Kuwabara *et al.*, 2000). Furthermore, Bookstrom *et al.* (2001) found large volumes of trace-element-rich sediments stored on or in the bed of the CDA River, particularly downstream of Cataldo where the riverbed gradient levels out (Figure 6). Lastly, whereas there is a limited amount of sediment remobilization from the floodplains of the CDA River and the lakebed of Lake CDA, it appears that the majority of the trace-element-rich sediments exported downstream into the Spokane River system occur in pulses that pass directly from the CDA River, through the lake, and into the Spokane River during flood (e.g. spring snowmelt, rain-on-snow) events (URS Greiner Inc. and CH2M-Hill, Inc., 2001).

The number of trace-element-rich sediment sources (e.g. floodplains, riverbed, lakebed), as well as the variety of available transporting mechanisms (e.g. baseflow, stormflow, post-depositional remobilization) in Lake CDA and the CDA and Spokane Rivers, creates substantial management/remediation problems. As such, the system has to be managed as a whole, rather than as individual parts, otherwise a number of potential management/remediation steps could be ineffective because they are counteractive or offsetting. Several examples follow.

(1) Dredge the lakebed to remove trace element-rich deposits. This step has potential downstream impacts due to physical remobilization; furthermore, if the upstream riverbed and floodplains are not cleared of trace-element-rich material, then the lake could refill with trace-element-rich sediment, and downstream transport into the Spokane River will continue.

(2) Clean up the upstream riverbed and floodplains. This step also has potential downstream impacts due to physical remobilization. Furthermore, it would do little to reduce the amount of material currently residing on the lakebed, which is acting as a trace-element source due to post-depositional remobilization.

(3) Stabilize the upstream floodplains. This step would decrease the amount of trace-element-rich material available for downstream transport due to erosion; however, if it is undertaken without dealing with the substantial quantities of trace-element-rich sediments currently in storage in the riverbed itself, it is unlikely to lead to substantial reductions.

(4) Institute nutrient management to limit post-depositional remobilization from the lakebed. This would entail improving the level of wastewater treatment in the areas upstream of Lake CDA. Further improvements also might be achieved through connecting many of the homes surrounding the lake to the public sewer system. Both steps could lower the eutrophication level of Lake CDA, which, in turn, could limit the amount of post-depositional remobilization of various trace elements from the sediment column. However, numerous efforts have been undertaken to revegetate areas in and around the Superfund Site itself to limit atmospheric remobilization of trace-element-rich material. This has led to the application of substantial amounts of fertilizer to promote growth. Subsequent runoff after these applications would be more than sufficient to counteract any improvements gained from additional wastewater treatment and/or connections to public sewers.

(5) Remove all or most of the dams on the Spokane River. This step could potentially limit the deposition of trace-element-rich sediment in the Spokane system and promote downstream removal to the Columbia River, where impacts might be mitigated by increased discharge and subsequent mixing with less trace-element-rich sediment. This accrues because examination of the chemistry, and dating of core samples from sections of the Spokane River, indicate that trace-element-rich sediment deposition coincided with dam completion (Grosbois *et al.*, 2001). However, the dams were installed to control flooding and to provide hydroelectric power. In fact, Upriver Dam (Figure 6) provides the power used to extract groundwater for local drinking water supplies for the city of Spokane and its environs.

More detailed discussions of management/remediation options and their various ramifications can be found in USEPA (2002) and these options are currently under evaluation. This example illustrates the complexities associated with attempting to manage large quantities of sediment that have elevated levels of trace elements within a system that is itself highly managed for flood control and hydroelectric power purposes. It is clear that any management option needs to consider the river basin as a whole.

PROGRAMMES AND INITIATIVES FOR THE MANAGEMENT OF FINE-GRAINED SEDIMENT IN RIVER SYSTEMS

The previous case studies illustrate the diversity of environmental impacts that increased fluxes of fine sediment (organic and inorganic) and associated chemicals can produce. They clearly demonstrate that land use changes (including deforestation and mining activities) and manipulation of stream channels (i.e. dam construction) can significantly alter the quantity and quality of sediment being delivered to and transported by rivers, and that this can have negative impacts on river ecology and habitats (especially fish habitats) and, potentially, human health. The following sections will review a selection of the existing programmes and initiatives developed to manage fine-grained sediment (in terms of both quantity and quality) and its impact on river systems. Given the nature of the case studies above, attention will focus on Canada, Europe, New Zealand and the USA. Finally, these programmes and initiatives will be evaluated in light of some of the issues highlighted in the case studies, and recommendations made for integrated sediment management in river basins.

Legislation and policy related to sediment management

At the local level (i.e. individual rivers, reservoirs, harbours etc.) specific issues (e.g. dredging, transport and operational considerations etc.) tend to dictate how and why sediment is managed. Most of the examples presented above, including, for example, the various reservoir management options, are examples of management at this scale. At the national scale and the scale of larger administrative units, such as the European Union (EU), legislation is usually the main driver of sediment management. However, only a relatively limited amount of legislation relates to sediment quality and quantity, with many countries having little or no appropriate legislation.

Where legislation exists, it cannot easily be associated with a single authority or governing body. A good example is the USA (USEPA, 2004), where no single agency is completely responsible for addressing the problem of contaminated sediment. More than ten federal laws give the USEPA, the US Army Corps of Engineers, the National Oceanic and Atmospheric Administration (NOAA) and other federal, state and tribal agencies, authority to address sediment quality issues. Some of the most important sources of sediment quality actions are the Clean Water Act (and in particular the Total Maximum Daily Load programme), and the Comprehensive Environmental Response Compensation and Liability Act, which established the Superfund programme. The case of the Coeur d'Alene and Spokane river basins in the USA, described above, is a good example of the role of the Superfund programme in managing contaminated sediment. Other relevant statutes in the USA include the National Environmental Policy Act, the Clean Air Act, the Coastal Zone Management Act, the Marine Protection, Research, and Sanctuaries Act, and the Great Lakes Programs Act of 1990. These laws address sediment quality by: identifying areas contaminated with chemicals; restricting or eliminating further discharges of pollutants into water bodies; and implementing a remediation strategy that will most effectively reduce the risk associated with the contaminated sediment (USEPA, 2004).

Similarly, there is at present no dedicated legislation at the EU level for managing the quantity or quality of sediment at the river basin scale. However, sediment issues interrelate with many other legislative fields such as waste legislation, various national soil protection strategies and communications, a range of treaties and conventions for dredged material and, perhaps most importantly, water legislation such as the Water Framework Directive (WFD, 2000/60/EG; also see Köthe, 2003). Although sediment does not feature explicitly within the WFD, it is an essential component in the management of the aquatic environment. One key aspect of the WFD for sediment management is the unequivocal recognition of the river basin as the fundamental unit of river systems and the need to consider the interconnectivity of all environments within the basin. Sediment is also being discussed within the EU Thematic Strategy for Soil Protection (Quevauviller and Olazabal, 2003) and may form part of future guidance and legislation that develops from this.

Whilst there is no direct legislation relating to sediment in New Zealand, the sediment issue is considered within the 1941 Soil Conservation and Rivers Control Act (SCRCA), established to limit the effects of soil erosion and flooding (and therefore incorporating policies to control sediment quantity), although this has been largely superseded by the 1991 Resource Management Act (RMA). The RMA serves as the current legislation for evaluating the environmental effects of catchment and river works and for setting and monitoring mitigation measures. While the RMA does not directly legislate relating to sediment, it is an enabling Act, and sets up the framework or hierarchy

of objectives, policies and rules from the national > regional > local levels. For example, under the Regional Policy Statement (which is mandatory under the RMA), for the Gisborne District of New Zealand the chapter on Land Management sets out objectives and policies, and the rules and methods are set out under the Combined Regional Land and District Plan. There are also two other important initiatives in the Gisborne District to control hill country erosion (since the Gisborne District has such a large area of severe erosion); firstly the East Coast Forestry Project (ECFP) which was introduced in 1992, a government funded scheme to control present and potential erosion on the severely eroded 'target' land. This scheme was reviewed in 1998/99 with the (new) objective to achieve sustainable land management on the worst 60 000 hectares of severely eroded (target) land. Secondly, the Sustainable Hill Country Project is being undertaken by the Gisborne District Council, which aims to work with farmers and landowners on changing land use on severely eroded pastoral hill country. This project will include some form of regulation over unsustainable pastoral land uses in eroding and erosion-prone areas of the District.

Sediment quality guidelines

In recognition of the detrimental effects associated with the *quality* of fine-grained sediment in river systems, some countries, such as Australia and New Zealand (ANZECC/ARMCANZ, 2000), Canada (Persaud *et al.*, 1993; CCME, 1999), Hong Kong (Chapman *et al.*, 1999), the Netherlands (Crommentuijn *et al.*, 1997; De Bruijn *et al.*, 1999) and the USA (USEPA, 2004), have developed Sediment Quality Guidelines (SQGs) (see also Power, 2002). The primary focus of such guidelines is the setting of permissible limits of key chemical parameters (such as levels of trace metals). In the USA, through its National Status and Trends (NS&T) programme, NOAA's SQGs were developed to rank estuarine and coastal marine areas that warranted further detailed study on the actual occurrence of adverse effects such as toxicity. These limits have now become synonymous with informal (non-regulatory) guidelines for use in interpreting chemical data from analyses of sediments (Long *et al.*, 1998). SQGs for the assessment and management of freshwater systems in the USA have been developed by the USEPA (1997).

Many SQGs are driven by the need to protect habitats and/or specific species. For example, in Canada the SQGs for the Protection of Aquatic Life were developed in 1990 to protect aquatic organisms in and on sediment in lakes and rivers (CCME, 1999). Similarly, in the UK, physical and chemical water quality objectives have been developed to protect cyprinid and salmonid waters under the EU Freshwater Fish Directive (78/659/EEC). At a European scale, the marine environment is subject to a series of guidelines for sediment quality. These focus on the protection of the marine environment but primarily relate to chemical quality in dredged materials and their environmentally sound disposal in the sea. Guidance includes the Oslo–Paris (OSPAR) Convention and international recommendations for the management of dredged material (such as PIANC); these are reviewed more fully in GIPME (2000) and Köthe (2003).

SQGs should not, however, be regarded as blanket values for national sediment quality. Variations in environmental conditions can affect sediment quality, and most of the guidelines developed require modification for local conditions such as assimilative capacity and sensitivity of species and habitat, particularly endangered components of the ecosystem. SQGs also define permissible limits for a limited number of chemical parameters, and are in danger of omitting contaminants that may have unpredicted but potentially critical effects (such as tributyl tin and endocrine-disrupting substances). The majority of SQGs tend to relate only to chemical standards and neglect to consider the detrimental content of certain physical and biological attributes and substances (GIPME, 2000). Other approaches for assessing sediment quality in Canada, for example, include biological guidelines or community assessments and toxicity tests such as the sediment toxicity identification evaluation and the Sediment Toxicity Index (Environment Canada, 2003).

Managing the quantity of sediment

Guidelines specifically setting standards for the quantity of sediment within river basins (including the coastal zone) are less well-developed, although a few are reviewed below. In France, for example, the French Water Law (3 January 1992) established two tools for managing rivers and river resources: Regional Directing Water Management Plans (SDAGE), and Catchment Water Management Plans (SAGE). Thus, within the SAGE for the Drôme River in France, sediment issues (such as over-mining of bed sediment) are clearly identified as of concern, and

action plans are listed to deal with these (DAVD, 2000). At a European level, guidelines for the quantity of sediment are frequently subsumed into programmes to manage flood or navigation concerns (Köthe, 2003).

In Spain, there is no specific legislation related to the management of sediment quantity. However, due to the increasing concern about loss of reservoir capacity and about downstream effects associated with reductions in sediment amount, as described above (also see Vericat and Batalla, 2005), new initiatives are about to be introduced. In particular, there is a government plan to artificially feed the lower Ebro River and its delta with sediment from the upstream Ribarroja reservoir. Sediment would be subsequently transported downstream during flushing flow releases. Such flows have been produced experimentally since 2002 as a result of collaboration between the Ebro Water Authorities, ENDESA (the hydroelectric power company that operates the dams) and the University of Lleida. The main concerns, however, are the quality of the sediment stored in the reservoir and the cost of transportation to specific downstream disposal/feeding sites of the river.

TOWARDS INTEGRATED SEDIMENT MANAGEMENT

All the case studies above have demonstrated the potential costs associated with sediment management, either directly (such as reservoir management and operational costs in Mediterranean countries, or the costs associated with dealing with large quantities of contaminated sediment in the USA) or indirectly (such as downstream flooding in New Zealand and fish habitats in Canada). It is clear, however, that despite the relative importance of sediment quality and quantity issues within river basins (including estuaries and the coastal zone near river mouths), there are few comprehensive national and international (i.e. EU) sediment management guidelines and plans that operate at the river basin scale, and none that can be said to be fully integrated. Guidelines for sediment quality (SQGs) are to some extent further developed than those for sediment quantity issues (although many are based on only a limited number of chemicals and do not consider biological and/or ecotoxicological effects), but there still remains the desire to treat sediment quality and quantity separately. The case studies presented above have demonstrated that both the amount of sediment and its quality, in terms of nutrient and contaminant content, need to be considered in management plans. The example of the Coeur d'Alene and Spokane rivers clearly demonstrates the need to consider both the quality (in terms of chemistry) and quantity of the sediment, and the examples from rivers in British Columbia show the need to consider sediment type as well as sediment amount. In reservoirs and other depositional environments (such as canals, harbours and estuaries), although the amount of sediment deposited and requiring removal is often of prime concern, the costs associated with its management often increase by an order of magnitude if the sediment is contaminated, due to additional removal, treatment and disposal costs, and there are often strict legislation requirements for contaminated sediment.

In addition to recognizing the need to address both the quantity of the sediment and its quality, for sediment management to be effective and sustainable the fundamental unit of management should be the river basin (Owens, 2005b). Increasingly, the river basin is becoming the scale of water management, as shown by the introduction of the Water Framework Directive in the EU. Sediment management should also operate at this scale, and there are new initiatives within the EU for this (such as the European Sediment Research Network; Brils and De Deckere, 2003; Owens *et al.*, 2004).

The use of the river basin as the scale of water and sediment management introduces some important issues. First, it is necessary to recognize the numerous environments within a river basin (including hillslopes, floodplains, rivers, etc.) and the interconnectivity between these environments (Owens *et al.*, 2004; Owens, 2005b). The interconnection between land use changes on hillslopes, sediment delivery and transport in rivers, and sediment deposition and flooding in downstream reaches has been demonstrated for the Waipaoa River in New Zealand. This and most of the other case studies illustrate the potential for targeted management in headwaters to control downstream problems (i.e. controlling the source of the problem as opposed to downstream management). Secondly, there are typically different 'users' in river basins (Owens *et al.*, 2004), and sediment management guidelines and plans should recognize these and attempt to balance their needs. The example of the Coeur d'Alene and Spokane Rivers in the USA illustrates that there are many different sediment management options available and that management options may impact differently on different users. For example, the removal of the dams on the Spokane River would affect flood protection and hydroelectric power generation. This introduces the need to involve

stakeholders (such as land planners, river authorities, water companies, fishing bodies, recreationists, etc.) in the decision-making process, and the need for tools such as cost–benefit analysis and risk assessment for identifying an optimum solution (Apitz and White, 2003; Owens *et al.*, 2004). Thirdly, and most importantly from a geomorphological perspective, there is a need for a greater understanding of the processes that control sediment transfers and of the role of magnitude–frequency effects and geomorphic thresholds. For example, the removal of the native forest in the Waipaoa River basin lowered the rainfall thresholds for landsliding and gully erosion, leading to an up-shift in the frequency of erosion events, thereby causing high sediment loads in rivers. The example of O’Ne-eil Creek demonstrated the importance of sediment flocculation in controlling sediment deposition on the riverbed. Similarly, the example of the Coeur d’Alene and Spokane Rivers illustrates the importance of sediment–water interactions and post-depositional resuspension processes in controlling the fluxes of contaminated sediment, and thus the evaluation of the various management options available. Such information is vital for developing integrated sediment management guidelines and plans for river basins.

CONCLUSIONS

The case studies contained in this paper exemplify the impact of changes in sediment quality and quantity on river systems. The examples also highlight the value of developing integrated approaches to managing fine-grained sediment. The development of integrated sediment management programmes will require a structure of supporting research, monitoring and evaluation (i.e. science), and legislation and guidelines that is currently unavailable. Thus, integrated sediment management necessitates a shift away from (a) discrete guidelines on a limited number of chemical attributes, (b) guidelines that are driven by individual policy objectives and (c) guidelines that govern only sub-components of the river system. There is also a need within integrative sediment management programmes at the river basin scale for mechanisms to evaluate the multiple uses and users within river basins and, in particular, the need both to involve stakeholders and to use appropriate tools (such as sediment fingerprinting techniques, modelling, scenario analysis, etc.) in the decision-making process. Finally, from a geomorphological perspective, there is a need to (a) understand how the processes that control sediment generation, delivery and transport within rivers operate at scales that are meaningful for management, (b) evaluate the role of magnitude–frequency effects and geomorphic thresholds on sediment transfers, and (c) develop an improved understanding of sediment interactions between the different environments (including soils/hillslopes, rivers, floodplains, wetlands, lakes/reservoirs and the coastal zone) within river basins.

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