10

The Fine-Sediment Cascade

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10.1 Introduction

Fine sediment is arguably the most important component of the sediment cascade – whether this is measured in terms of flux, its role in transporting nutrients and contaminants, or its importance to aquatic ecosystems. This chapter focuses on the transport and storage of fine sediment in the river system, and assesses our knowledge at a range of scales from point processes, through individual river reaches and the dynamic behaviour of fine sediment, to consideration of the large-catchment scale and the role of the entire river network in the fine-sediment cascade. Interactions with channel sources and sinks, as well as the links with other chapters, are indicated in the schematic shown in Figure 10.1. First, the importance of the fine-sediment cascade and its relationship to its geomorphological setting and the time and space scales of interest are examined.

10.1.1 Importance of Fine Sediment

Globally, the fluvial system contributes an estimated 13.5–22 billion tonnes of fine sediment per year to the coastal oceans (Holeman, 1968; Panin, 2004; Syvitski *et al.*, 2005; Walling, 2006), making up an estimated 90–95% of the total sediment flux (Syvitski *et al.*, 2003). This overall flux is affected by two dominant anthropogenic impacts which act in opposite ways. Land-use change – particularly deforestation and intensive agriculture – has led to increases in soil erosion and delivery to the river system, particularly for small- to medium-sized catchments (Owens and Walling, 2002; Dearing and Jones, 2003; Walling *et al.*, 2003a). However, at the large basin scale, the building of reservoirs means that an estimated 25–30% of the global fine-sediment flux is retained within some 45 000 reservoirs (Vörösmarty *et al.*, 2003). Much of the global picture relating to sediment flux is dominated by a few very large basins which are explored in detail in Chapter 13. For Europe, sediment production is estimated to be 1800×10^6 t yr^{-1}, with 540×10^6 t yr^{-1} stored in rivers and on

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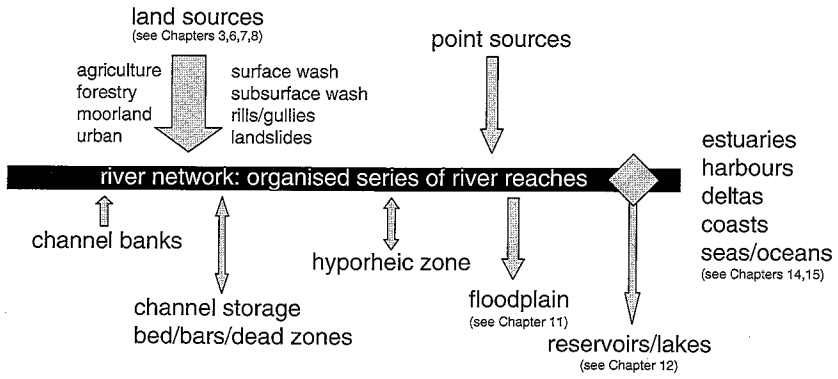

Figure 10.1 Schematic of the fine-sediment cascade showing dominant interactions and links with other chapters

floodplains, 346×10^6 t yr stored in reservoirs and 200×10^6 t yr^{-1} mined from fluvially active areas, leaving a flux of 714×10^6 t yr^{-1} (i.e. 40% production) which is deposited in lowland zones (estuaries, harbours and deltas) or discharged into the surrounding seas and oceans (Owens, 2007).

In addition to its dominance with regard to sediment flux, fine sediment is a major player in the transport of nutrients and contaminants within fluvial systems. The silt and clay fraction of fine sediment is chemically active, due to its large surface area and ionic charge. More than 90% of the total riverine flux of P, Ni, Si, Rb, U, Co, Mn, Cr, Th, Pb, V and Cs, and almost all Fe, Al and rare earth elements are carried as particulates (Martin and Meybeck, 1979). In addition, some 55% nitrogen flux (Meybeck, 1982) and 27% carbon flux (Meybeck, 1982; Degens, Kempe and Richey, 1991) from rivers to the world's oceans may be linked to particulates, although this percentage varies substantially between catchments (Lal, 2002; Alvarez-Cobelas, Angeler and Sánchez-Carrillo, 2008). Within river systems, it is now established that fine sediment is a key factor in the transport, storage and recycling of both nutrients (Bowes and House, 2001; Clarke and Wharton, 2001; House, 2003; Evans, Johnes and Lawrence, 2004; Bowes, Leach and House, 2005; Jarvie *et al.*, 2005) and contaminants (Singh *et al.*, 1997; Macklin, Hudson-Edwards and Dawson, 1997; Rees *et al.*, 1999; Kronvang *et al.*, 2003; Collins, Walling and Leeks, 2005). Hence, knowledge of the transport and behaviour of fine sediment is highly important for understanding the eutrophication of water bodies and impacts on ecosystem and human health.

Fine sediment is also fundamentally important for a range of aquatic habitats. Here, there are issues of sediment quantity as well as quality. High concentrations of suspended sediment have been shown to be detrimental to fish and a comprehensive review of the effects on a range of fish species dependent on both the concentration of suspended sediment and the duration of exposure is presented by Newcombe and Jensen (1996). Evidence for the detrimental impact of both surface and subsurface deposition of fine sediment on periphyton, invertebrates and fish species comes from a range of field and experimental studies (e.g. Quinn *et al.*, 1992; Soulsby *et al.*, 2001; Yamada and Nakamura, 2002; Pedersen, Friberg and Larsen, 2004; Rabeni, Doisy and Zweig, 2005; Matthaei *et al.*, 2006; Niyogi *et al.*, 2007). In particular, the settling and infiltration of fine sediment into gravel interstices impedes water flow within the hyporheic zone and reduces oxygen levels, adversely affecting both benthic organisms and fish spawning grounds (Beschta and Jackson, 1979;

Acornley and Sear, 1999; Soulsby *et al.*, 2001). Here, the effect of particle size and organic content has been shown to be particularly important (Greig, Sear and Carling, 2005; Heywood and Walling, 2007). At the other end of the spectrum, supply of fine sediment is critical to the maintenance of habitats on floodplains, mud flats and deltas – problems with too little sediment are reported by Batalla (2003).

Fine sediment is also responsible for reservoir siltation, significantly reducing the life of high capital cost impoundments for water supply and irrigation, and for river aggradation, leading to problems for flood defence and navigation (Owens *et al.*, 2005). Dredging is an expensive option and problematic for contaminated sediments (Köthe, 2003). All these impacts underline the importance of fine sediment and the need to understand the fine-sediment cascade in order to provide effective management strategies (see Chapters 1 and 7).

10.1.2 Geomorphological Setting, Time and Space Scales

In describing the fine-sediment cascade, it is essential to be aware of both the geomorphological setting and the time and space scales of relevance to fine-sediment transport. Fine sediment, which is sourced from the land, input from external point sources (e.g. construction sites, industrial or sewage effluent) or derived from bank erosion, can be moved through all types of river reach including bedrock, cohesive-bed, boulder-bed, gravel-bed and sand-bed rivers. To encapsulate transport in these settings, three terms are useful. *Washload* consists of material which moves through the river system but has no interaction with the river bed. Silt and clay generally fall into this category, particularly in the context of sand-bed rivers where they are present in the bed in only negligible quantities. *Throughput load* is a term which has been coined to define the transport of fine material which has some interaction with the bed. For example, in gravel-bed rivers, sand, silt and clay move as a type of washload but may be deposited in the interstices of gravel or in limited areas of the channel such as bars, benches, pools and dead zones. This fine sediment is insufficient to cover the bed and does not determine the bed morphology. However, it is of prime concern for aquatic ecosystems and is the subject of a great deal of current research. This deposited fine sediment may be mobilized as part of the active bed layer, but may subsequently move either as bedload, by saltation or rolling, or in suspension. *Bed material load* is that portion of the transported load which is found on the bed of the stream and undergoes exchange between the bed and the water column. Bed material load may move as bedload or in suspension but is an integral part of the channel morphology. The movement of sand as dunes or sand sheets and the movement of sediment in alluvial channels fall into this category.

In structuring our knowledge of the fine-sediment cascade, it is helpful to consider the time and space scales of interest. Loosely based on Church (1996), three domains can be identified: these have different modes of explanation and are described in Figure 10.2. The first of these is the domain of hydraulics in which the physics of sediment transport is used to determine the flux of fine sediment through river cross-sections or short river reaches. Here the explanation is deterministic, with space–time averaging of turbulent eddy scales and short duration burst–sweep cycles which are responsible for the movement of individual grains but where flux is determined by the steady-state average behaviour of the fluid. Expanding both time and space scales, the domain of hydrology is entered where the important characteristics of sediment behaviour are the dynamics over hydrological

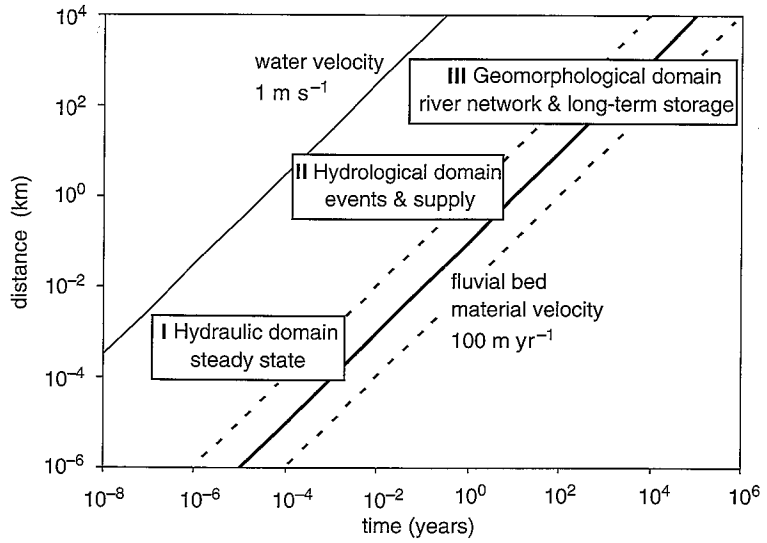

Figure 10.2 Time-space scales in the sediment cascade showing domains of interest. Also shown are the virtual velocities for water (thin black line) and fluvial bed material (thick black line and dashed lines showing possible range of values) as given in Church (1996); suspended sediment takes a trajectory somewhere between the velocities of water and bed material which may itself depend on scale

events. Here, the fine-sediment flux is described by the interplay between the hydrology and sediment storage, with the role of channel processes and sediment routing becoming more important and the emergence of hysteretic behaviour in the observed dynamics. For larger catchments and longer time scales, the role of geomorphology becomes increasingly important and the flux now becomes contingent on the structure of the river network and the history of sediment erosion and transfer throughout the entire basin.

This chapter takes each of the three domains in turn and reviews recent research which has contributed significantly to improving our understanding of the fine-sediment cascade. It predominantly focuses on fine sediment that is moved as washload or throughput load and transported in suspension. The interaction of fine sediment with floodplain and channel morphology is covered in Chapter 11.

10.2 Fine-Sediment Transport

The first domain of interest is the hydraulic domain in which the focus is on the physics of sediment transport and how this controls fine-sediment conveyance through a cross-section or a short river reach. First, the nature of fine sediment needs to be understood.

10.2.1 The Nature of Fine Sediment

Fine sediment is normally taken to comprise sand, silt and clay particles, that is those grain sizes with a diameter <2 mm. Grain size may also be quoted in phi units (defined as

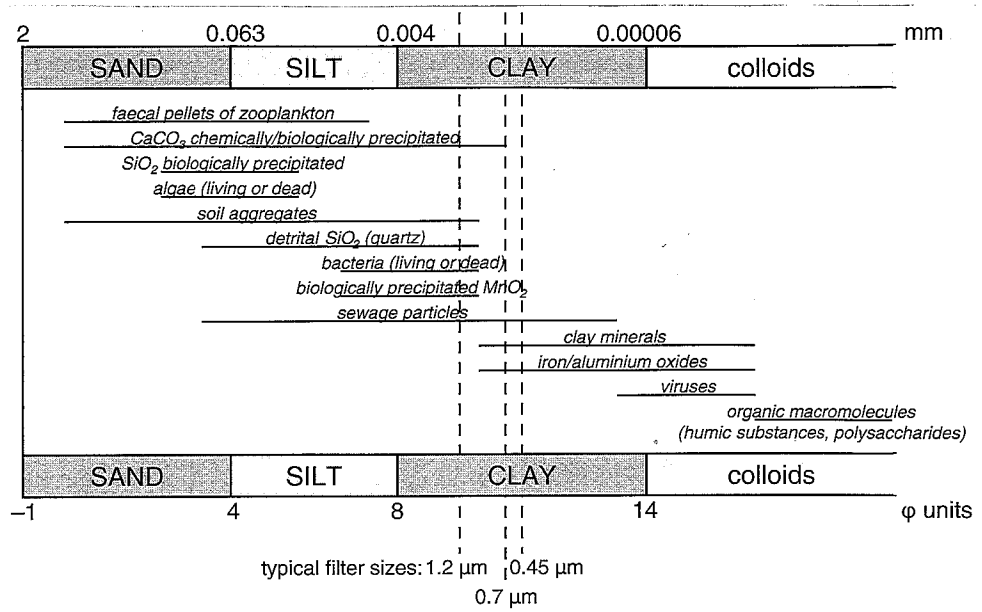

Figure 10.3 Definition of fine-sediment size characteristics, including organic and colloidal material using size ranges given in Tipping (1988)

$\varphi = \log_2[D/D_0]$ where D is the grain size in mm and D_0 is 1 mm). Figure 10.3 gives the standard definition of sediment size fractions in terms of particle diameter in both millimetres (on a logarithmic scale) and phi units. It also shows typical filter sizes (1.2, 0.7 and 0.45 μm) used in the measurement of suspended sediment. While once the term sediment strictly referred to mineral grains, the definition of fine riverine sediment has gone through something of a revolution in recent years (Droppo, 2001) and it is now accepted that it includes both organic and flocculated material. This is important for understanding both the flux of material and its transport characteristics. Accordingly, Figure 10.3 includes the particle size ranges of the common organic materials, flocs and, for completeness, colloids found in aquatic systems (Tipping, 1988).

As particle size decreases, the surface area per unit volume of the particle increases and interparticle, or cohesive, forces dominate particle behaviour. There is no clear size boundary between cohesive and non-cohesive sediment. Sand-sized material is generally non-cohesive. Clay-sized material is cohesive and exhibits very strong inter-particle forces due to its surface ionic charge. Silt may be cohesive, dependent on the presence of clay and organic material, and is generally classed as such. Cohesive sediments consist of both inorganic minerals and organic material such as plant and animal detritus and bacteria. The term *seston* is used in the ecological community to refer to any particulate matter such as plankton or other living organisms as well as organic detritus and inorganic particles. Thus, an additional component of the fine-sediment cascade in its broadest sense is autochthonous material derived from biological components within the river system. An example of this is the faecal pellets of blackfly larvae which can make up some 40–60% of the fine material deposited on the bed of chalk streams (Wharton *et al.*, 2006). Knowledge of the

characteristics (particle size and organic content) of this biogenic material is generally lacking but is important for understanding both the flux of fine sediment and its effect on aquatic ecosystems, particularly in relation to the functioning of the hyporheic zone or permeable region beneath a stream bed.

Cohesive sediment is commonly transported in a flocculated or aggregated form (Droppo and Ongley, 1992). Flocs or aggregates are heterogeneous, composite structures composed of an active biological component, a non-viable biological component, inorganic particles and water held within or flowing through pores (Droppo, 2001). They are never purely inorganic. They are formed either within the water column or in the surface of the bed or transported to aquatic systems as water-stable soil aggregates. While some large flocs may readily break up, the majority of riverine flocs are stable (Droppo, 2004). Liao *et al.* (2002) showed that van der Waal and/or hydrophobic interactions were important in the development phase of flocs by bringing particles close enough to form specific interactions. However, once flocs are initiated, microbial binding through bacterial secretion of extracellular polymeric substances (EPS) takes over, in conjunction with further strengthening via ionic interactions and hydrogen bonding. Flocculation fundamentally alters the hydrodynamic properties of the sediment by increasing the effective particle size by orders of magnitude and by changing the shape, density, porosity and composition of the particle. This changes the downward flux of fine sediment and is a fundamental factor in the deposition of fine material both in channels (Tipping, Woof and Clarke, 1993) and on floodplains (Nicholas and Walling, 1996).

The effect on particle size is shown in Figure 10.4. The pictogram in Figure 10.4a shows an image of flocculated sediment in suspension and a disaggregated suspension following sonification. The change in particle size is clearly visible. Flocs are found to comprise about 10–27% total number of particles but represent about 92–97% of the total volume of suspended sediment. Grain sizes between 1 and 2.6 μm are entirely incorporated into flocs (Droppo and Ongley, 1992). Figure 10.4b shows example distributions of both effective particle size and absolute (disaggregated) particle size for both suspended sediment and bed sediments taken from Phillips and Walling (1999). It clearly shows the shift in size with the median size of the flocculated sediment lying between 20 and 80 μm compared with an absolute value of about 5 μm. Phillips and Walling (1999) also show a seasonal variation in particle size, with the size of flocculated particles being higher in the summer when biological activity is greatest but with the absolute particle size being higher in winter when erosion is more active.

10.2.2 Settling Velocity of Fine Sediment

The primary characteristic of fine sediment which dictates its transport and storage within river systems is its settling velocity. Very small particles (<1 μm) and colloids are subject to Brownian diffusion and do not settle. For larger particles where gravitational forces exceed the effects of diffusion, the settling velocity of small individual particles travelling through static water may be calculated, assuming spherical particles, from Stokes' Law

$$V_g = \frac{RgD^2}{C_1 \nu} \tag{10.1}$$

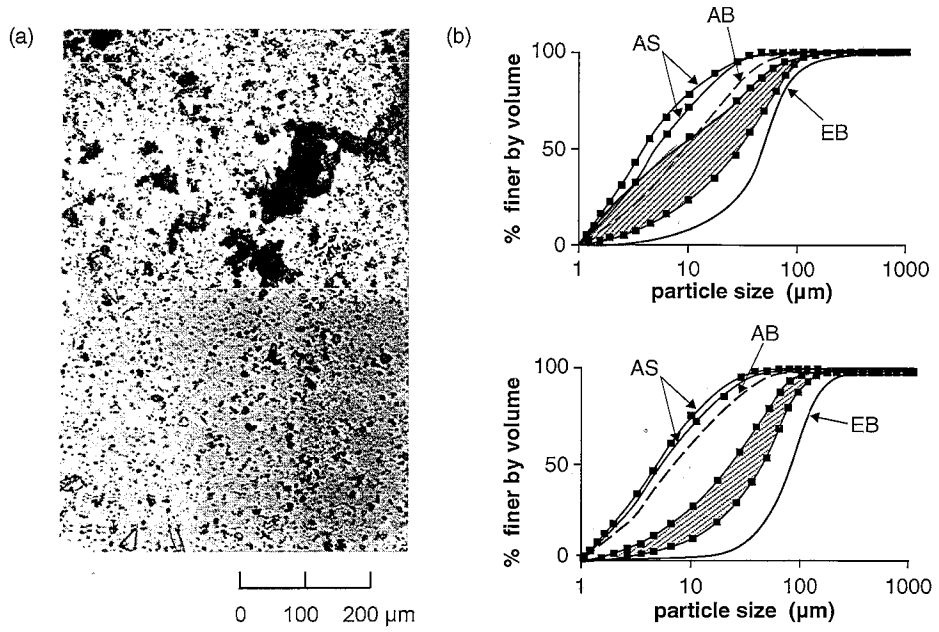

Figure 10.4 Effect of flocculation on particle size.: (a) Pictogram of flocculated suspension and disaggregated suspension following sonification
(reprinted, with permission, from Droppo, I.G. and Ongley, E.D. (1992) The state of suspended sediment in the freshwater fluvial environment: a method of analysis. Water Research, 26, 65–72. © Elsevier.); (b) Example distributions of effective and absolute particle size: AB and EB are absolute and effective size of bed material respectively; AS is absolute size of suspended material; shading denotes range of effective size of suspended material.
(reprinted, with permission, from Phillips, J.M. and Walling, D.E. (1999) The particle size characteristics of fine-grained channel deposits in the River Exe Basin, Devon, UK. Hydrological Processes, 13, 1–19. © John Wiley & Sons Ltd).

where V_g is settling velocity, R is submerged specific gravity or $(\rho_s - \rho)/\rho$, ρ_s is particle density, ρ is density of fluid, g is acceleration due to gravity, D is particle diameter, ν is kinematic fluid viscosity ($10^{-6}\,m^{-2}\,s^{-1}$ for water at 20 °C) and C_1 is a constant with a theoretical value of 18. This gives accurate results for spherical particles provided that the particle Reynolds number ($V_g D/\nu$) is less than 1.0, indicating that viscous forces dominate fluid resistance. At large particle Reynolds numbers, when inertial forces dominate, boundary-layer separation occurs behind the particle such that its rapid settling is resisted predominantly by the turbulent drag of the wake behind the particle. In this case, the settling velocity is given by

$$V_g = \sqrt{\frac{4}{3}\frac{RgD}{C_2}} \tag{10.2}$$

where C_2 is the constant asymptotic value of the drag coefficient for particle Reynolds numbers between 10^3 and 10^5. Experiments have shown C_2 to be 0.4 for smooth spheres and approximately 1 for natural grains (Cheng, 1997). For the transitional range of particle

Reynolds numbers between 1 and 10^3, equivalent to the sand to fine gravel size range of $0.1 < D < 4$ mm, a number of different equations have been put forward (Rubey, 1933; Gibbs, Matthews and Link, 1971; Dietrich, 1982; Hallermeier, 1981; Ahrens, 2000; Ferguson and Church, 2004). The most recent of these by Ferguson and Church (2004) has the advantages of being dimensionally correct, providing a smooth transition between Equations 10.1 and 10.2 to which it is asymptotic, and of being able to accommodate both spherical particles and natural grains through specification of its parameters. It is given by

$$V_g = \frac{RgD^2}{C_1\nu + \sqrt{0.75C_2RgD^3}} \tag{10.3}$$

The constants C_1 and C_2 take the values of 18 and 0.4 for smooth spheres; for typical natural sands, values of 18 and 1.0 are proposed for use with size specified in sieve diameters. Values of 20 and 1.1 are proposed for use with nominal diameters, with a likely limit for very angular grains of 24 and 1.2. The proposed curves for spheres and natural sediments ($R = 1.65$) are shown in Figure 10.5a. Methods for measuring particle density are given in Lal (2006).

The controls on floc-settling velocities are rather different. Measurements have shown that as floc size increases, floc density decreases and floc porosity increases (Droppo *et al.*, 1997). Thus, although the primary control on settling velocity is still floc size, there is much more scatter in the relationship. Floc densities are typically between the density of water and 1.4 g cm^{-3}, with the majority being around 1.1 g cm^{-3} (Droppo, Walling and Ongley, 2002). Settling rates are, therefore, about an order of magnitude lower than a similar size of solid particle. Some typical relationships reported in the literature are shown in Figure 10.5b. It should be noted that, compared to the exponent of 2 in the Stokes' equation, these relationships have exponents of particle diameter in the range 0.5 to 1.0 for flocs and about 1.2–1.3 for soil aggregates. Williams, Walling and Leeks (2008) identify the other controls on the settling velocity of flocs and aggregates as the porosity of the particle and its fractal dimension. Although these relationships plot well below the Stokes' Law indicating lower settling velocities for the given size, it should be remembered that the flocs are composed of particles which may be an order of magnitude or more smaller in size and therefore this represents an increase in settling velocity for those particles, which enhances their propensity to deposit. Thus, the process of flocculation and the transport of fine sediment as flocs and aggregates are clearly fundamental for understanding the dynamics of the fine-sediment cascade. For further details on the transport of cohesive sediment, the reader is referred to the excellent review in Krishnappan (2007) and the applications given in Haralampides, Corquodale and Krishnappan (2003) and Bungartz and Wanner (2004).

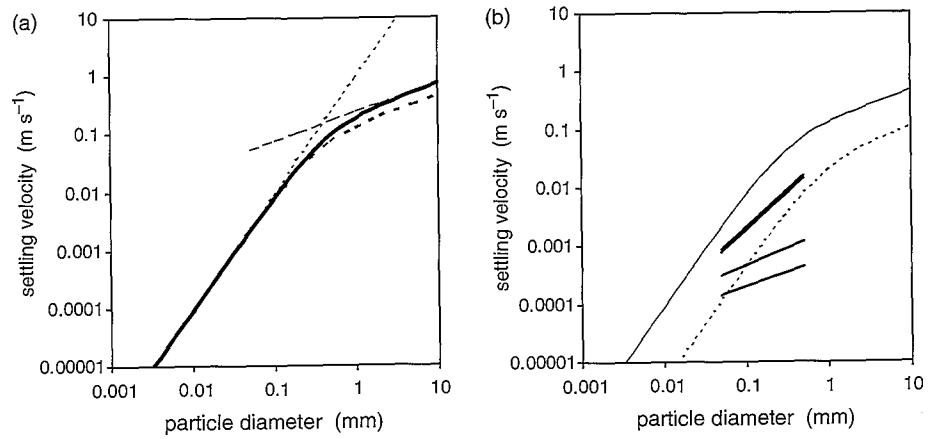

Figure 10.5 Settling velocity as a function of particle size. (a) Stokes Law (black dotted line), wake law for smooth spheres (black dashed line), Ferguson and Church (2004) for spheres (heavy black solid curve) and natural sediments (heavy black dashed curve) with $R = 1.65$. (b) Typical settling velocities for flocs, for example soil aggregates (upper heavy black line) and suspended solids (lower heavy black lines) after Williams, Walling and Leeks (2008) with Ferguson and Church (2004) settling velocities for spheres with $R = 1.65$ (black solid curve) and $R = 0.11$ (black dotted curve)

For very high sediment concentrations, mutual particle hindrance and increased drag cause a reduction in the settling velocity compared to that for individual grains. This effect may be represented as

$$V'_g = V_g(1-C)^n \tag{10.4}$$

where V'_g is settling velocity in a dispersion of other grains, V_g is settling velocity of a single grain, C is *volume* concentration and n is an exponent which varies between 2.32 and 4.65 dependent on grain Reynolds number (Richardson and Zaki, 1958). Typical high values of suspended sediment concentrations are of the order of 1000 mg L^{-1} which, assuming a particle density of 2650 kg m^{-3}, gives a volume concentration of 10^{-4} implying a negligible 0.001% reduction in settling velocity. However, hyperconcentrated flows have also been reported in Chinese rivers with concentrations of 300 g L^{-1} (Xu, 2002). Applying the same calculation gives a reduction in settling velocity of about 30%. Hyperconcentration also occurs near the river bed, giving rise to 'fluffy' surficial deposits with a high water content which may subsequently be readily entrained (Droppo and Stone, 1994).

10.2.3 Conveyance of Fine Sediment

Settling velocity determines both the transport mode of fine sediment as well as its propensity for deposition. Silt, clay and flocculated material will normally travel in suspension while sand may be transported either in suspension or as bedload, by rolling or saltation, dependent on the flow conditions. Of key importance for calculating the flux of suspended material is the distribution of sediment concentration with depth.

Suspended sediment includes all grains kept aloft by fluid turbulence such that the weight of suspended material is balanced by an upward momentum transfer from fluid eddies (Leeder, 1982). Thus, the quantity of particles in suspension depends on the fluid velocity and turbulence as well as on the settling velocity of the sediment. Typical measured concentration profiles are illustrated graphically in Figure 10.6. This clearly shows that the higher the settling velocity of the particle, the higher is the concentration near the bed, while particles with a very low settling velocity are evenly distributed throughout the water column.

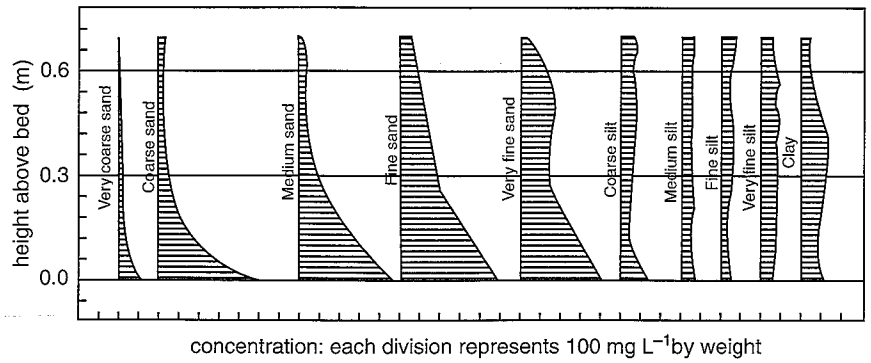

Figure 10.6 Typical concentration profiles for suspended sediment of a range of particle sizes/settling velocities in the Missouri River at Kansas City, USA
(reprinted from Brakensiek, D.L., Osborn, H.B. and Rawls, W.J. (coords.) 1979 Field Manual for Research in Agricultural Hydrology. United States Department of Agriculture, Agricultural Handbook 224. 550 pp. Courtesy of the United States Department of Agriculture).

Assuming a logarithmic velocity distribution, particles in suspension will exhibit a vertical concentration profile which can be calculated from diffusivity theory (Rouse, 1937) as

$$C_y/C_a = [(d-y)/y.\, a/(d-a)]^z \qquad (10.5)$$

where C_y is concentration of suspended sediment at height y above the bed, C_a is the reference concentration at height a above the bed, d is total flow depth and $z = V_g/\beta\kappa u_*$ where V_g is settling velocity, β is the ratio of the diffusivity of suspended sediment to that of water and is often taken to be 1, κ is Von Karman's constant and u_* is bed shear velocity. The Rouse equation has been found to agree with concentration profiles in the lower part of stream flows but tends to underestimate concentrations in the upper parts of the flow (e.g. Bennett, Bridge and Best, 1998). Various criticisms have been made of the Rouse equation which are summarized in Bridge (2003). The main problem lies in the calculation of the sediment diffusivity and alternative formulations for β have been cited (e.g. van Rijn, 1984). In practice, C_a and a must also be measured or calculated and there are various methods for doing this (e.g. van Rijn, 1984; Cao, 1999). An alternative to the convection–diffusion approach is through an explicit two-phase flow model (e.g. Greimann and Holly, 2001) but these methods are as yet relatively undeveloped.

In order to calculate the suspended sediment conveyance or transport capacity, the velocity and suspended sediment profiles must be determined for the full width of the channel and their product integrated for the whole cross-section. Alternatively, there is a plethora of empirical functions and sediment transport models available which are reviewed by Papanicolaou *et al.* (2008).

Of particular interest for the fine-sediment cascade is the conveyance of suspended sediment through vegetated channels where the assumption of a logarithmic velocity profile

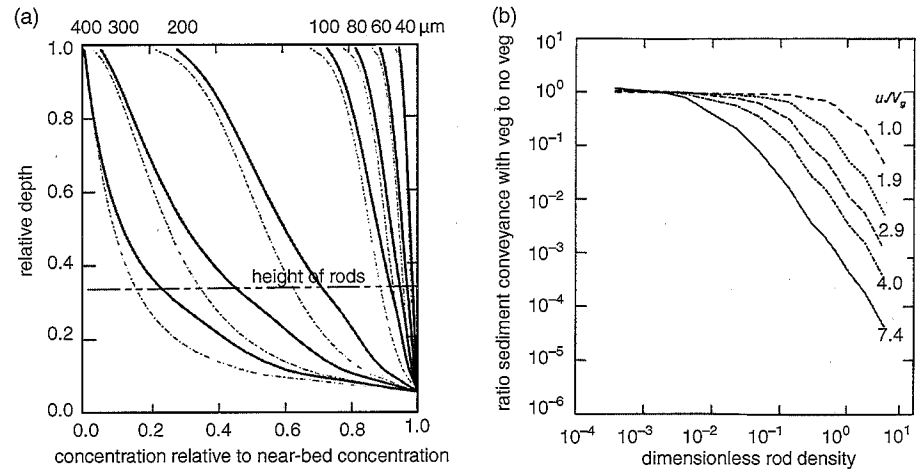

Figure 10.7 Effect of vegetation on sediment conveyance.: (a) Vertical concentration profiles with vegetation (solid lines) compared to Rouse model (dot-dash lines) for a range of grain sizes indicated along the top of the graph.; (b) Reduction in sediment conveyance in the vegetated case for a range of grain sizes as indicated by the ratio of shear velocity (u*) to settling velocity (V_g)
(reproduced from López, F. and Garcia, M. (1998) Open-channel flow through simulated vegetation: suspended sediment transport modelling. Water Resources Research, 34, 2341-2352. Courtesy of the American Geophysical Union).

no longer holds and a double-averaging methodology needs to be adopted. An example using vertical rods to represent rigid vegetation is provided by López and Garcia (1998). They use a modified k–ε turbulence model with additional drag terms to close the Reynolds-averaged Navier–Stokes equations for continuity and momentum to give velocity profiles for clear water in vegetated channels. This is then applied in conjunction with the equation for the vertical diffusion of sediment to give concentration profiles in the presence of vegetation. Figure 10.7a shows that, compared to the Rouse distributions, the presence of vegetation has a tendency to produce a more uniform distribution of fine sediment – particularly for the coarser size fractions. The transport capacity is calculated by numerically integrating the product of the double-averaged downstream velocity and sediment concentration. Figure 10.7b shows the impact on transport capacity of vegetation at a range of densities for sediment with different settling velocities. The rapid reduction in transport capacity with increasing vegetation density is readily apparent, particularly at high particle Reynolds numbers.

In practice, vegetation is not a uniform field of rigid rods but provides a varied hydraulic environment with both marginal vegetation and in-channel submerged vegetation. In the case of large trailing macrophytes, fine sediment may be found in patches in the lee of stems (Cotton *et al.*, 2006). This vegetation also creates a spatially organized flow pattern or pseudo-braiding which may actually increase the overall sediment transport capacity. The exchange of fine sediment with marginal habitats (Gurnell *et al.*, 2006) is another interesting feature of natural channels in which lateral diffusivity is important for modelling conveyance and deposition (Sharpe and James, 2006). Further research is needed to

understand and model the flow patterns in vegetated channels as well as their effect on sediment conveyance.

10.3 Reach-Scale Dynamics, Sources and Storage

In the previous section it was shown how the conveyance capacity of river channels for fine sediment under steady flow conditions can be calculated. While this is an important upper limit on the fine-sediment flux, there is also a need to understand sediment transport under unsteady conditions and in non-capacity channels. Expanding the time and space scales to that of the hydrological domain (Figure 10.2), the dynamics of fine-sediment movement during storm events and the role of sediment supply on the fine-sediment cascade are now considered.

10.3.1 Measurement of Fine-Sediment Flux

The flux of suspended sediment is usually derived from measurements of water discharge and suspended sediment concentrations. This assumes that the sediment travels at the same speed as the water. This assumption has recently been brought into question by experimental work of Muste *et al.* (2005) and neglect of this may lead to an overestimate of flux (Aziz, Prasad and Bhattacharya, 1992). However, perhaps more significant is the need for effective temporal resolution in flux monitoring. It is well known that $> 90\%$ of fine-sediment flux is carried in $< 10\%$ time. An example time series of flow and suspended sediment concentration is shown in Figure 10.8. It is evident from this that fine sediment may vary by several orders of magnitude over a single flow event. For this reason, good flux estimates rely heavily on event sampling coupled with continuous turbidity measurements, generally using optical back-scatter, and there are a number of well-established instrumentation techniques and protocols available (Evans, Wass and Hodgson, 1997; Wass and Leeks, 1999; Old *et al.*, 2006).

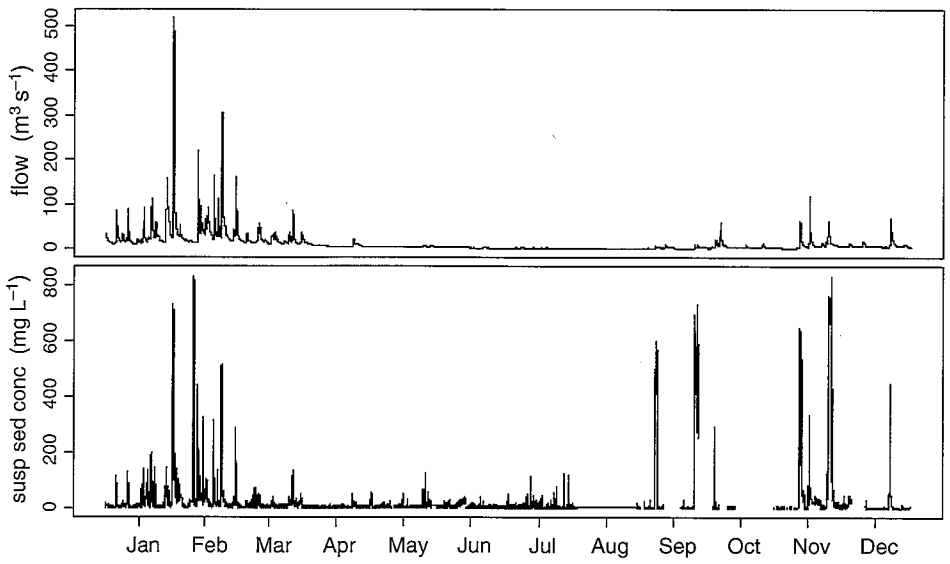

Figure 10.8 Example time series of flow and suspended sediment concentration for 1995 from the River Swale, UK based on continuous turbidity and storm event sampling

As these protocols reveal, the reliability of determining suspended sediment from turbidity depends on rigorous weekly or fortnightly cleaning of the turbidity sensor, regular calibration of the probe using standards and the stability of the relationship between suspended sediment and turbidity. A number of factors, such as particle size, shape, composition and water colour, have been identified as intervening in this relationship and a comprehensive review is given in Gippel (1995). The uncertainty associated with these variables may preclude the use of turbidity at very low suspended sediment concentrations ($<10\,\mathrm{mg\,L^{-1}}$) so that calculation of flux is best achieved using a median value of suspended sediment concentration from grab samples taken say weekly to indicate the background suspended solids during low flows, coupled with event sampling.

Even in small catchments, the relationship between suspended sediment and turbidity can be quite scattered (Figure 10.9a). In large catchments with multiple sources, the relationship between suspended sediment and turbidity may vary between each storm. This is shown in Figure 10.9b for the River Swale over a series of storm events sampled during 1994 and 1995; the relationship during an individual storm is often extremely good but the overall scatter is high. This emphasizes the importance of using *both* turbidity and automatic sediment sampling in tandem in order to obtain good continuous data and therefore good flux measurements. Newer approaches using acoustic or fibre optic technologies may have potential for development in the future.

10.3.2 Fine-Sediment Dynamics over Hydrological Events

The part of the fine-sediment cascade which is dominated by washload or throughput load may be characterized as a 'high flux–low storage' system. One of the reasons that it is so

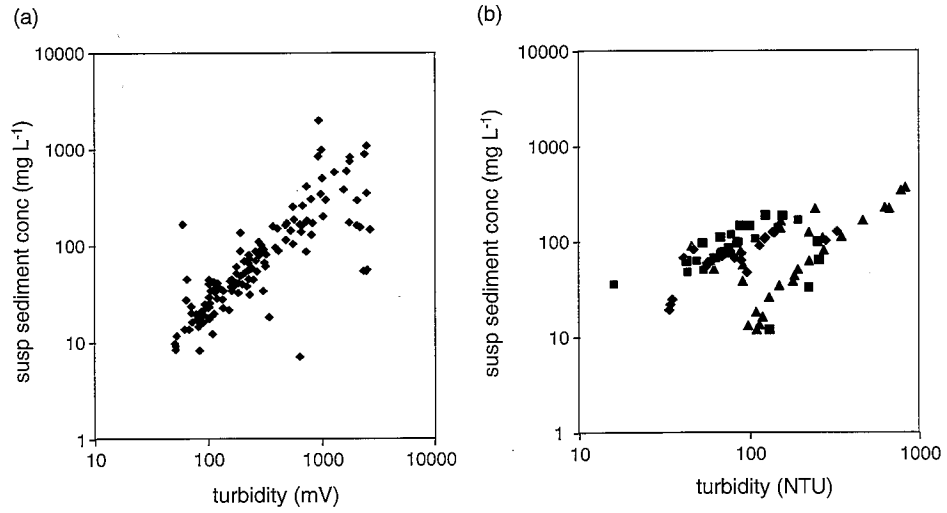

Figure 10.9 Example relationships between turbidity and suspended sediment. (a) Small catchment with well-defined relationship (Denbrook, Devon, UK – data collected by Barnaby Smith, CEH and Patricia Butler, North Wyke Research used with permission). (b) River Swale – each symbol represents a different event
(after Smith *et al.*, 2003a).

difficult to predict and model in detail is that much of the time fine-sediment flux is limited by its availability, that is the flow has the capacity to convey much more fine sediment than is available to be transported. At other times, fine sediment is transport-limited which leads to deposition. In order to understand the dynamics of fine-sediment storage in the channel, it is therefore important to recognize the times, places and conditions under which these different conditions occur.

If fine sediment were not limited by storage, then sediment rating curves would show a tightly defined relationship between fine-sediment concentration and river discharge. However, sediment rating curves in general show a very high degree of scatter. This has variously been attributed to variations with season, sediment source area and the rising and falling limbs of the hydrograph. In this last case, patterns of hysteresis can provide a useful tool for exploring sediment dynamics. Many catchments, particularly small ones, exhibit clockwise or positive hysteresis, that is sediment concentration increases more rapidly than river discharge, often peaks before discharge and shows much lower concentrations at the same discharge on the falling limb of the hydrograph. The cause of this has generally been attributed to depletion of the store of available sediment (Bogen, 1980; Walling and Webb, 1982) or an increased proportion of subsurface flow during the recession limb of a hydrograph (Wood, 1977; Becht, 1989). Anticlockwise or negative hysteresis occurs less frequently and has been associated with cases where sediment sources are distant from the point of measurement (Heidel, 1956) or where sediment is derived from bank collapse following the flood peak (Sarma, 1986; Ashbridge, 1995) or mobilized from the bed following biofilm break-up (Lawler *et al.*, 2006). For larger catchments, other factors need to be considered such as the downstream propagation of the flood wave (Petts *et al.*, 1985; Bull, 1997), the timing of water and sediment inputs from tributary streams (Smith *et al.*, 2003a), size of temporary storage within the river channel (Asselman, 1999) and the relative velocity of the water and the sediment.

Many of these points can be illustrated by reference to measurements taken over a 55 km stretch of the River Swale in North Yorkshire, UK. Figure 10.10 shows both the hydrograph and sedigraph for a simple in-bank event for the upstream and downstream measurement sites and the corresponding hysteresis curves. In this event, most of the water and sediment was sourced upstream of the upper measuring point. The total volume of water passing through the upstream site is $7.4 \times 10^6\,m^3$ compared with $8.5 \times 10^6\,m^3$ for the downstream site. The hydrograph and sedigraph clearly show the attenuation of the event as it passes downstream. This is much more pronounced for the sedigraph than for the hydrograph and may be due to the different velocity of the water and the sediment. The net effect of this is a gradual reduction in conveyance capacity and significant within-reach deposition during this event – an estimated 2230 tonnes of fine sediment passed through the upstream site whereas only 901 tonnes passed through the downstream site.

Figure 10.10 shows that during this event, the upstream site shows a limited degree of clockwise hysteresis suggesting that more sediment is mobilized on the rising limb of the hydrograph and that there is some depletion of the available sediment. The dominant pattern at the downstream site is one of marked clockwise hysteresis. In this case, it reflects the progressive deposition of sediment during its travel down the reach and a consequent reduction in available sediment. Later in the season, similar events show anticlockwise hysteresis at the upstream site which is consistent with the hypothesis that in-channel sources have largely been exhausted and material is being sourced from more distal sources. This effect is less pronounced at the downstream site due to the supply of in-channel

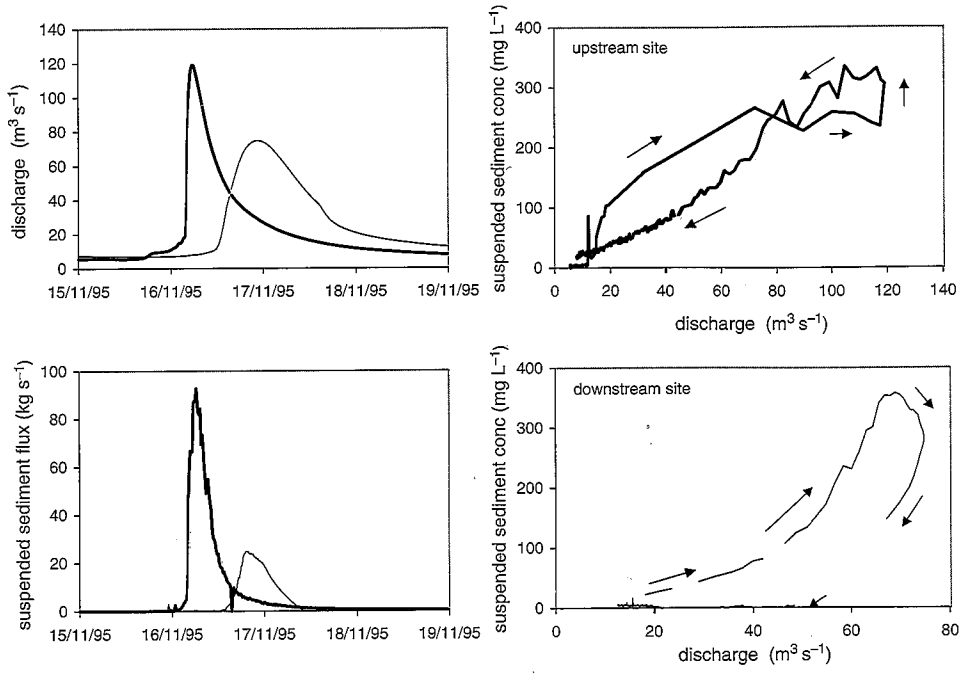

Figure 10.10 Passage of water and sediment downstream for River Swale, North Yorkshire, UK, during an event largely sourced in the headwaters: thick line denotes upstream site of Catterick; thin line denotes downstream site of Leckby Grange

sediment deposited in the intervening reach by events such as that described in Figure 10.10. Thus, over an annual period and particularly in events where both water and sediment is largely sourced from above the upstream site, a slug of fine sediment is seen as being progressively cascaded down through the river reach.

Figure 10.11 shows a contrasting type of in-bank event. Here, the entire catchment is contributing with both water and sediment input from tributaries joining the main channel throughout the monitored reach. In this case, although the timing of the peak at the downstream site is later than that at the upstream site, both the hydrograph and the sedigraph peaks increase as tributary rivers bring in more sediment and water. The water flux through the upstream site is $15.8 \times 10^6\,m^3$ and through the downstream site is $23.3 \times 10^6\,m^3$; the associated sediment flux is 516 tonnes and 1017 tonnes respectively. It should also be noted that this event has much lower sediment concentrations compared to the earlier event suggesting that available sediment is more limited. For the upstream site, both sedigraphs of this double peaked event show anticlockwise hysteresis with the first event having higher concentrations of fine sediment compared to the second event. The anticlockwise hysteresis suggests that material comes from more distal sources; the progressive reduction in concentration over the two events suggests a reduction in the availability of sediment with each successive event. At the downstream site, there is evidence for increased mobility of sediment for flows greater that $50\,m^3\,s^{-1}$ which may indicate mobilisation from within the channel. There is only limited anticlockwise hysteresis but a pronounced drop in concentration for a given flow during the second of the two events, implying a reduction in sediment availability.

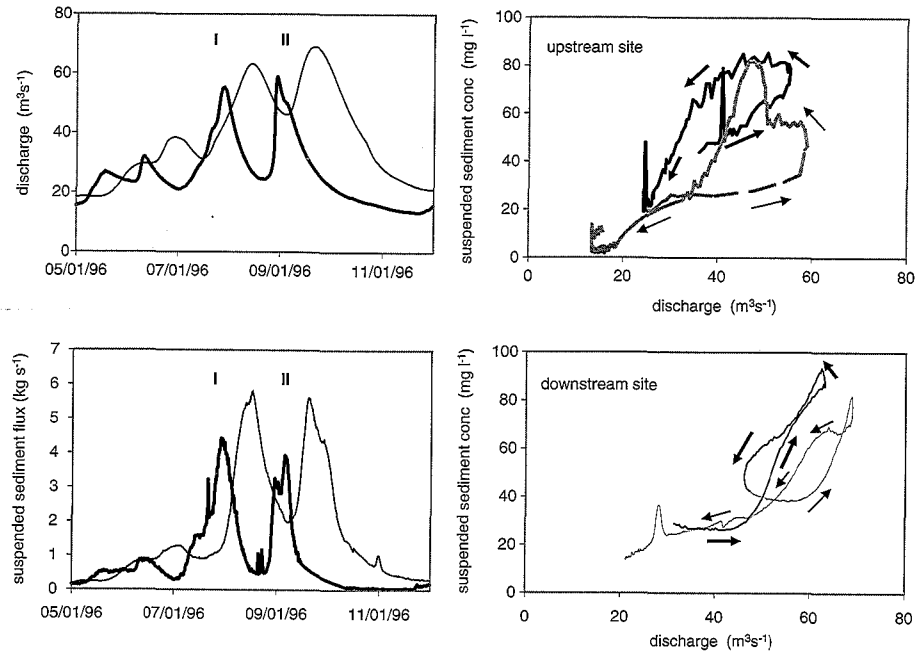

Figure 10.11 Passage of water and sediment downstream for River Swale, North Yorkshire, UK, during a double event sourced throughout the larger catchment: thick line denotes upstream site of Catterick; thin line denotes downstream site of Leckby Grange. Hysteresis patterns for the two major events (labelled I and II) are shown in solid and dashed lines respectively

These findings for the River Swale are similar to those of Asselman (1999) for the River Rhein in Germany where the mixing and routing of water from different sources as well as the amount of sediment in storage were also found to be important drivers of the sediment flux during events. A full analysis of all the events on the Swale over the period 1994–1996 also points to the importance of a small number of overbank events and to changing sediment storage within the reach (Smith *et al.*, 2003a, 2003b).

10.3.3 In-Channel Storage

Following on from the dynamics illustrated above, it is clear that in order to understand the fine-sediment cascade, it is important to be able to quantify in-transit storage, that is the amount of sediment that is temporarily stored *en route* to the sea. Floodplain storage is dealt with in Chapter 11 and may account for between 10 and 50% of the annual flux (Walling, Owens and Leeks, 1999). The focus here is on in-channel storage, particularly in relation to gravel-bed rivers in which the storage of fine sediment may be relatively short-term and unimportant in terms of volume but may be a substantial proportion of the annual fine-sediment flux and is critical for both biota and biogeochemistry or water quality.

Fine sediment may be stored on the river bed in discrete patches around vegetation (Cotton *et al.*, 2006) or in vegetated channel margins (Gurnell *et al.*, 2006), in the lee of

cobbles or pebble clusters (Brayshaw, Frostick and Reid, 1983), as sand ribbons (Bridge and Jarvis, 1976) or drapes in pools (Lisle and Hilton, 1999), in dead zones (Tipping, Woof and Clarke, 1993) or on channel bars (Gurnell, Blackall and Petts, 2008). These stores may respond to individual flood events (Krein, Petticrew and Udelhovem, 2003); they may be seasonal in character such as those associated with vegetation growth; or they may reflect the passage of sediment waves downstream. Examples of the latter include short-term effects such as the reservoir release of *c.* 7000 m^3 of silt to pebble-sized sediment reported by Wohl and Cenderelli (2000). Here, fine sediment was deposited in downstream pools but then reworked in successive events such that the fine sediment passed almost entirely through the 12 km reach over a single year. Passage of a sediment wave downstream on the River Piddle is also reported by Walling and Amos (1999) who attributed it to the reworking of sediment deposited in the upper and middle reaches of this small stream following erosion of cultivated areas during the winter months. In this case, fine sediment was only slowly transmitted downstream due to the low energy of this groundwater-fed chalk stream. Longer-term impacts due to catchment disturbance (e.g. Bartley and Rutherfurd, 2005) are considered in the next section.

In addition to surface deposits, fine sediment may also be deposited within the hyporheic zone of gravel-bed rivers in the interstices between individual clasts. This may happen through simultaneous deposition of the gravel framework and fine matrix material (Andrews and Parker, 1987). Alternatively, fine sediment may subsequently be deposited within clean gravels (Schälchli, 1995) or move down into the subsurface as the gravel framework dilates at flows near the threshold of motion (Allan and Frostick, 1999). The importance of intergravel flows, rather than just surface infiltration, has also been demonstrated (Petticrew, Krein and Walling, 2007). This fine sediment fundamentally affects the permeability of the bed and the oxygenation of the gravels vital to fish-egg survival (Acornley and Sear, 1999; Greig, Sear and Carling, 2005) and the benthic and hyporheic invertebrate communities (Wood and Armitage, 1997). It is difficult to be precise about the depth to which fine sediment may be deposited within a gravel bed and the depth to which the active bedload layer, required to remobilize the contained fine sediment, may extend. In gravel-bed rivers which exhibit armouring, the depth of infiltration of fines will depend on the grain size of the armour layer, water depth and velocity. Beschta and Jackson (1979), Frostick, Lucas and Reid (1984) and Lisle (1989) found that this depth typically ranged between 5 and 10 cm, although, in very high flows, it may be more than twice the median grain size of the armour layer.

There are various techniques used for determining fine-sediment storage. The prime method for determining the content of fines at depth is freeze-coring (Petts *et al.*, 1989). This provides a measure of the fine-sediment content as a percentage of the total core by weight, and figures for the chemically/ecologically important silt and clay fractions vary between 0 and 20%. Milan, Petts and Sambrook (2000) give typical values for the upper 30 cm gravel from three types of rivers in the south of the UK (Table 10.1). Type I rivers are on impermeable geology while Type II rivers are chalk and Type III rivers have either a limestone or sandstone geology.

Freeze-coring is an expensive and disruptive method of measurement and, for surface and near-surface (upper 5–10 cm) interest, the disturbance technique of Lambert and Walling (1988) refined by Collins and Walling (2007a) has been used to determine channel storage of fine sediment. In this method, a metal cylinder is carefully lowered into the channel until it rests on the channel bed. The cylinder is then slowly rotated and pushed

Table 10.1 Typical values for fine sediment content in the upper 30 cm of gravel-bed rivers in southern UK (after Milan, Petts and Sambrook, 2000); mean percentage by weight, range given in brackets

	Type I stream impermeable ($n=20$)	Type II stream chalk ($n=11$)	Type III stream sandstone/limestone ($n=20$)
D_{50} of armour layer (mm)	55 (31–73)	42 (20–84)	38 (13–60)
D_{50} substrate (mm)	26.6 (14–48)	5.6 (0.5–12)	10.1 (1.1–29)
Sand (0.063–2 mm) fraction %	11 (6.5–16.5)	42 (28.0–64.1)	21.5 (9.5–43.0)
Silt (0.004–0.062 mm) fraction %	3.5 (0.6–7.3)	4.9 (0.9–8.1)	7.4 (2.0–18.0)
Clay (<0.004) fraction %	0.6 (<0.1–1.9)	0.6 (<0.1–1.2)	1.7 (0.3–5.2)

downwards in order to create a seal with the bed. The contained area of bed is then disturbed to release the fine sediment. Disturbance of the water within the cylinder will simply release surface sediment; disturbance of the bed will release fine sediment stored down to the disturbance depth (usually about 5 cm). Representative samples of the water within the cylinder are taken and its sediment content measured. The measurements provide a snapshot in time; assuming that fine sediment is mobilized during high flows, the highest values of storage might be expected during prolonged low flows. Aside from this time dimension, estimates of channel storage are only as good as representative sampling of sediment patches and procedures for scaling up to river reaches (multiplying by the width of the channel and the length of the reach) allow. However, they provide a useful indicator of the amount of storage and its relation to estimates of the annual flux of sediment. Published values for rivers in the UK are given in Table 10.2 which includes the range of measured point storage values.

Sampled values of storage are similar to those quoted for Ontario rivers by Droppo and Stone (1994). Some indication of the variation between site measurements for each main river is indicated. All figures relating to both storage and flux in Table 10.2 should be taken as estimates with broad error bands which have yet to be fully quantified. The high percentage of the annual load seen in the cases of the Tern, Pang and Lambourn are consistent with the low flushing capacity of these predominantly groundwater-fed rivers which experience large amounts of macrophyte growth during the summer months. In other rivers, the low percentage storage is relative to a high flux but the amount of fine sediment per unit bed area stored within these rivers can be just as high as that of chalk streams.

The aggregated estimates for individual rivers given in Table 10.2 mask a number of important variations noted in the literature. An important variation is the increase in storage with distance downstream; the ranges given in Table 10.2 for the large catchments in Yorkshire (Swale, Ure, Nidd and Wharfe) illustrate the difference between the most upstream and the most downstream reach which is partly a function of the width of the channel and partly a reflection of changes in point measurements per unit bed area. Downstream effects were also noted in the Frome and Piddle catchments (Collins and Walling, 2007c). Seasonal patterns have been observed at individual sites but no consistent pattern has been found across sites, which implies that local factors are important in determining fine-sediment storage (Collins and Walling, 2007b). Summer maxima (Adams and Beschta, 1980; Frostick, Lucas and Reid, 1984; Walling, Owens and Leeks, 1998; Walling *et al.*, 2003b) may reflect both flow regime, land use and macrophyte growth.

Table 10.2 Sediment storage in channel bed (fine sediment in upper 5 cm of gravel-bed rivers)

River	Catchment area, km^2	Point storage range, $g\ m^{-2}$	Reach storage, t	Storage, $t\ km^{-1}$	Annual sediment flux, $t\ yr^{-1}$	Channel store as % annual flux	Reference
Lowland groundwater-dominated rivers in the UK							
Tern	231	860–5500	639	13	1733	17–61	Collins and Walling, 2007b
Pang	166	470–2290	191	5	498	7–92	Collins and Walling, 2007b
Lambourn	234	770–1760	229	7	1076	4–34	Collins and Walling, 2007b
Frome	437	410–2630	795	2–29	4370	11–39	Collins and Walling, 2007c
Piddle	138	260–4340	730	4–19	1281	29–97	Collins and Walling, 2007c
Large UK catchments with moorland headwaters and agricultural areas in the lower reaches							
Tweed	4390	120–960	4329		66 010	7	Owens, Walling and Leeks, 1999
Swale	1457	170–3730	3798	3–93	42 352	9	Walling, Owens and Leeks, 1998
Ure	983	180–850	3710	6–21	28 887	13	Walling, Owens and Leeks, 1998
Nidd	549	580–2410	1333	9–36	7719	17	Walling, Owens and Leeks, 1998
Wharfe	818	510–2670	1866	8–53	10 816	17	Walling, Owens and Leeks, 1998

Winter maxima have also been observed (Sear, 1993; Acornley and Sear, 1999; Walling and Amos, 1999) which tie in with increased sediment delivery. The source of these sediments is now explored.

10.3.4 Source Apportionment

A fundamental consideration when describing the fine-sediment cascade is the source of the sediment. Except in very small catchments (e.g. Bartley *et al.*, 2007), the individual monitoring of all the components is precluded by the intensive and expensive spatial and temporal sampling that would be required. Accordingly, the past two decades have seen the continued development and application of tracing and fingerprinting techniques for apportioning sediment sources. Specific advances have been made in composite fingerprinting and some attempt, albeit not generally implemented as yet, to quantify uncertainty.

Many papers report the proportion of suspended sediment or the proportion of fine material found on the river bed from various sources based on these techniques so it is important to understand the method, the various assumptions made and the potential uncertainty in these estimates. The key assumption in fingerprinting is that one or more properties of the transported sediment reflect those of the sources involved. Early work looked at single tracer groups, for example mineralogy, mineral-magnetic, radiometric, organic, chemical, isotopic or physical, but no single property was found that would reliably distinguish different sources and reliance shifted to composite signatures (Walling, Woodward and Nicholas, 1993; Collins, Walling and Leeks, 1997). Figure 10.12 shows the basic steps in source apportionment through composite fingerprinting based on Collins, Walling and Leeks (1997), Rowan, Goodwill and Franks (2000), Motha *et al.* (2002) and

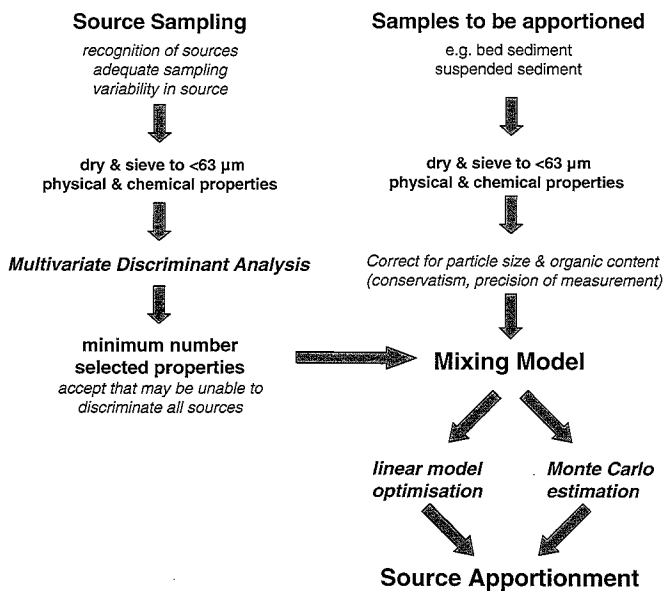

Figure 10.12 Annotated outline of composite fingerprinting method

Motha *et al.* (2003). Also shown in italics are some of the important issues encountered at each step.

Two sets of samples need to be collected: a selection of source materials needed to characterize the material likely to be eroded and the set of suspended sediment or bed sediment samples for which source apportionment is required. The collection of source materials is clearly a key determinant of the results and should both focus on material likely to be eroded (top 2 cm surface, eroding banks, poached areas, eroding tracks, etc.) and encompass variations in surface types (e.g. different land uses) and different geology as appropriate. Less obvious or hidden sources, such as subsurface soils in areas where underdrainage of clay soils promotes subsurface erosion (Chapman *et al.*, 2005; Bilotta *et al.*, 2008), should not be overlooked. A wide range of sediment chemical and physical properties is then needed to identify those properties which may be able to distinguish between different sources. Which ones are effective will vary from catchment to catchment. Once these have been identified using some form of multivariate discriminant analysis, a simple mixing model (Equation 10.6) is applied to measurements of these properties in each of the samples to be apportioned. This should use the minimum possible number of properties as the model is likely to be overparameterized. If different sources are indistinguishable, they will need to be amalgamated. Corrections for both particle size and organic content should be applied as these parameters fundamentally affect the ability of the sediment to absorb chemistry (Collins, Walling and Leeks, 1997). Corrections for conservatism (Motha *et al.*, 2002) and weights to reflect precision of measurement (Collins, Walling and Leeks, 1997) may also be applied. At its simplest, the mixing model can be expressed for each sample to be apportioned as

$$\hat{C}_i = \sum_{j=1}^{n} (p_j \, s_{ij} \, k) \text{ subject to } \sum_{j=1}^{n} p_j = 1 \text{ and } 0 \leq p_j \leq 1 \qquad (10.6)$$

where $\hat{C}_i$ is the predicted concentration of property i in the sample, p_j is the proportion of source type j, s_{ij} is a representative concentration of property i for source j and k is a correction factor for the sample.

There are two basic approaches to fitting the model: optimization using constrained linear programming (Collins, Walling and Leeks, 1997) or some form of Monte Carlo simulation which recognizes that there is unlikely to be a single optimum solution (Rowan, Goodwill and Franks, 2000; Motha *et al.*, 2002; Collins and Walling, 2007a). Results from Monte Carlo simulations may indicate relatively wide uncertainty bands for the derived proportions but generally give distinct upper limits and the same order of importance of the different sources as more traditional optimization techniques. Thus, although precise values may need to be treated with caution, the overall relative importance of sources is generally reliable. Example surveys of suspended sediment samples in the UK (Walling, 2005) clearly separate those catchments where channel bank or subsurface erosion dominates from those where surface erosion dominates (Figure 10.13a). Regional contrasts (Figure 10.13b) have also been identified in the source of bed-sediment samples (Walling, Collins and McMellin, 2003c).

In addition to the dominant climate, soil type, land management and bank erodibility factors which clearly have a role in the observed pattern, distance downstream is also important in the cascade of fine sediment. Work using radionuclides within the Yellowstone

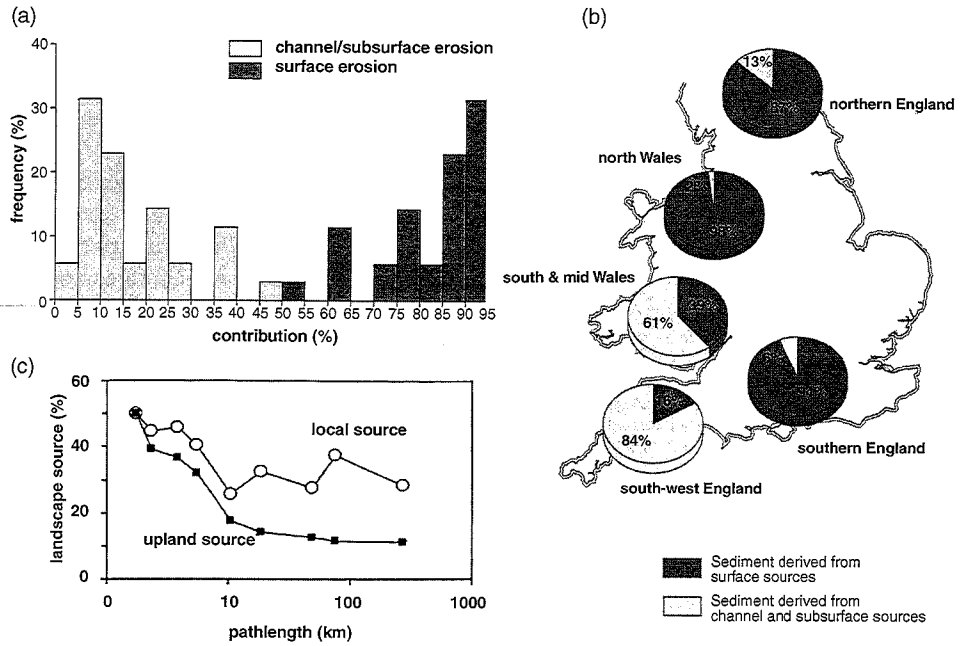

Figure 10.13 Source apportionment.: (a) Suspended sediment in UK rivers
(reproduced, with permission, from Walling, D.E. (2005) Tracing suspended sediment sources in catchments and river systems. Science of the Total Environment, 344, 159–184. © Elsevier).
(b) Provenance of interstitial sediment in the UK (With kind permission from Springer Science + Business Media: Walling, D.E., Collins, A.L. and McMellin, G. (2003) A reconnaissance survey of the source of interstitial fine sediment recovered from salmonid spawning gravels in England and Wales. Hydrobiologia, 497, 91–108.) (c) Downstream trends in provenance from Yellowstone
(reproduced from Whiting, P.J., Matisoff, G. and Fornes, W. (2005) Suspended sediment sources and transport distances in the Yellowstone River basin. Geological Society of America Bulletin, 117, 515-529. Courtesy of the Geological Society of America).

River basin clearly demonstrates that the dominance of upstream sources diminishes with distance downstream (Figure 10.13c) as transport distances increase with catchment area and the relative importance of river banks increases due to lateral erosion and interaction between the river and its floodplain (see Chapter 11).

10.4 A Whole-Catchment View

The key issues in the fine-sediment cascade highlighted above are the source of the sediment and the importance of sediment routing and channel storage. It has also been seen that fine-sediment transport is highly intermittent and shows behaviour which is both threshold-dependent and hysteretic. In this section, it is shown that assembling this information at the large basin scale requires both proper identification of time and space scales, appropriate simplification of process representation and a spatially distributed approach.

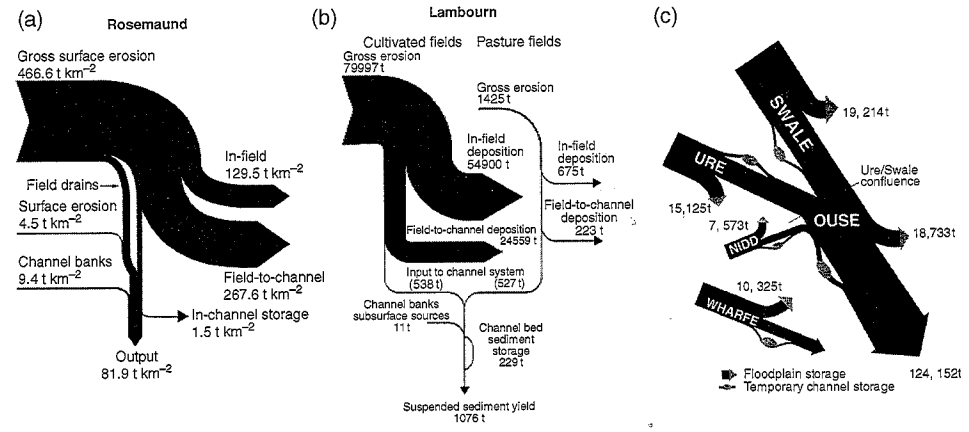

Figure 10.14 Sediment budgets for two contrasting small catchments in the UK and for the River Ouse, North Yorkshire, UK
(reproduced, with permission, from Walling, D.E., Russell, M.A., Hodgkinson, R.A. and Zhang, Y. (2002) Establishing sediment budgets for two small lowland agricultural catchments in the UK. Catena, 47, 323–353. © Elsevier; from Walling, D.E., Collins, A.L., Jones, P.A., Leeks, G.J.L. and Old, G. (2006) Establishing fine-grained sediment budgets for the Pang and Lambourn LOCAR study catchments. Journal of Hydrology, 330, 126–141. © Elsevier; Walling, D.E., Owens, P.N. and Leeks, G.J.L. (1998) The role of channel and floodplain storage in the suspended sediment budget of the River Ouse, Yorkshire, UK. Geomorphology, 22, 225–242. © Elsevier).

10.4.1 Examples of Fine-Sediment Budgets

Once sources are apportioned and storage assessed, an overall fine-sediment budget can be constructed. Examples of the range of contemporary fine-sediment budgets are given in Figure 10.14. They have been constructed to represent the annual sediment yield on the basis of short-term records and an array of fingerprinting and other tracing techniques. Figures 10.14a and 10.14b are for contrasting types of small catchment. Both show the importance of within-field and field-to-channel deposition, with relatively small amounts of fine sediment being conveyed through the channel system. This is especially the case for the River Lambourn which is a chalk catchment, fed predominantly by groundwater. Figure 10.14b also highlights the important contribution of cultivated compared to pasture fields. In underdrained clay soils and in wetter areas with steeper slopes, the contribution from pasture fields will be much higher (Bilotta *et al.*, 2008). Figure 10.14c shows an example of the much larger catchment of the River Ouse which shows the relative importance of flux, floodplain and channel storage. Figures for in-channel storage are given in Table 10.2 and amount to 10–20% of the total flux; Figure 10.14c gives the figures for floodplain losses which account for 10–50% of the overall fine-sediment flux.

The budgets shown in Figure 10.14 represent the annual flux, based on a relatively short record of flux data. However, another characteristic of sediment flux, occasioned not only by its relationship with flow but also by depletion of available catchment storage, is its high variability from year to year. In the UK, measurements made on the Swale and Calder in Yorkshire (Wass and Leeks, 1999), the Tweed in Southern Scotland (Bronsdon and Naden, 2000) and the Cyff and Tanllwyth in Wales show

differences in annual sediment yields of up to a factor of five, from three to six complete years of monitoring. Long-term data from the Rivers Creedy, Culm and Exe in Devon, UK, give coefficients of variation (i.e. standard deviation as a percentage of the mean) in annual sediment yields of 116.3, 96.4 and 88.8% respectively over the ten years from 1994 to 2003 (Harlow, Webb and Walling, 2006). On the River Creedy, yields varied between about 10 and 74 $t\,km^{-2}\,yr^{-1}$.

10.4.2 Sediment Delivery Ratio Revisited

To consider the fine-sediment cascade in its entirety, it is necessary to be able to express the relationship between upland erosion and downstream sediment flux. Such a description will enable management issues such as the lifetime of reservoirs and the maintenance of downstream habitat to be addressed. The sediment delivery ratio (SDR), that is the ratio of the sediment yield of a catchment compared to the average sediment erosion across the catchment, has in the past been used as a lumped descriptor of the fine-sediment cascade. However, there are a number of conceptual and practical problems associated with this lumped measure which have recently been highlighted. Parsons *et al.* (2006) point to issues relating to quoted hillslope erosion rates and the definition of area used in the delivery ratio, while Lu and Richards (2008) emphasize issues relating to the time periods over which erosion rates and sediment yields produce meaningful averages – a factor which is not helped by the lack of long-term data on sediment flux through river networks.

For landscape units in steady state or equilibrium, catchment yield should be approximately equal to the amount eroded from upstream slopes with no net change in storage, and the sediment delivery ratio should equal 1. If SDR $\neq 1$ then it implies aggradation or degradation over the chosen time period. For larger catchments, it is therefore clear that the SDR, as calculated over observational time periods, is a function of time and the catchment condition as the system is not stationary over these time periods but contingent on its erosional history as dictated by both anthropogenic and geomorphological change. Human colonization, the expansion of agriculture and the associated increase in soil erosion have been widely documented in the USA (Trimble, 1975, 1983; Meade, Yuzyk and Day, 1990), Australia (Wasson, Olive and Rosewell, 1996; Wasson *et al.*, 1998; Rutherfurd, 2000) and the UK (Macklin, 1999; Macklin and Lewin, 2008). Timescales for the passage of sediment slugs following human disturbance can be several centuries dependent on volumes and calibre of material. Examples of recovery from human disturbance are given in Wohl and Cenderelli (2000) and Bartley and Rutherfurd (2005). The legacy of geomorphological change following glaciation is also evident in examples from Canada (Church *et al.*, 1999; Church, 2002) where the characteristic time for sediment transfer in large basins has been estimated to be of the order of 10^2–10^6 years.

It is also clear that as spatial scale increases, the system moves from a condition in which the hillslope is dominant to a system in which the channel network dominates and the importance of travel distance and in-channel storage as well as the link to geomorphology and floodplain storage (see Chapter 11) becomes paramount. The scale at which this happens depends on the relative travel times. Lu, Moran and Sivapalan (2005) present a simple lumped two-store linear model which recognizes the roles of hillslope and channel storage and the processes of redeposition and reworking of sediment (Figure 10.15). It is analogous to the hydrological model of Sivapalan, Jothityangkoon and Menabde (2002).

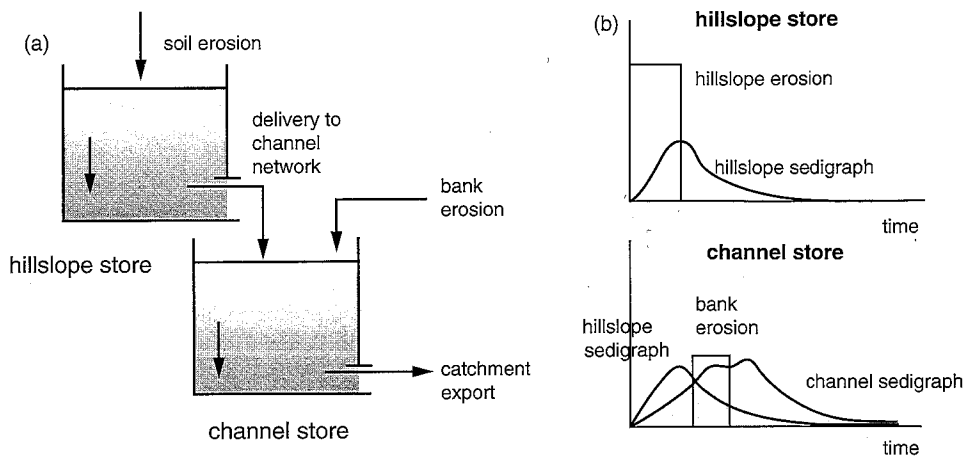

Figure 10.15 Simple two store linear model (reproduced from Lu, H., Moran, C.J. and Sivapalan, M. (2005) A theoretical exploration of catchment-scale sediment delivery. Water Resources Research, 41, Article no. W09415. Courtesy of the American Geophysical Union).

The SDR for an event may be derived as

$$\gamma_e = \frac{t_{er}}{t_t}\frac{1}{B_n}\left(\frac{1}{A_h} + \frac{e_n t_i}{e_h t_{er}}\right) \quad \text{where} \quad A_h = 1 + \lambda_h t_h \quad \text{and} \quad B_n = 1 + \lambda_n t_n \tag{10.7}$$

where γ_e is event SDR, t_{er} is effective storm duration, t_t is event time, e_n is channel-network erosion rate, t_i is duration of channel erosion, e_h is upland erosion rate, λ_h is proportion of hillslope sediment redeposited per unit time, t_h is mean residence time within the hillslope store, λ_n is proportion of channel erosion redeposited per unit time and t_n is mean residence time within the channel store. This model has been shown to fit the SDR data of Roehl (1962) and, with a suitable choice of parameters, can simulate all the observed behaviour in SDR with catchment area. The shift from hillslope to channel dominance may be calculated as

$$\frac{1}{A_h} < \frac{e_n t_t}{e_h t_{er}} \tag{10.8}$$

While the lumped approach given in Figure 10.15 is one way of putting together the hillslope and network routing components of the fine-sediment cascade, for large catchments it is often necessary to link specific upstream inputs to downstream impacts in order to provide a basic understanding of the system for the purpose of managing fine sediment. This requires a spatially distributed approach which is exemplified by the SedNet model presented by Prosser *et al.* (2001), Lu *et al.* (2004), Lu, Moran and Prosser (2006) and Ding and Richards (2009). This takes a similar approach to that shown in Figure 10.15 in that it separates out hillslope and channel components of the system and treats individual sediment sources separately but it is implemented within a spatially distributed GIS framework. Individual processes are approximated in a simple way and the linkage between

source and sea is essentially treated as a chained set of reservoirs in which there is the potential for deposition. One application is to the Murray–Darling basin in Australia which has an area of about $1.1 \times 10^6\,\mathrm{km}^2$. The model is set up using spatial units of 50–100 km^2. Annual sediment yields from each unit are given by

$$Y_i = T_i + B_i + G_i + \gamma_i E_i - D_i \tag{10.9}$$

where Y_i is sediment yield ($\mathrm{t\,yr}^{-1}$), T_i is input from upstream tributaries, B_i is mean annual supply from bank erosion, G_i is mean annual supply from gully erosion, γ_i is a hillslope delivery ratio, E_i is mean annual input from hillslope erosion and D_i is a deposition or loss term which includes channel deposition and losses to floodplains, lakes and reservoirs. For an individual unit the SDR is $Y_i/(Y_i + D_i)$ and for any downstream link, k, the mean annual delivery of sediment from upstream link i is given by

$$\lambda_{ik} = I_i \prod_{j=1}^{M_{ik}} \gamma_j \tag{10.10}$$

where I_i is the sediment supply from within the link i, M_{ik} is the number of river links along the route from link i to location k, and γ_j are the successive link element SDRs which represent the probability of sediment passing through river link j as determined by the amount of deposition in that river link. The total sediment yield at the downstream point is given by

$$T_k = \sum_{i}^{N} \lambda_{ik} \tag{10.11}$$

where N is the total number of link elements contributing to location k.

An example of the results from this model is given in Figure 10.16 for the sediment delivery ratio for both the clay and silt fractions of fine sediment in the Murray–Darling

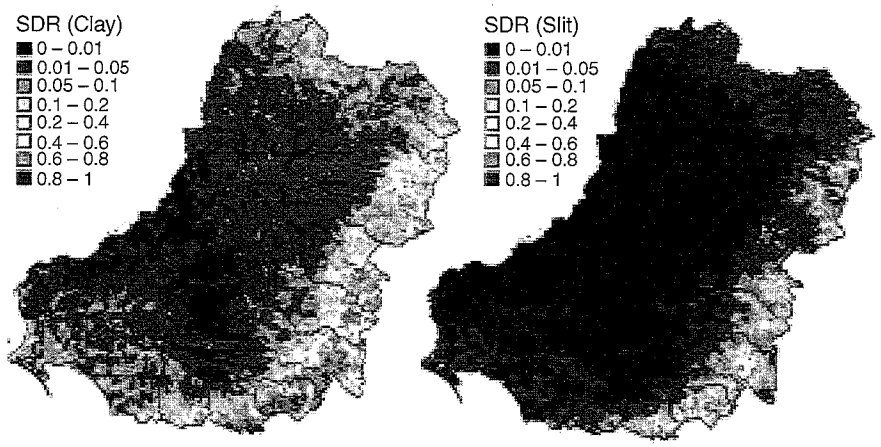

Figure 10.16 Results of SDR for clay and silt fractions in the Murray–Darling basin (reproduced, with permission, from Lu, H., Moran, C.J., Prosser, I.P. (2006) Modelling sediment delivery ratio over the Murray Darling Basin. Environmental Modelling and Software, 21, 1297–1308. © Elsevier).

Basin. The calibre of the sediment affects the residence time of the sediment via the settling velocity. It is apparent from Figure 10.16 that very little of the sediment generated in the uplands reaches the basin outlet on an annual timescale and, in this particular example, the main management concern in the region is the delivery of fine sediment to lowland rivers and the impact on aquatic ecosystems.

Lu *et al.* (2004) use the model to examine the cost-effectiveness of various management scenarios to reduce the delivery of fine sediment generated by upland soil erosion to the channels of the lowland area. The model could also be used to look at longer term impacts of climate, land use or other environmental change based on a range of scenarios. The approach focuses on an appropriate level of detail for the scale of the problem. Further work is needed to develop simplified formulations of the governing processes in line with time-integration of our physical understanding. Perhaps this, together with the basic data collection and testing of model outputs, is one of most important challenges for the future.

10.5 Conclusion – the Need for Future Research

This chapter has sought to highlight areas of the fine-sediment cascade in which significant progress has been made in the past few decades. It has spanned the three major disciplines of hydraulics, hydrology and geomorphology in order to bring out the key advances and identify some of the remaining issues. The fundamental influence of time and space scales on current thinking in these areas has also been demonstrated. Looking to the future, a number of areas for future research can be identified.

In the hydraulics field, there is still a need to improve estimates of fine-sediment conveyance capacity and move away from empirical relationships. Given the complex flow fields found in natural channels, this will require the development of two-phase space–time averaged models. A particular requirement is parameterization of the trapping of fine sediment in gravel beds and vegetation. Both unsteady and non-capacity flows need to be considered. In developing these models, it is important to recognize the process of flocculation and the specific characteristics of flocculated and biogenic sediments, and to develop sound protocols for their measurement.

A great deal of progress has been made in the monitoring of fine-sediment fluxes and collecting data on both in-channel and floodplain storage. However, there is still very limited long-term monitoring of sediment flux through entire river networks. This is a crucial requirement for the effective management of fine sediment and provision of test data for GIS models at the larger scale. New technologies such as acoustics or fibre optics need to be explored as to their applicability. It is also increasingly necessary to provide proper estimates of uncertainty in flux measurements, source apportionment and volumes of channel and floodplain storage.

At the whole-catchment scale, the development and testing of simplified process-based models, a recognition of time-dependence in sediment transfer, the development of better relationships between sediment transport and storage, and estimates of sediment residence times are fundamental requirements. In parallel, it is also necessary to quantify the timing, amounts, types and quality of sediment which are detrimental to ecosystems and human well-being and infrastructure. This information then needs to be coupled with an understanding of the fine-sediment cascade in order to provide a sound basis for sediment management, policy and application of mitigation measures.

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References

Acornley, R.M. and Sear, D.A. (1999) Sediment transport and sedimentation of Brown trout (*Salmo trutta* L) spawning gravels in chalk streams. *Hydrological Processes*, **13**, 447–458.

Adams, J.N. and Beschta, R.L. (1980) Gravel composition in Oregon coastal streams. *Canadian Journal of Fisheries and Aquatic Sciences*, **37**, 1514–1521.

Ahrens, J.P. (2000) A fall-velocity equation. *Journal of Waterway, Port, Coastal, and Ocean Engineering, American Society of Civil Engineers*, **126**, 99–102.

Allan, A. and Frostick, L.E. (1999) Framework dilation, winnowing and matrix particle size: the behaviour of some sand-gravel mixtures in a laboratory flume. *Journal of Sedimentary Research*, **69**, 21–26.

Alvarez-Cobelas, M., Angeler, D.G. and Sánchez-Carrillo, S. (2008) Export of nitrogen from catchments: a worldwide analysis. *Environmental Pollution*, **156**, 261–269.

Andrews, E.D. and Parker, G. (1987) Formation of a coarse surface layer as the response to gravel mobility, in *Sediment Transport in Gravel-Bed Rivers* (eds C.R. Thorne, J.C. Bathurst and R.D. Hey), John Wiley and Sons, Chichester, pp. 269–325.

Ashbridge, D. (1995) Processes of river bank erosion and their contribution to the suspended sediment load of the River Culm, Devon, in *Sediment and Water Quality in River Catchments* (eds I.D.L. Foster, A.M. Gurnell and B.W. Webb), John Wiley and Sons, Chichester, pp. 229–245.

Asselman, N.E.M. (1999) Suspended sediment dynamics in a large drainage basin: the River Rhine. *Hydrological Processes*, **13**, 1437–1450.

Aziz, N.M., Prasad, S.N. and Bhattacharya, S.K. (1992) Suspended sediment concentration profiles using conservation laws. *Journal of Hydraulic Research*, **30**, 539–554.

Bartley, R. and Rutherfurd, I. (2005) Re-evaluation of the wave model as a tool for quantifying the geomorphic recovery potential of streams disturbed by sediment slugs. *Geomorphology*, **64**, 221–242.

Bartley, R., Hawdon, A., Post, D.A. and Rothe, C.H. (2007) A sediment budget for a grazed semi-arid catchment in the Burdekin basin, Australia. *Geomorphology*, **87**, 302–321.

Batalla, R.J. (2003) Sediment deficit in rivers caused by dams and instream gravel mining. A review with examples from NE Spain. *Cuaternario y Geomorfología*, **17**, 79–91.

Becht, M. (1989) Suspended load yield of a small alpine drainage basin in upper Bavaria, in *Landforms and Landform Evolution in West Germany* (ed. F. Ahnert). *Catena (Supplement)*, vol. **15**, pp. 329–342.

Bennett, S.J., Bridge, J.S. and Best, J.L. (1998) The fluid dynamics of upper-stage plane beds. *Journal of Geophysical Research*, **103**, 1239–1274.

Beschta, R.L. and Jackson, W.L. (1979) The intrusion of fine sediments into a stable gravel bed. *Journal of the Fisheries Research Board of Canada*, **36**, 204–210.

Bilotta, G.S., Brazier, R.E., Haygarth, P.M. *et al.* (2008) Rethinking the contribution of drained and undrained grasslands to sediment-related water quality problems. *Journal of Environmental Quality*, **37**, 906–914.

Bogen, J. (1980) The hysteresis effect of sediment transport systems. *Norsk Geografiska Tidsskrift*, **34**, 45–54.

Bowes, M.J. and House, W.A. (2001) Phosphorus and dissolved silicon dynamics in the River Swale catchment, UK: a mass balance approach. *Hydrological Processes*, **15**, 261–280.

Bowes, M.J., Leach, D.V. and House, W.A. (2005) Seasonal nutrient dynamics in a chalk stream: the River Frome, Dorset, UK. *Science of the Total Environment*, **336**, 225–241.

Brakensiek, D.L., Osborn, H.B. and Rawls, W.J. (coords.) (1979) Field Manual for Research in Agricultural Hydrology, United States Department of Agriculture, Agricultural Handbook 224. 550 pp.

Brayshaw, A.C., Frostick, L.E. and Reid, I. (1983) The hydrodynamics of particle clusters and sediment entrainment in coarse alluvial channels. *Sedimentology*, **30**, 137–143.

Bridge, J.S. (2003) *Rivers and Floodplains. Forms, Processes and Sedimentary Record*, Blackwell, Oxford. 491 pp.

Bridge, J.S. and Jarvis, J. (1976) Flow and sedimentary processes in meandering River South Esk, Glen Clova, Scotland. *Earth Surface Processes and Landforms*, **1**, 303–336.

Bronsdon, R.K. and Naden, P.S. (2000) Suspended sediment in the Rivers Tweed and Teviot. *Science of the Total Environment*, **251/252**, 95–113.

Bull, L.J. (1997) Relative velocities of discharge and sediment waves for the River Severn, UK. *Hydrological Sciences Journal*, **42**, 649–660.

Bungartz, H. and Wanner, S.C. (2004) Significance of particle interaction to the modelling of cohesive sediment transport in rivers. *Hydrological Processes*, **18**, 1685–1702.

Cao, Z. (1999) Equilibrium near-bed concentration of suspended sediment. *Journal of Hydraulic Engineering ASCE*, **125**, 1270–1278.

Chapman, A.S., Foster, I.D.L., Lees, J.A. and Hodgkinson, R. (2005) Sediment sources and transport pathways in the Rosemaund experimental catchment, Herefordshire, UK. *Hydrological Processes*, **19**, 2875–2897.

Cheng, N.-S. (1997) Simplified settling velocity formula for sediment particle. *Journal of Hydraulic Engineering ASCE*, **123**, 149–152.

Church, M. (1996) Space, Time and the Mountain – how do we order what we see?, in The Scientific Nature of Geomorphology: Proceedings of the 27th Binghampton Symposium in Geomorphology (eds B.L. Rhoads and C.E. Thorn), pp. 147–170.

Church, M. (2002) Fluvial sediment transfer in cold regions, in *Landscapes of Transition: Landform Assemblages and Transformations in Cold Regions* (eds K. Hewitt, M.-L. Byrne, M. English and G. Young), Kluwer Academic, Netherlands, pp. 93–117.

Church, M., Ham, D., Hassan, M. and Slaymaker, O. (1999) Fluvial clastic sediment yield in Canada: scaled analysis. *Canadian Journal of Earth Sciences*, **36**, 1267–1280.

Clarke, S.J. and Wharton, G. (2001) Sediment nutrient characteristics and aquatic macrophytes in lowland English rivers. *Science of the Total Environment*, **266**, 103–112.

Collins, A.L. and Walling, D.E. (2007a) Sources of fine sediment recovered from the channel bed of lowland groundwater-fed catchments in the UK. *Geomorphology*, **88**, 120–138.

Collins, A.L. and Walling, D.E. (2007b) The storage and provenance of fine sediment on the channel bed of two contrasting lowland permeable catchments, UK. *River Research and Applications*, **23**, 429–450.

Collins, A.L. and Walling, D.E. (2007c) Fine-grained bed sediment storage within the main channel systems for the Frome and Piddle catchments, Dorset, UK. *Hydrological Processes*, **21**, 1448–1459.

Collins, A.L., Walling, D.E. and Leeks, G.J.L. (1997) Source type ascription for fluvial suspended sediment based on a quantitative composite fingerprinting technique. *Catena*, **29**, 1–27.

Collins, A.L., Walling, D.E. and Leeks, G.J.L. (2005) Storage of fine-grained sediment and associated contaminants within the channels of lowland permeable catchments in the UK, in *Sediment*

Budgets I, IAHS Publication 291 (eds D.E. Walling and A.J. Horowitz), IAHS Press, Wallingford, UK, pp. 259–268.

Cotton, J.A., Wharton, G., Bass, J.A.B. *et al.* (2006) The effects of seasonal changes to in-stream vegetation cover on patterns of flow and accumulation of sediment. *Geomorphology*, **77**, 320–334.

Dearing, J.A. and Jones, R.T. (2003) Coupling temporal and spatial dimensions of global sediment flux through lake and marine sediment records. *Global and Planetary Change*, **39**, 147–168.

Degens, E.T., Kempe, S. and Richey, J.E. (1991) Summary: biogeochemistry of major world rivers, in *Biogeochemistry of Major World Rivers* (eds E.T. Degens, S. Kempe and J.E. Richey), John Wiley and Sons, Chichester, pp. 323–347.

Dietrich, W.E. (1982) Settling velocity of natural particles. *Water Resources Research*, **18**, 1615–1626.

Ding, J. and Richards, K.S. (2009) Preliminary modelling of sediment production and delivery in the Xihanshui River basin, Gansu, China. *Catena*. doi: 10.1016/j.catena.2009.05.014.

Droppo, I.G. (2001) Rethinking what constitutes suspended sediment. *Hydrological Processes*, **15**, 1551–1564.

Droppo, I.G. (2004) Structural controls on floc strength and transport. *Canadian Journal of Civil Engineering*, **31**, 569–578.

Droppo, I.G. and Ongley, E.D. (1992) The state of suspended sediment in the freshwater fluvial environment: a method of analysis. *Water Research*, **26**, 65–72.

Droppo, I.G. and Stone, M. (1994) In-channel surficial fine-grained sediment laminae. Part I: Physical characteristics and formational processes. *Hydrological Processes*, **8**, 101–111.

Droppo, I.G., Walling, D.E. and Ongley, E.D. (2002) Suspended sediment structure: implications for sediment transport/yield modelling, in *Modelling Erosion, Sediment Transport and Sediment Yield*, UNESCO International Hydrological Programme Technical Documents in Hydrology no. 60 (eds W. Summer and D.E. Walling), UNESCO, Paris, pp. 205–228.

Droppo, I.G., Leppard, G.G., Flannigan, D.T. and Liss, S.N. (1997) The freshwater floc: a functional relationship of water and organic and inorganic floc constituents affecting suspended sediment properties. *Water, Air and Soil Pollution*, **99**, 43–53.

Evans, D.J., Johnes, P.J. and Lawrence, D.S. (2004) Physico-chemical controls on phosphorus cycling in two lowland streams. Part 2 – the sediment phase. *Science of the Total Environment*, **329**, 165–182.

Evans, J.G., Wass, P.D. and Hodgson, P. (1997) Integrated continuous water quality monitoring for the LOIS river programme. *Science of the Total Environment*, **194/195**, 111–118.

Ferguson, R.I. and Church, M. (2004) A simple universal equation for grain settling velocity. *Journal of Sedimentary Research*, **74**, 933–937.

Frostick, L.E., Lucas, P.M. and Reid, I. (1984) The infiltration of fine matrices into coarse-grained alluvial sediments and its implications for stratigraphical interpretation. *Journal of the Geological Society*, **141**, 955–965.

Gibbs, R.J., Matthews, M.D. and Link, D.A. (1971) The relationship between sphere size and settling velocity. *Journal of Sedimentary Petrology*, **41**, 7–18.

Gippel, C.J. (1995) Potential of turbidity monitoring for measuring the transport of suspended solids in streams. *Hydrological Processes*, **9**, 83–97.

Greig, S.M., Sear, D.A. and Carling, P.A. (2005) The impact of fine sediment accumulation on the survival of incubating salmon progeny: implications for sediment management. *Science of the Total Environment*, **344**, 241–258.

Greimann, B.P. and Holly, F.M. (2001) Two-phase flow analysis of concentration profiles. *Journal of Hydraulic Engineering ASCE*, **127**, 753–762.

Gurnell, A.M., Blackall, T.D. and Petts, G.E. (2008) Characteristics of freshly deposited sand and finer sediments along an island-braided gravel-bed river. *Geomorphology*, **99**, 254–269.

Gurnell, A.M., Van Oosterhout, M.P., De Vlieger, B. and Goodson, J.M. (2006) Reach-scale interactions between aquatic plants and physical habitat: River Frome, Dorset. *River Research and Applications*, **22**, 667–680.

Hallermeier, R.J. (1981) Terminal settling velocity of commonly occurring sand grains. *Sedimentology*, **28**, 859–865.

Haralampides, K., Corquodale, J.A. and Krishnappan, B.G. (2003) Deposition properties of fine sediment. *Journal of Hydraulic Engineering ASCE*, **129**, 230–234.

Harlow, A., Webb, B. and Walling, D. (2006) *Sediment yields in the Exe Basin: a longer-term perspective, in Sediment dynamics and the hydromorphology of fluvial systems*, IAHS Publication 306 (eds J.S. Rowan, R.W. Duck and A. Werrity), IAHS Press, Wallingford, UK, 12–20.

Heidel, S.G. (1956) The progressive lag of sediment concentration with flood waves. *Transactions of the American Geophysical Union*, **37**, 56–66.

Heywood, M.J.T. and Walling, D.E. (2007) The sedimentation of salmonid spawning gravels in the Hampshire Avon catchment, UK: implications for the dissolved oxygen content of intragravel water and embryo survival. *Hydrological Processes*, **21**, 770–788.

Holeman, J.N. (1968) The sediment yield of major rivers of the world. *Water Resources Research*, **4**, 737–747.

House, W.A. (2003) Geochemical cycling of phosphorus in rivers. *Applied Geochemistry*, **18**, 739–748.

Jarvie, H.P., Jurgens, M.D., Williams, R.J. *et al.* (2005) Role of bed sediments as sources and sinks of phosphorus across two major eutrophic UK river basins: the Hampshire Avon and Herefordshire Wye. *Journal of Hydrology*, **304**, 51–74.

Köthe, H. (2003) Existing sediment management guidelines: an overview. *Journal of Soils and Sediments*, **3**, 139–143.

Krein, A., Petticrew, E. and Udelhovem, T. (2003) The use of fine sediment fractal dimensions and colour to determine sediment sources in a small watershed. *Catena*, **53**, 165–179.

Kronvang, B., Laubel, A., Larsen, S.E. and Friberg, N. (2003) Pesticides and heavy metals in Danish streambed sediment. *Hydrobiologia*, **494**, 93–101.

Krishnappan, B.G. (2007) Recent advances in basic and applied research in cohesive sediment transport in aquatic systems. *Canadian Journal of Civil Engineering*, **34**, 731–743.

Lal, R. (2002) Soil erosion and the global carbon budget. *Environment International*, **29**, 437–450.

Lal, R. (2006) *Encyclopedia of Soil Science*, 2nd edn, CRC Press. 1600 pp.

Lambert, C.P. and Walling, D.E. (1988) Measurement of channel storage of suspended sediment in a gravel-bed river. *Catena*, **15**, 65–80.

Lawler, D.M., Petts, G.E., Foster, I.D.L. and Harper, S. (2006) Turbidity dynamics during spring storm events in an urban headwater. *Science of the Total Environment*, **360**, 109–126.

Leeder, M.R. (1982) *Sedimentology. Process and Product*, George Allen and Unwin, London. 344 pp.

Liao, B.Q., Allen, D.G., Leppard, G.G. *et al.* (2002) Interparticle interactions affecting the stability of sludge flocs. *Journal of Colloid and Interface Science*, **249**, 372–380.

Lisle, T.E. (1989) Sediment transport and resulting deposition in spawning gravels, north coastal Carolina. *Water Resources Reseach*, **26**, 1303–1319.

Lisle, T.E. and Hilton, S. (1999) Fine bed material in pools of natural gravel bed channels. *Water Resources Research*, **35**, 1291–1304.

López, F. and Garcia, M. (1998) Open-channel flow through simulated vegetation: suspended sediment transport modelling. *Water Resources Research*, **34**, 2341–2352.

Lu, H. and Richards, K.S. (2008) Sediment delivery: new approaches to modelling an old problem, in *River Confluences, Tributaries and the Fluvial Network* (eds S.P. Rice, A.G. Roy and B. Rhoads), John Wiley and Sons, Chichester, 337–366.

Lu, H., Moran, C.J. and Prosser, I.P. (2006) Modelling sediment delivery ratio over the Murray Darling Basin. *Environmental Modelling and Software*, **21**, 1297–1308.

Lu, H., Moran, C.J. and Sivapalan, M. (2005) A theoretical exploration of catchment-scale sediment delivery. *Water Resources Research*, **41**, W09415, doi: 10.1029/2005WR004018

Lu, H., Moran, C.J., Prosser, I.P. and DeRose, R. (2004) Investment prioritisation based on broadscale spatial budgeting to meet downstream targets for suspended sediment loads. *Water Resources Research*, **40**, W09501, doi: 10.1029/2003WR002966

Macklin, M.G., Hudson-Edwards, K.A. and Dawson, E.J. (1997) The significance of pollution from historic metal mining in the Pennine orefields on river sediment contaminant fluxes to the North Sea. *Science of the Total Environment*, **194**, 391–397.

Macklin, M.G. (1999) Holocene river environments in prehistoric Britain: human interaction and impact. *Journal of Quarternary Science*, **14**, 521–530.

Macklin, M.G. and Lewin, J. (2008) Alluvial response to the changing Earth system. *Earth Surface Processes and Landforms*, **33**, 1374–1395.

Martin, J.-M. and Meybeck, M. (1979) Elemental mass-balance of material carried by major world rivers. *Marine Chemistry*, **7**, 173–206.

Matthaei, C.D., Weller, F., Kelly, D.W. and Townsend, C.R. (2006) Impacts of fine sediment addition to tussock, pasture, dairy and deer farming streams in New Zealand. *Freshwater Biology*, **51**, 2154–2172.

Meade, R.H., Yuzyk, T.R. and Day, T.J. (1990) Movement and storage of sediment in rivers of the United States and Canada, in *Surface Water Hydrology* (eds M.G. Wolman and H.C. Riggs), Geological Society of America, Boulder, Colorado, pp. 255–280.

Meybeck, M. (1982) Carbon, nitrogen and phosphorus transport by world rivers. *American Journal of Science*, **282**, 401–450.

Milan, D.J., Petts, G.E. and Sambrook, H. (2000) Regional variations in the sediment structure of trout streams in southern England: benchmark data for siltation assessment and restoration. *Aquatic Conservation*, **10**, 407–420.

Motha, J.A., Wallbrink, P.J., Hairsine, P.B. and Grayson, R.B. (2002) Tracer properties of eroded sediment and source material. *Hydrological Processes*, **16**, 1983–2000.

Motha, J.A., Wallbrink, P.J., Hairsine, P.B. and Grayson, R.B. (2003) Determining the sources of suspended sediment in a forested catchment in southeastern Australia. *Water Resources Research*, **39**, 1056, doi: 10.1029/2004WR000794

Muste, M., Yu, K., Fujita, I. and Ettema, R. (2005) Two-phase versus mixed-flow perspective on suspended sediment transport in turbulent channel flows. *Water Resources Research*, **41**, W10402, doi: 10.1029/2004WR003595

Newcombe, C.P. and Jensen, J.O.T. (1996) Channel suspended sediment and fisheries: a synthesis for quantitative assessment of risk and impact. *North American Journal of Fisheries Management*, **16**, 693–727.

Nicholas, A.P. and Walling, D.E. (1996) The significance of particle aggregation in the over-bank deposition of suspended sediment on river floodplains. *Journal of Hydrology*, **186**, 275–293.

Niyogi, D.K., Koren, M., Arbuckle, C.J. and Townsend, C.R. (2007) Stream communities along a catchment land-use gradient: subsidy-stress responses to pastoral development. *Environmental Management*, **39**, 213–225.

Old, G.H., Leeks, G.J.L., Packman, J.C. *et al.* (2006) River flow and associated transport of sediments and solutes through a highly urbanised catchment, Bradford, West Yorkshire. *Science of the Total Environment*, **360**, 98–108.

Owens, P.N. (2007) Introduction. Background and Summary of this issue on Sediment linkages. *Journal of Soils and Sediments*, **7**, 273–276.

Owens, P.N. and Walling, D.E. (2002) Changes in sediment sources and floodplain deposition rates in the catchment of the River Tweed, Scotland, over the last 100 years: the impact of climate and land use change. *Earth Surface Processes and Landforms*, **27**, 403–423.

Owens, P.N., Walling, D.E. and Leeks, G.J.L. (1999) Deposition and storage of fine-grained sediment within the main channel system of the River Tweed, Scotland. *Earth Surface Processes and Landforms*, **24**, 1061–1076.

Owens, P.N., Batalla, R.J., Collins, A.J. *et al.* (2005) Fine-grained sediment in river systems: environmental significance and management issues. *River Research and Applications*, **21**, 693–717.

Panin, A. (2004) Land-ocean sediment transfer in palaeotimes, and implications for present-day natural fluvial fluxes, in *Sediment transfer through the fluvial system*, IAHS Publication 288 (eds V. Golosov, V. Belyaev and D.E. Walling), IAHS Press, Wallingford, UK, 115–124.

Papanicolaou, A.N.T., Elhakeem, M., Krallis, G. *et al.* (2008) Sediment transport modelling review – current and future developments. *Journal of Hydraulic Engineering ASCE*, **134**, 1–14.

Parsons, A.J., Wainwright, J., Brazier, R.E. and Powell, D.M. (2006) Is sediment delivery a fallacy? *Earth Surface Processes and Landforms*, **31**, 1325–1328.

Pedersen, M.L., Friberg, N. and Larsen, S.E. (2004) Physical habitat structure in Danish lowland streams. *River Research and Applications*, **20**, 653–669.

Petticrew, E.L., Krein, A. and Walling, D.E. (2007) Evaluating fine sediment mobilization and storage in a gravel-bed river using controlled reservoir releases. *Hydrological Processes*, **21**, 198–210.

Petts, G.E., Foulger, T.R., Gilvear, D.J. *et al.* (1985) Wave-movement and water quality variations during a controlled release from Kielder Reservoir, North Tyne River, UK. *Journal of Hydrology*, **80**, 371–389.

Petts, G.E., Thoms, M.C., Brittan, K. and Atkin, B. (1989) A freeze-coring technique applied to pollution by fine sediments in gravel-bed rivers. *Science of the Total Environment*, **84**, 259–272.

Phillips, J.M. and Walling, D.E. (1999) The particle size characteristics of fine-grained channel deposits in the River Exe Basin, Devon, UK. *Hydrological Processes*, **13**, 1–19.

Prosser, I.P., Rutherfurd, I.D., Olley, J.M. *et al.* (2001) Large-scale patterns of erosion and sediment transport in river networks, with examples from Australia. *Marine and Freshwater Research*, **52**, 81–99.

Quinn, J.M., Davies-Colley, R.J., Hickey, C.W. *et al.* (1992) Effects of clay discharge on streams: 2. benthic invertebrates. *Hydrobiologia*, **248**, 235–247.

Rabeni, C.F., Doisy, K.E. and Zweig, L.D. (2005) Stream invertebrate community functional responses to deposited sediment. *Aquatic Sciences*, **67**, 395–402.

Rees, J.G., Ridgeway, J., Knox, R.W.O.B. *et al.* (1999) Sediment-borne contaminants in rivers discharging into the Humber estuary, UK. *Marine Pollution Bulletin*, **37**, 316–329.

Richardson, J.F. and Zaki, W.N. (1958) Sedimentation and fluidisation. *Transactions of Institute of Chemical Engineers*, **32**, 35–53.

Roehl, J.E. (1962) Sediment source areas, delivery ratios and influencing morphological factors. *International Association of Hydrological Sciences Publication*, **59**, 202–213.

Rouse, H. (1937) Modern conceptions of the mechanics of turbulence. *Transactions of American Society of Civil Engineers*, **102**, 463–543.

Rowan, J.S., Goodwill, P. and Franks, S.W. (2000) Uncertainty estimation in fingerprinting suspended sediment sources, in *Tracers in Geomorphology* (ed. I.D.L. Foster), John Wiley and Sons, Chichester, UK, pp. 279–290.

Rubey, W. (1933) Settling velocities of gravel, sand and silt particles. *American Journal of Science*, **225**, 325–338.

Rutherfurd, I.D. (2000) Some human impacts on Australian stream channel morphology, in *River Management: the Australasian Experience* (eds S. Brizga and B. Finlayson), John Wiley and Sons, Chichester, UK, pp. 11–50.

Sarma, J.N. (1986) Sediment transport in the Burhi Dihing River, India, in *Drainage Basin Sediment Delivery*, IAHS Publication 159 (ed. R.F. Hadley), International Association of Hydrological Sciences, Wallingford, pp. 199–215.

Schälchli, U. (1995) Basic equations for siltation of riverbeds. *Journal of Hydraulic Engineering*, **121**, 274–287.

Sear, D.A. (1993) Fine sediment infiltration into gravel spawning beds within a regulated river experiencing floods – ecological implications for salmonids. *Regulated Rivers – Research and Management*, **8**, 373–390.

Sharpe, R.G. and James, C.S. (2006) Deposition of sediment from suspension in emergent vegetation. *Water SA*, **32**, 211–218.

Singh, M., Ansari, A.A., Muller, G. and Singh, I.B. (1997) Heavy metals in freshly deposited sediments of the Gomati River (a tributary of the Ganges River) – effects of human activities. *Environmental Geology*, **29**, 246–252.

Sivapalan, M., Jothityangkoon, C. and Menabde, M. (2002) Linearity and non-linearity of basin response as a function of scale: discussion of alternative definitions. *Water Resources Research*, **38**, 1012, doi: 10.1029/2001 WR000482

Smith, B.P.G., Naden, P.S., Leeks, G.J.L. and Wass, P.D. (2003a) The influence of storm events on fine sediment transport, erosion and deposition within a reach of the River Swale, Yorkshire, UK. *Science of the Total Environment*, **314–316**, 451–474.

Smith, B.P.G., Naden, P.S., Leeks, G.J.L. and Wass, P.D. (2003b) Characterising the fine sediment budget of a reach of the River Swale, Yorkshire, UK during the 1994 to 1995 winter season. *Hydrobiologia*, **494**, 135–143.

Soulsby, C., Youngson, A.F., Moir, H.J. and Malcolm, I.A. (2001) Fine sediment influence on salmonid spawning habitat in a lowland agricultural stream: a preliminary assessment. *Science of the Total Environment*, **265**, 295–307.

Syvitski, J.P.M., Peckham, S.D., Hilberman, R. and Mulder, T. (2003) Predicting the terrestrial flux of sediment to the global ocean: a planetary perspective. *Sedimentary Geology*, **162**, 5–24.

Syvitski, J.P.M., Vörösmarty, C.J., Kettner, A.J. and Green, P. (2005) Impact of humans on the flux of terrestrial sediment to the global coastal ocean. *Science*, **308**, 376–380.

Tipping, E. (1988) Colloids in the aquatic environment. *Chemistry and Industry*, **15**, 485–490.

Tipping, E., Woof, C. and Clarke, K. (1993) Deposition and resuspension of fine particles in a riverine 'dead zone'. *Hydrological Processes*, **7**, 263–277.

Trimble, S.W. (1975) Denudation studies: can we assume stream steady state? *Science*, **188**, 1207–1208.

Trimble, S.W. (1983) A sediment budget for Coon Creek basin in the Driftless Area, Wisonsin, 1853–1977. *American Journal of Science*, **283**, 454–474.

Van Rijn, L.C. (1984) Sediment transport, Part II: Suspended load transport. *Journal of Hydraulic Engineering*, **110**, 1613–1641.

Vörösmarty, C.J., Meybeck, M., Fekete, B. *et al.* (2003) Anthropogenic sediment retention: major global impact from registered river impoundments. *Global and Planetary Change*, **39**, 169–190.

Walling, D.E. (2005) Tracing suspended sediment sources in catchments and river systems. *Science of the Total Environment*, **344**, 159–184.

Walling, D.E. (2006) Human impact on land-ocean sediment transfer by the world's rivers. *Geomorphology*, **79**, 192–216.

Walling, D.E. and Amos, C.M. (1999) Source, storage and remobilisation of fine sediment in a chalk stream. *Hydrological Processes*, **13**, 323–340.

Walling, D.E. and Webb, B.W. (1982) Sediment availability and the prediction of storm-period sediment yields, in *Recent developments in the explanation and prediction Of erosion and sediment yield*, IAHS Publication 137 (ed D.E. Walling), IAHS Press, Wallingford, UK, pp. 327–337.

Walling, D.E., Collins, A.L. and McMellin, G. (2003) A reconnaissance survey of the source of interstitial fine sediment recovered from salmonid spawning gravels in England and Wales. *Hydrobiologia*, **497**, 91–108.

Walling, D.E., Owens, P.N. and Leeks, G.J.L. (1998) The role of channel and floodplain storage in the suspended sediment budget of the River Ouse, Yorkshire, UK. *Geomorphology*, **22**, 225–242.

Walling, D.E., Owens, P.N. and Leeks, G.J.L. (1999) Rates of contemporary overbank sedimentation and sediment storage on the floodplains of the main channel systems of the Yorkshire Ouse. *Hydrological Processes*, **13**, 993–1009.

Walling, D.E., Woodward, J.C. and Nicholas, A.P. (1993) A multi-parameter approach to fingerprinting suspended sediment sources, in *Tracers in Hydrology*, IAHS Publication 215 (eds N.E. Peters, E. Hoehn, Ch. Leibundgut, N. Tase and D.E. Walling), IAHS Press, Wallingford, UK, pp. 329–337.

Walling, D.E., Russell, M.A., Hodgkinson, R.A. and Zhang, Y. (2002) Establishing sediment budgets for two small lowland agricultural catchments in the UK. *Catena*, **47**, 323–353.

Walling, D.E., Owens, P.N., Foster, I.D.L. and Lees, J.A. (2003a) Changes in the sediment dynamics of the Ouse and Tweed basins in the UK, over the last 100–150 years. *Hydrological Processes*, **17**, 3245–3269.

Walling, D.E., Owens, P.N., Carter, J. *et al.* (2003b) Storage of sediment-associated nutrients and contaminants in river channel and floodplain systems. *Applied Geochemistry*, **18**, 195–220.

Walling, D.E., Collins, A.L., Jones, P.A. *et al.* (2006) Establishing fine-grained sediment budgets for the Pang and Lambourn LOCAR study catchments. *Journal of Hydrology*, **330**, 126–141.

Wass, P.D. and Leeks, G.J.L. (1999) Suspended sediment fluxes in the Humber catchment, UK. *Hydrological Processes*, **13**, 935–953.

Wasson, R.J., Olive, L.J. and Rosewell, C.J. (1996) Rates of erosion and sediment transport in Australia, in *Variability in Stream Erosion and Sediment Transport*, IAHS Publication 224 (eds L.J. Olive, R.J. Loughran and J.A. Kesby), IAHS Press, Wallingford, UK, pp. 269–279.

Wasson, R.J., Mazari, R.K., Starr, B. and Clifton, G. (1998) The recent history of erosion and sedimentation on the Southern Tablelands of southeastern Australia: sediment flux dominated by channel incision. *Geomorphology*, **24**, 291–308.

Wharton, G., Cotton, J.A., Wotton, R.S. *et al.* (2006) Macrophytes and suspension-feeding invertebrates modify flows and fine sediments in the Frome and Piddle catchments, Dorset (UK). *Journal of Hydrology*, **330**, 171–184.

Whiting, P.J., Matisoff, G. and Fornes, W. (2005) Suspended sediment sources and transport distances in the Yellowstone River basin. *Geological Society of America Bulletin*, **117**, 515–529.

Williams, N.D., Walling, D.E. and Leeks, G.J.L. (2008) An analysis of the factors contributing to the settling potential of fine fluvial sediment. *Hydrological Processes*, **22**, 4153–4162.

Wohl, E.E. and Cenderelli, D.A. (2000) Sediment deposition and transport patterns following a reservoir sediment release. *Water Resources Research*, **36**, 319–333.

Wood, P.A. (1977) Controls of variation in suspended sediment concentration in Rover Rother, West Sussex, England. *Sedimentology*, **24**, 437–445.

Wood, P.J. and Armitage, P.D. (1997) Biological effects of fine sediment in the lotic environment. *Environmental Management*, **21**, 203–217.

Yamada, H. and Nakamura, F. (2002) Effect of fine sediment deposition and channel works on periphyton biomass in the Makomanai River, northern Japan. *River Research and Applications*, **18**, 481–493.

Xu, J. (2002) Implication of relationships among suspended sediment size, water discharge and suspended sediment concentration: the Yellow River basin, China. *Catena*, **49**, 289–307.