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# Documenting catchment suspended sediment sources: problems, approaches and prospects

A.L. Collins* and D.E. Walling

Department of Geography, School of Geography, Archaeology and Earth Resources, University of Exeter, Exeter EX4 4RJ, UK

**Abstract**: Establishing catchment suspended sediment sources is fraught with difficulty. Data collection comprises indirect and direct approaches and an overview is provided. The indirect approach uses a range of techniques to measure or evaluate sediment mobilization. Yet, although recent technological advances in surveying, remote sensing and photogrammetry provide improved resolution of temporal and spatial patterns of catchment erosion, these procedures take no account of source–river connectivity and the uncertainties associated with sediment routing. It is therefore only possible to infer the provenance of suspended sediment loads on the exclusive basis of on-site erosion data for different portions of the upstream catchment unless supportive information on sediment delivery is readily available. In contrast, the direct approach attempts to link sediment sources and flux using alternative means and therefore avoids the need for complementary information. Sediment fingerprinting best represents the direct approach to sediment sourcing and there remains substantial scope for exploiting the potential of this technique. The spatial complexity of sediment mobilization and transfer at the catchment scale necessitates a distributed approach to modelling. Recent developments in computer power and programming techniques are proving useful in this respect, but assembling the input and validation data required by distributed models continues to pose problems and it is frequently difficult to apportion the relative contributions from individual sediment sources. General prospects for future developments are discussed.

**Key words**: catchment suspended sediment sources, direct approach, indirect approach, modelling, sediment fingerprinting.

## I Introduction

The principal sources of the suspended sediment fluxes from many river basins have not been documented. It is, however, increasingly recognized that reliable

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*Author for correspondence.

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information on the nature and relative significance of catchment suspended sediment sources represents an important requirement. For instance, such information is required for establishing catchment sediment budgets (Reid and Dunne, 1996; Walling *et al.*, 2001), for assisting the interpretation and modelling of suspended sediment yields (Dedkov and Moszherin, 1992; Summer *et al.*, 1996) and for elucidating the importance of secondary sediment sources associated with the remobilization of sediment stored in depositional sinks (Phillips, 1993). Equally, an improved understanding of catchment suspended sediment sources represents an essential prerequisite for assisting the design and implementation of targeted management strategies for controlling off-site sediment-associated environmental problems (United States Environmental Protection Agency, 1999; Collins *et al.*, 2001a).

Despite the dearth of information on the provenance of fluvial suspended sediment loads, considerable progress has been made in terms of conceptualizing and understanding the key controls of erosivity and erodibility governing sediment mobilization in drainage basins (Morgan, 1995). More specifically, the potential for different portions of a river basin to contribute to the downstream suspended sediment flux is controlled by a complex interplay of factors of strength, morphological, locational and filter resistance (cf. Brunsden, 1993; Burt, 2001). The former two factors control sediment mobilization *in situ* and the latter govern the delivery of mobilized particles to the river channel.

Whilst it is over simplistic to discuss these factors of resistance individually, their importance with respect to the provenance of fluvial suspended sediment loads can be usefully demonstrated in this manner. A classic example of the influence of strength resistance on sediment origin is provided by the recent shift in the UK from spring- to autumn-sown cereal crops. Autumn sowing renders bare rolled soils susceptible to erosion during winter rains by lowering strength resistance and is thereby partly responsible for an increase in the proportion of suspended sediment loads in the UK reported to be originating from cultivated fields (Boardman, 1990). Because locational resistance is dependent upon the juxtaposition of suspended sediment sources and the river, eroding channel banks may contribute significantly to suspended sediment loads. Filter resistance is controlled by the density of roads, paths, tracks or field drains and by the occurrence of hedges or buffer strips and is especially important in governing the delivery of sediment from distal sources to the stream network (Laubel *et al.*, 1999; Ziegler *et al.*, 2000). Road-to-stream linkages lower filter resistance by enhancing drainage density and can be generated by gully growth between road drain outlets and river channels or direct river crossings by paved and unpaved routes (Croke and Mockler, 2001; La Marche and Lettenmaier, 2001). Equally, the reduced filter resistance caused by the low density of field boundaries or hedges in the open upland and lowland arable landscapes of the UK mean that such areas are frequently characterized by more efficient sediment delivery to river channels. Tectonic activity can also influence the magnitude of filter resistance. In tectonically active areas, drainage densities are typically higher, causing a reduction in filter resistance and an increase in slope–channel coupling. Alternatively, slopes and stream networks are frequently de-coupled in tectonically stable areas, thereby increasing filter resistance to sediment delivery (Harvey, 1994). Under the latter circumstances, although soil erosion may be severe, the source of fluvial suspended sediment may be reworked material deposited in alluvial stores (Fryirs and Brierley, 1999). Clearly, however, these factors of resistance typically interact. For example, even where a sediment source is characterized by low strength and morphological resistance to erosion, the sediment released may not contribute significantly to the suspended sediment load measured downstream if locational and filter resistance are high.

Given the catchment-specific nature of the complex interplay of the principal factors controlling sediment mobilization and delivery to river channels, it is not surprising that existing studies of the origin of fluvial suspended sediment report contrasting results. In many instances, the erosion of surface soils has been identified as the primary source of suspended sediment flux, reflecting the detrimental environmental impact of various land management practices including, amongst others, commercial forestry (Stott, 1986), grazing (Evans, 1997) and winter cereal production (Evans, 1990). Alternatively, research has also demonstrated that in some cases, channel bank erosion can be an important, if not dominant, source of suspended sediment loads (Duijsings, 1987; Church and Slaymaker, 1989).

## II The problem

Assembling meaningful information on the primary sources of the suspended sediment loads transported by rivers is highly problematic. Although many difficulties and operational problems are specific to particular measurement and monitoring procedures (see following discussion), two principal constraints are common to most of the methods employed. First, suspended sediment sources are spatially and temporally variable in response to the complex interactions between the major factors governing sediment mobilization and delivery. It is therefore necessary to undertake measurements at a range of spatial locations and over different temporal scales in order to obtain representative data. The need to address potential spatio-temporal variations in the relative contributions from individual sediment sources inevitably introduces logistical, practical and sampling constraints. Secondly, the costs of employing many of the available methods constrain the spatial coverage and temporal duration of monitoring programmes and therefore further compound the problems of obtaining representative data. The problems of representativeness and cost combine to compromise the reliability of the information reported by many studies (Stocking, 1987).

## III Data collection on sources of fluvial suspended sediment

A logical framework for conducting an assessment of catchment suspended sediment sources using available methods of data collection is outlined in Figure 1. The individual components are discussed in the following sections.

### 1 Initial field observations

Field walking in a catchment during rainstorms affords a valuable opportunity for observing and appraising fine sediment sources. Visits to the field should ideally form the preliminary stage in any sediment source investigation. Visual observations

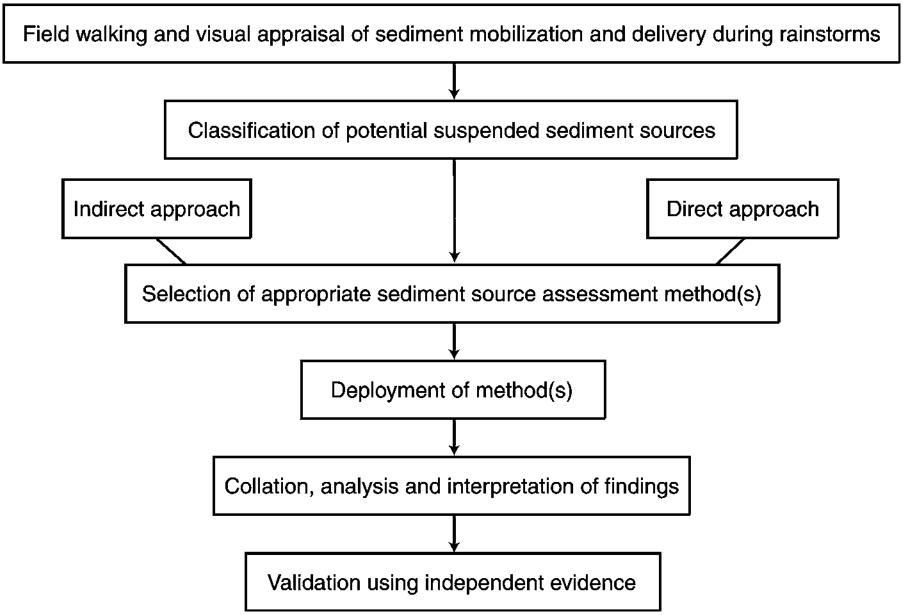

**Figure 1** A logical framework for investigating fluvial suspended sediment sources

are particularly useful for identifying the areas of a catchment experiencing erosion and for confirming the linkages between sediment sources and the stream network. Wherever possible, it is advisable to make several return visits to different areas of the drainage basin, as a means of encompassing the spatio-temporal variability of erosion and sediment delivery. Although commonly qualitative in nature (e.g., Lawler *et al.*, 1997), field observations can be based on a simple scoring system incorporating factors such as tree root exposure, soil surface crusting, rill or gully size and plant cover (Morgan, 1995). It is, however, important to exercise care during the visual appraisal of suspended sediment sources because subjectivity poses a problem in relation to the interpretation of evidence. For example, the occurrence of bare river banks is not necessarily indicative of substantial bank erosion and it is therefore advisable to record supportive information, e.g., overhangs, tension cracks and basal accumulations of spalled aggregates. Despite these problems, field observations provide a useful complement to the methods available for documenting catchment suspended sediment sources.

## 2 Classifying potential sources of fluvial suspended sediment

Following visual appraisal of field evidence for sediment mobilization and delivery, potential sources of the suspended sediment load in a catchment should be grouped into categories in order to organize and rationalize data collection and interpretation. Because suspended sediment sources are predominantly diffuse in nature, it is inappropriate to adopt the point and nonpoint source categories traditionally used in water quality studies. A number of classification schemes can be employed depend-ing upon whether information on the *types* or *spatial location* of individual sediment sources is required. Different types of suspended sediment sources can be readily classified in terms of hillslopes and river channels, or the surface and subsurface portions of a catchment, whilst spatial provenance can be easily categorized on the basis of individual tributary subcatchments or geological units (see Figure 2).

The components of these principal sediment source categories will inevitably depend upon the major erosive processes in the study catchment and any measurement or monitoring programme should be directed accordingly. Owing to the likelihood of sediment deposition, storage and remobilization, potential sediment source types can be further subdivided into primary and secondary categories and these can be either proximal or distal to river channels (see Figure 3). In contrast, spatial provenance groupings combine primary and secondary, as well as proximal and distal sediment sources.

Selection of the most appropriate classification scheme is principally governed by study catchment size and data requirements. In smaller ($<50\ \mathrm{km}^2$) catchments, where the number and spatial complexity of sediment sources can be expected to be lower, it is frequently most meaningful to investigate suspended sediment provenance in terms of individual source types. Alternatively, in larger drainage basins, where the opposite is true, it is frequently more practical and meaningful to address the spatial location of sediment sources. The intended use of the sediment provenance data should, nevertheless, be carefully considered. In the context of catchment management, information on individual source types is generally more appropriate for devising sediment control strategies. Assembling such information for larger drainage basins remains, however, a difficult task and a compromise between data requirements and practical considerations may therefore be necessary. Similarly, the inclusion of all potential sediment sources in measurement programmes is frequently impractical and constrained by available resources. Consequently, most sediment sourcing investigations target the primary sources of suspended sediment transport.

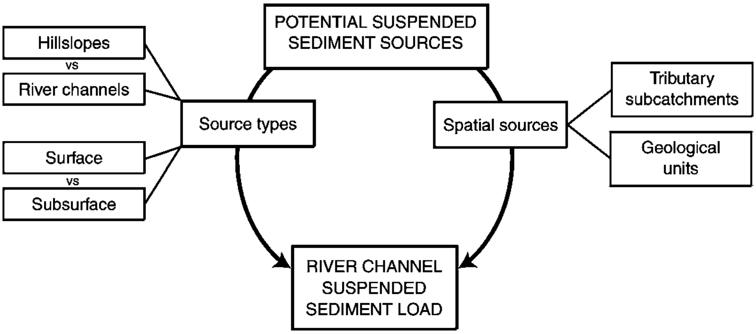

**Figure 2** An elementary classification of potential fluvial suspended sediment sources

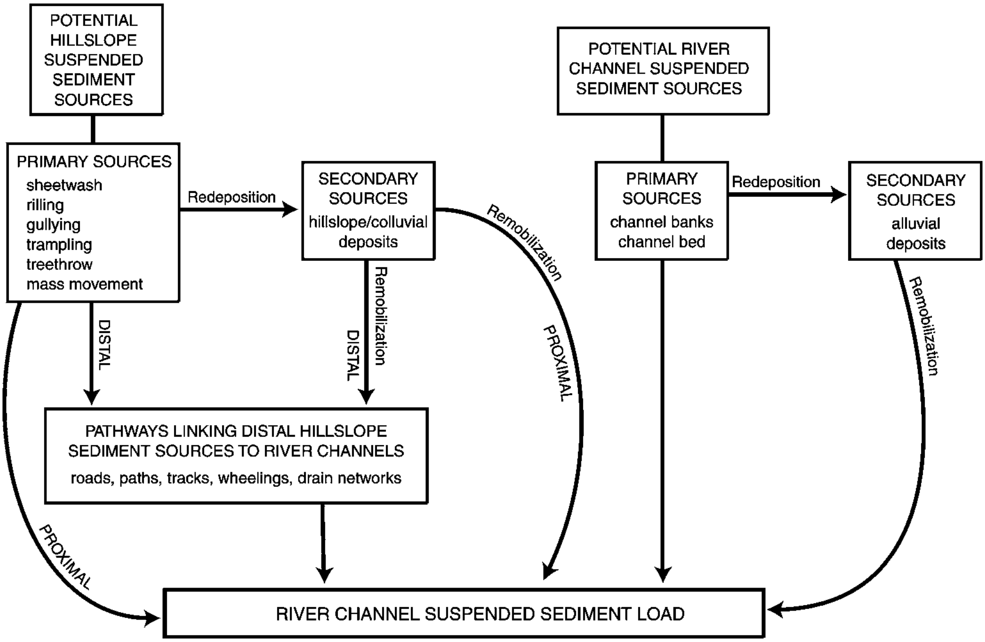

**Figure 3** An example of an advanced classification of potential hillslope and river channel suspended sediment sources

## 3 Available methods of data collection

Existing approaches to assembling data on catchment suspended sediment sources comprise two basic categories (Loughran and Campbell, 1995). The indirect approach to sediment source assessment is founded upon the use of a range of methods to measure or evaluate sediment mobilization *in situ*. By virtue of being primarily developed in association with erosion rather than sourcing studies, these methods take no account of the uncertainties in linking potential suspended sediment sources to the river channel. Sediment sourcing studies are, by definition, concerned with the major sources contributing to downstream sediment flux as opposed to those portions of a catchment experiencing erosion *per se*. Whilst the latter, *sensu stricto*, represent sediment sources, the former can only be inferred using the indirect approach, unless the linkages between erosion, transport, deposition and sediment yields are quantified. Numerous uncertainties are associated with these linkages because of the sediment delivery problem (Walling, 1983) and it is therefore essential that the findings provided by the indirect approach to sediment source assessment are interpreted on the basis of complementary information on the remaining components of the sediment delivery system. By contrast, the direct approach to sediment source assessment attempts to link sources to the stream channel using alternative means and thereby avoids inference or the need to supplement estimates of sediment mobilization *in situ* with information on the catchment sediment budget.

A range of techniques is available for measuring or inferring sediment mobilization. Selection of the most suitable technique or combination of techniques rests heavily upon available resources and a clear understanding of sediment mobilization and delivery in the study catchment. The following sections provide an overview of the major existing techniques comprising indirect and direct approaches to documenting the provenance of fluvial suspended sediment loads.

*a The indirect approach*: Estimates of erosion rates collected using the following techniques must be interpreted on the basis of complementary information on sediment routing and sediment yield in order to provide a reliable means of apportioning the relative contributions from a number of individual sources to the sediment flux measured downstream. Where erosion measurements do not encompass all potential sediment sources, the lumped contribution from those portions of a catchment not included in a monitoring programme can be estimated indirectly by calculating the difference between the contribution from monitored sources and the measured sediment load.

(i) Mapping. Mapping represents an important traditional method of recording information on suspended sediment provenance (Skrodzki, 1972; Lao and Coote, 1993). Sediment source maps can be used to provide semi-quantitative assessments of sediment origin when produced sequentially and are particularly useful for relat-

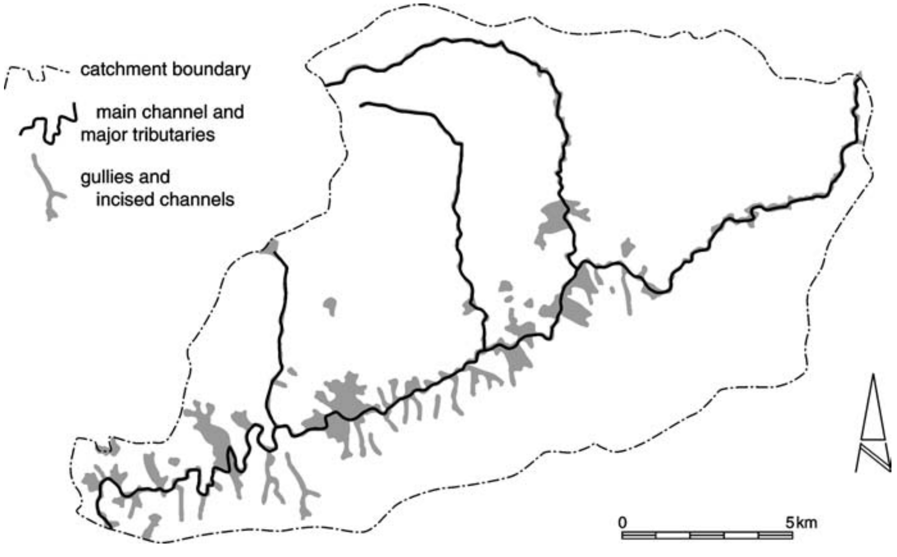

**Figure 4** A map of gullying in the Bell River catchment, South Africa
*Source*: after Dollar and Rowntree (1995), with permission of the Society of South African Geographers, publishers of the *South African Geographical Journal*.

ing information on the spatial distribution of erosion to corresponding information on physiographic, ecological and anthropogenic controls (Morgan, 1995). Maps have been employed to record the occurrence of particular types of erosion including rilling (Hasholt and Hansen, 1993), gullying (Dollar and Rowntree, 1995; see Figure 4) and channel bank degradation (Hooke and Redmond, 1989; Thorne *et al.*, 1993; Lawler *et al.*, 1997), as well as the percentage of bare ground (Kirkbridge and Reeves, 1993), the number of fields evidencing erosion (Boardman, 1990), or the extent of tree root exposure (Carrara and Carroll, 1979).

Advanced mapping procedures have been proposed by a number of workers. For example, Williams and Morgan (1976) described a geomorphological mapping system for recording information on the types and distribution of erosion and for interpreting the resulting maps in terms of a number of catchment attributes including erosivity, runoff and land use. Mapping has also been used in conjunction with the 'pedogenic baseline approach' to evaluate soil erosion (Yanda, 2000) or landslide hazard (Guzzetti *et al.*, 1999) on the basis of soil profiles.

Amongst the principal disadvantages of using mapping as a tool for assessing suspended sediment provenance are: subjectivity; the need for cartographic skills: difficulties in interpreting whether eroded surfaces are contemporary or historical; and the time-consuming nature of map production.

(ii) Surveying. The use of surveying techniques to evaluate sediment mobilization is founded upon the establishment of a datum relative to which erosion or deposition can be measured.

(1) *Profilometers.* One of the most commonly used devices for assessing surface advance or retreat is the profilometer, comprising a frame mounted on permanent benchmarks and with a series of vertical rods that can be lowered to the ground surface. The length of the rods can be repeatedly measured in the field or determined from sequential photographs as a means of assessing erosion or aggradation. Examples of profilometers include the apparatus reported by Toy (1983), which takes three measurements of the designated surface and the devices described by Lam (1977) and McCool *et al.* (1981), which take more measurements and comprise a more stable platform. A lightweight version, termed the 'erosion bridge', has recently been described by Shakesby (1993).

The principal advantages of employing profilometers to measure sediment mobilization include the minimal disturbance of the catchment surface and the negligible interference with the processes of erosion or deposition (Campbell, 1981). Potential disturbance of the benchmarks by erosion, cultivation or vandalism, the cumbersome nature of the available devices and the associated operator requirements are amongst the principal disadvantages. Difficulties are frequently experienced in the use of these devices to measure soil loss in stony locations or areas where a deep litter layer exists (Shakesby, 1993). The spatial coverage of a profilometer is minimal, although a series of frames can be used to establish a slope monitoring network (Lam, 1977).

(2) *Erosion pins.* The insertion of rods or nails into the surface of slopes and channel banks can provide a datum against which erosion or deposition can be manually assessed on the basis of the length of pin exposed or movement of a washer placed on the pin. Pin readings can be taken with either vernier or digital calipers. A number of

recommendations for the use of manual erosion pins are provided by Haigh (1977). These emphasize that pins should be nonrustable, deployed in clusters and measured at least every six months.

Although cheap and relatively simple to use, a range of problems are encountered with the deployment of erosion pins. Couper *et al.* (2002) summarize the major difficulties. First, the reliability of pin readings can be compromised by pin movements associated with operator, animal or tillage disturbance, frost heave, pin loss in noncohesive materials or other disturbances in dynamic environments (cf. Thorne, 1981; Lawler, 1993). Secondly, measurement errors can be caused by changes in the elevation of the slope or channel bank occurring independently of erosion or deposition, e.g., as a result of swelling or shrinkage. Thirdly, pin insertion can interfere with erosion processes by reinforcing soil peds or cause deposition by intercepting material moving downslope. Fourthly, vandalism can result in measurement errors or the loss of pins. Erosion pins are inappropriate for detecting micro-changes in surface elevation in situations where banks are prone to mass failure, or where retreat rates between site visits exceed pin length (Lawler *et al.*, 1997). The spatial resolution of pin measurements is restricted to the points under investigation.

Despite these problems, erosion pins have been used to monitor a variety of suspended sediment sources including soil erosion by sheetwash (Haigh, 1977) or gullying (Oostwoud Wijdenes and Bryan, 2001) and channel bank retreat (Lawler, 1993; Lawler *et al.*, 1997). The latter, in particular, has been the focus of a great deal of attention using manual erosion pins. For instance, Stott (1999) deployed conventional pins to measure main channel, tributary and forest ditch bank erosion rates in the Nant Tanllwyth catchment, UK and reported an increase in sediment supply from these sources in association with clear felling. Alternatively, a study on the River Arrow, UK, by Couper and Maddock (2001) identified the importance of subaerial weathering of river banks during low flow periods. Negative pin readings, however, can pose an important problem for the monitoring of bank erosion rates and reflect a number of factors including deposition during high flows, soil fall from the upper to lower bank and expansion of bank surfaces resulting from temperature or moisture fluctuations. Couper *et al.* (2002) report a useful examination of these factors on the Afon Trannon, Nant Tanllwyth and River Arrow, UK, concluding that no single factor accounts for negative readings and that studies employing pins should indicate how such readings are treated in the derivation of mean bank erosion rates.

An important development in the use of erosion pins to study channel bank suspended sediment sources is the Photo-Electronic Erosion Pin (PEEP) monitoring system (Lawler, 1991). This instrument comprises a row of photovoltaic solar cells in a sensor that, once inserted in the bank surface and connected to a datalogger, can be used to record quasi-continuous information on the magnitude, frequency and timing of erosion or deposition, on the basis of peaks, ramparts and troughs in the voltage record. The deployment of the PEEP system has greatly improved the temporal resolution of information on channel bank erosion. For example, Lawler *et al.* (1997) demonstrated that bank erosion on the Upper Severn, UK, occurred during a series of large discrete events rather than as a slow continuous process and that bank erosion may continue after the flood peak because of the draw-down effect caused by the removal of lateral support for bank faces in association with receding water levels. Bull (1997), using PEEPs and estimates of suspended sediment flux in the same study area, estimated that bank erosion contributed 38% and 64% of the sus-

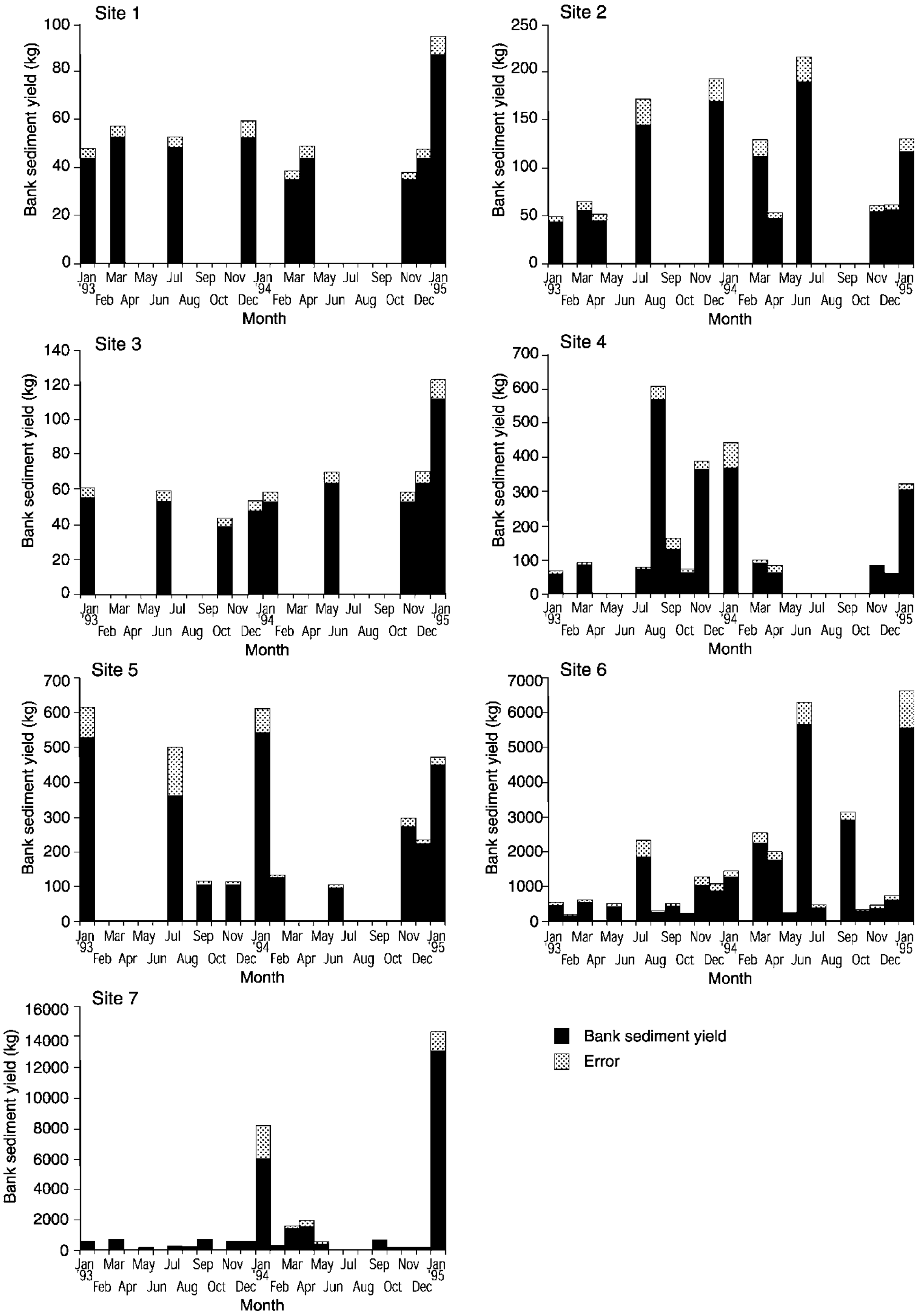

**Figure 5** Monthly suspended sediment yields from eroding channel banks in the Upper Severn catchment, UK

*Source*: after Bull (1997), with permission of John Wiley and Sons Ltd, publishers of *Earth Surface Processes and Landforms*.

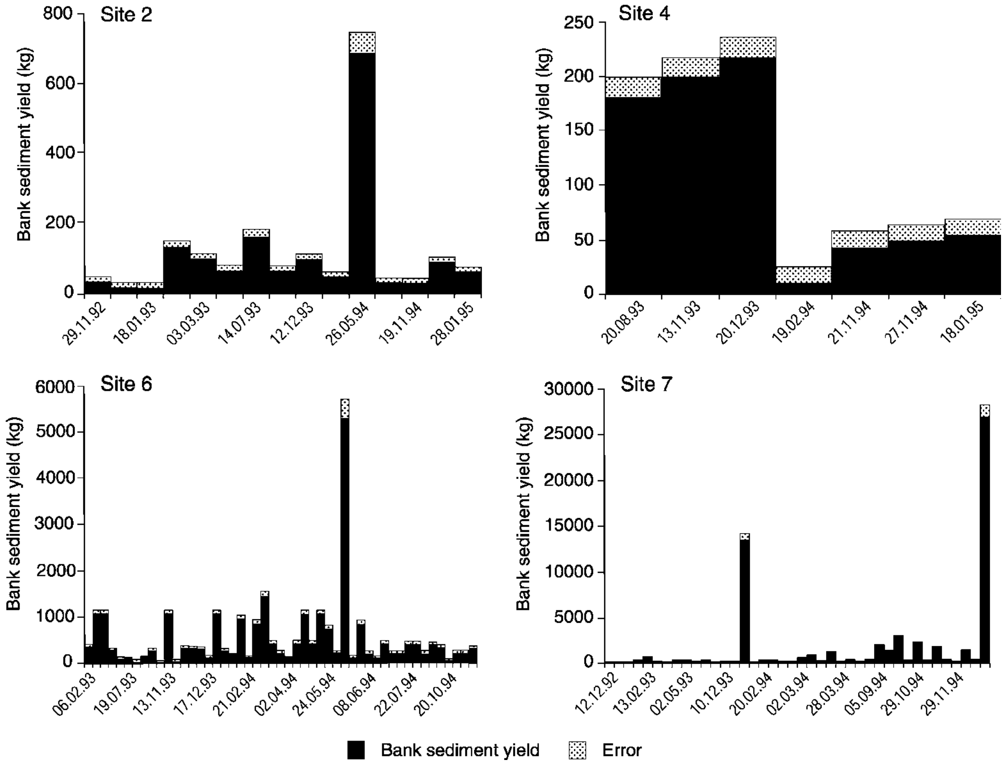

**Figure 6** Event suspended sediment yields from eroding channel banks in the Upper Severn catchment, UK
*Source*: after Bull (1997), with permission of John Wiley and Sons Ltd, publishers of *Earth Surface Processes and Landforms.*

pended sediment load at the monthly and event timescales, respectively (see Figures 5 and 6). PEEPs have also proved useful in examining the relationship between spatial variations in bank erosion rates and downstream changes in channel hydraulics or bank material properties (Lawler *et al.*, 1999).

(3) *Cross-profiling.* The accurate surveying of cross-profiles has been widely used to determine the volumes of sediment exported from rills and gullies (Evans, 1993; Fryirs and Brierley, 1999; Steegen *et al.*, 2000). This approach does, however, frequently underestimate gross erosion rates by failing to take account of soil loss by sheetwash on the intervening areas of catchment slopes and the reliable identification of pre-erosion surfaces can prove difficult. Repeat cross-section surveys have also been commonly exploited as a means of determining rates of channel bank erosion (Lawler, 1993). Such procedures typically involve the establishment of monumented cross-sections, which are repeatedly surveyed using a variety of means including inclinometers (Kesel and Baumann, 1981) or scour chains (Battala *et al.*, 1995). Superimposition of the cross-profiles recorded at different times allows the retreat of the entire designated river bank to be estimated. In a recent example, Springer *et al.* (2001) reported the use of cross-profiling to measure channel erosion rates in two mountainous drainage basins in Virginia, USA.

(4) *GPS*. Geomorphologists are increasingly exploiting the potential for using Global Positioning System (GPS) techniques in monitoring landscape systems (e.g., Gili *et al.*, 2000; Malet *et al.*, 2002). GPS techniques lend themselves to periodic or continuous monitoring and can be used to detect short-duration change more readily than alternative survey. Furthermore, GPS techniques can provide centimetric precision, are nondependent upon direct lines of sight between measurement points and can be employed in a wide range of weather and light conditions. Assuming a reliable power supply, GPS equipment requires less maintenance than conventional geodetic equipment and the processing of data can be conveniently undertaken by nonspecialists using commercially available computer software.

It is, nevertheless, important to note that GPS techniques are constrained by a number of problems. For example, it is necessary to ensure that the sky is visible is all directions in order to guarantee receipt of the signals emitted by at least four satellites and the baseline of measurement must be $<5$ km in order to maximize accuracy (Malet *et al.*, 2002). The identification of fixed survey points in highly unstable areas can pose additional problems, whilst antennas must be inserted within 10 cm of the ground surface in order to limit problems of wind turbulence. Despite such limitations, GPS offers a convenient and increasingly affordable means of assembling quasi-real time information. Although to date, deployment has focused on the monitoring of landslides, volcanoes and glaciers, alternative applications to the study of catchment suspended sediment sources are likely to prove equally successful because GPS techniques provide both a complement and alternative to conventional survey.

(5) *Miscellaneous*. Some studies have combined surveyed estimates of differences in height between ground protected by shrub canopies and that of the surroundings, with tree ring information to assess sediment loss from different portions of river catchments (e.g., Stromquist, 1981). So-called dendrochronological methods (Alestalo, 1971) have also been employed to quantify sediment mobilization from gullies (Vandekerckhove *et al.*, 2001) and mass movement (Fantucci, 1999; Lang *et al.*, 1999).

Conventional surveying has been used in reconnaissance surveys to provide information on the length, width and depth of erosion features. Grieve *et al.* (1995) used surveying to evaluate the extent of sheetwash in upland Scotland, UK, whilst more recently, McHugh *et al.* (2002) reported the use of conventional surveying to estimate upland soil erosion in the UK at established field sites located on an orthogonal grid.

(iii) Photogrammetry. The use of photographs in fluvial geomorphology has traditionally involved the interpretation of sequential air photos to provide qualitative information (e.g., Werrity and Ferguson, 1980). Modern methods of photogrammetry advance photographic interpretation by virtue of extracting quantitative information on the landforms under investigation by terrestrial or aerial means. Choosing between the latter is heavily dependent upon scale and financial considerations.

Photogrammetry affords a number of advantages compared with alternative techniques (Lane *et al.*, 1993; Chandler, 1999). Photographs can be used for detecting morphological change at the micro-, meso- and macro-scales, record the spatial relationship of landforms and provide three-dimensional information that can be used to construct Digital Terrain Models (DTMs), as well as supplementary details useful for interpreting erosion rates or patterns, e.g., vegetation cover. The collection of photographs requires minimal landform disturbance, reduces the need for alternative expensive fieldwork and provides a means of archiving information. Current quantitative procedures based on the analytical or mathematical approach, pose fewer optical and mechanical limitations compared with the traditional analogue method and produce digital output (Lane *et al.*, 1993). The software required for the digital processing of photographs is now available at commercially competitive rates. Among the main disadvantages of photogrammetry are the high cost of phototheodolites, difficulties in locating stable camera stations for repeat photography and problems caused by poor light incidence or obstacles between camera and subject (Barker *et al.*, 1997; Chandler, 1999). Photographs represent incidental measurements, which may not take appropriate account of the frequency of observation necessary for reliably monitoring a given subject and require careful calibration. The grain size resolution of the camera film employed can preclude the accurate assessment of erosion rates.

Both aerial and terrestrial photogrammetry has been used to monitor a range of fluvial suspended sediment sources including eroding channel banks (Painter *et al.*, 1974; Bathurst *et al.*, 1986; Barker *et al.*, 1997). These studies demonstrate the utility of photogrammetry for documenting the spatial variability of bank erosion rates on account of photos retaining spatial rather than point-specific information. Photogrammetry has also been employed to monitor landslides (Matthews and Clayton, 1986) and gullying (Nachtergaele and Poesen, 1999). Despite the associated costs, aerial photogrammtery has proved useful for undertaking reconnaissance surveys of soil erosion at a range of spatial and temporal scales (Whiting *et al.*, 1987; Vandaele *et al.*, 1996).

(iv) Erosion plots. Erosion plots, which provide a simple and widely used means of obtaining data on soil erosion rates, can be conveniently divided into bounded and unbounded categories (Loughran, 1989). Bounded plots comprise small areas of demarcated hillslope from which runoff and sediment are collected over a storm event or alternative temporal basis (United States Department of Agriculture, 1979). Numerous examples of the use of bounded plots are reported in the literature. For instance, Thomas *et al.* (1981) used bounded plots to investigate sediment mobilization from areas supporting different land use in a 11.3 km$^2$ catchment in Kenya, whilst Lewis and Nyamulinda (1996) and Vacca *et al.* (2000) describe similar studies in Rwanda and Sardinia, respectively.

A number of potential problems and limitations are associated with the use of bounded plots. First, bounded plots are partially closed systems and are therefore not wholly representative of natural conditions, especially because of so-called ‘boundary effects’. Monitoring programmes employing bounded plots need to be of long duration and based on numerous plots, in order to improve the reliability of erosion data (Elwell, 1990). However, the erosion estimates provided by essentially uniform plots during the same rainstorm events are frequently characterized by appreciable differences in magnitude (Wendt *et al.*, 1986). Nonstandardization of plot design and measurement period mean that it is frequently impossible to undertake meaningful comparisons of the results of independent studies. Significant errors are commonly associated with sediment concentration estimates for plots, because of sedimentation in runoff collection tanks or unrepresentative sampling by automatic equipment (Lang, 1992; Morgan, 1995). Plots typically overestimate erosion rates by failing to encompass major catchment sediment stores. Extrapolation of erosion estimates directly from plot to basin scale therefore involves many problems and uncertainties (Roels, 1985; Evans, 1990, 1993, 1995; Brown and Schneider, 1999).

Unbounded plots are most commonly represented by Gerlach troughs and comprise metal gutters installed perpendicular to the slope axis to collect runoff and sediment (Mutchler *et al.*, 1988). These installations avoid 'boundary effects' and are cheap and simple to use. It is, however, difficult to determine accurately the contributing area, although topographic survey or the confirmation of runoff paths using dyed water has proved useful in this respect (Loughran, 1989). Numerous troughs are required to ensure representative soil erosion estimates (Roels and Jonker, 1983; Roels, 1985; Evans, 1995). Unbounded plots have been used to estimate soil erosion rates in many environments, including the tropics (Brown and Schneider, 1999). Megahan *et al.* (2001) report the use of 75 unbounded plots to estimate sediment mobilization from cutslopes in the aftermath of forest road construction in Idaho, USA.

(v) Suspended sediment flux monitoring. An alternative approach, which has proved particularly convenient for helping to document sediment sources in larger drainage basins, is the monitoring of suspended sediment fluxes from individual tributary subcatchments. Comparison of the latter estimates with the total sediment flux at the basin outlet provides a means of evaluating the relative contributions from individual spatial sources represented by the subcatchments.

Monitoring programmes aimed at assembling suspended sediment flux estimates are dependent upon the collection of discharge and sediment concentration data. The latter information has traditionally been collected using a range of manual sampling devices (World Meteorological Organisation, 1989), but the associated logistical problems and financial constraints mean that most manual sampling strategies fail to coincide with the main periods of sediment transport, i.e., flood events. Although automatic sampling equipment has helped to address this problem, automated sample collection programmes continue to fall short of providing a practical means of assembling continuous information on suspended sediment concentration. In the absence of a detailed temporal record of suspended sediment concentration, sediment loads can be estimated using a range of conventional load calculation procedures that interpolate or extrapolate the available data (Phillips *et al.*, 1999). It is, nevertheless, important to note that these methods are confounded by more general problems of accuracy and precision and it is now generally accepted that sediment load estimation in anything other than large catchments requires short-duration sampling intervals (Olive and Rieger, 1988).

The collection of high frequency sediment concentration data has been greatly assisted by the development of commercially available optical tubidity sensors. However, these devices must be used in conjunction with a number of supportive procedures including regular calibration, lens cleaning and the development of a rating relationship for converting turbidity readings to actual suspended sediment concentration (Walling and Collins, 2000). The recent development of self-cleaning probes has reduced the lens cleaning problem. Although not without problems

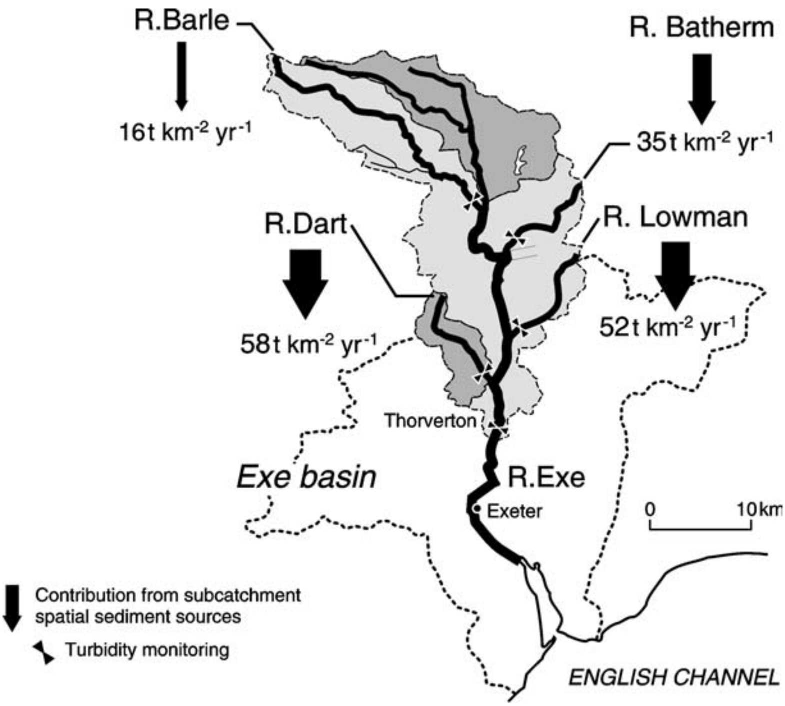

**Figure 7** The estimated typical contributions of suspended sediment from individual tributary sub-catchments in the Exe basin, UK
*Source*: based on the estimates reported by Walling and Webb (1987).

(Gippel, 1995), the use of turbidity sensors offers a more economical means of assembling reliable information on suspended sediment fluxes because the errors are less than those associated with regular but infrequent water sampling programmes.

A classic example of the estimation of suspended sediment fluxes from tributary subcatchments is provided by the Exe basin study, UK (Walling and Webb, 1987). Figure 7 shows the estimated contributions from a selection of the tributary subcatchments included in the monitoring programme. Likewise, Wass and Leeks (1999) used turbidity sensors to estimate sediment fluxes from ten major tributaries of the River Humber, UK, and Rondeau *et al.* (2000) reported a similar study on the St Lawrence River, Canada. Sutherland and Bryan (1990) describe the use of this approach to calculate sediment contributions from the different portions of a small catchment in Kenya.

The use of sediment flux estimates to represent the relative contributions from individual spatial sources in larger drainage basins avoids spatial sampling constraints. Many of the uncertainties associated with sediment routing are avoided. This approach does not readily lend itself to interpreting the relative significance of key sediment mobilization processes or land management practices, except in situations where these factors are tributary-specific.

(vi) Remote sensing. The use of remote sensing as a monitoring tool in geomorphology is underpinned by a number of assumptions (Milton *et al.*, 1995). These include, first, that the geomorphic processes of interest produce detectable changes in the spatial or temporal pattern of electromagnetic radiation and, secondly, that any geometric distortions arising from the sensor can be discriminated from real changes in landscape features.

Remote sensing instruments are carried by aircraft or satellites. Monitoring geomorphic systems with these sensors is founded on a process of geomorphic registration. The transformation of the image geometry to fit a map projection is normally accomplished by matching ground control points on the image and on a map of an appropriate scale of the corresponding area. The pixel values in the corrected image are interpolated using a procedure known as resampling. Resampling typically involves the choice between convolution, cubic, bilinear or nearest-neighbour algorithms and these need to be complemented by human interpretation by trained personnel (Duggin and Robinove, 1990). The nearest-neighbour method is recommended for quantitative analysis because this interpolation procedure leaves digital information unchanged. The geometric correction of two images taken at different times and coregistered using the above procedure provides a basis for monitoring change.

Remote sensing affords a useful tool for visualizing and analysing geomorphic systems over numerous temporal and spatial scales. Satellite systems are most suited to larger-scale surveys and provide the only practical means of assembling multiregional or global information (Donoghue, 1999). Airborne sensors are best suited to monitoring smaller areas and to responding to specific geomorphic events and therefore offer improved temporal flexibility (Donoghue, 2000). Potential problems include costs, practical difficulties arising from cloud cover, flight path courses or timings and unfavourable geometry and the contrasting results yielded by different algorithms for detecting change (Wilson, 1994; Lyon *et al.*, 1998). The mathematical transformation of airborne images is more difficult owing to the corrections required for aircraft altitude and stability (Wilson, 1994). Training is required in the interpretation and analysis of spectral images. Recent developments in syntghetic aperture radar are, however, helping to avoid problems associated with weather conditions and the spatial resolution of remote sensing imagery continues to be improved (e.g., 65 cm for Quickbird, compared with 15 m for Landsat ETM+ and 5 m for SPOT-5 HRV).

Both airborne and satellite remote sensing platforms have been deployed to investigate suspended sediment mobilization in river basins. With sensors detecting electromagnetic radiation at an increasing range of wavelengths and at a wider variety of spatial, temporal and spectral scales (Curran *et al.*, 1998), the use of remote sensing for such purposes is likely to increase. Bryant and Gilvear (1999) report the use of multispectral airborne images to quantify geomorphic changes associated with an extreme flood event on the River Tay, UK. Bocco *et al.* (2001) describe the use of Landsat images to evaluate land degradation arising from deforestation in Michoacan State, Mexico. Alternatively, Islam *et al.* (2001) report the use of Landsat TM data to investigate seasonal variations in the relative suspended sediment loads of individual tributaries in the Ganges-Brahmaputra system. More recently, the spatial distribution of erosion and deposition in four small catchments in Australia has been estimated on the basis of gamma radiometric data (K, Th, U) recorded using airborne remote sensing surveys (Pickup and Marks, 2000). This approach is, nevertheless, confounded by a number of problems; K, Th and U are the only geogenic radioisotopes with gamma ray emissions of sufficient energy to be detected by this procedure and gamma ray signals are attenuated by dense forest and soil or surface water. Improved procedures are required to differentiate between gamma ray patterns caused by erosion and geological variability.

(vii) Soil erosion tracers. Owing to the problems and limitations associated with conventional methods for evaluating soil erosion, the use of fallout radionuclides (i.e., $^{137}$Cs, unsupported $^{210}$Pb, $^{7}$Be) has attracted increasing attention. The application of environmental radionuclides in soil erosion surveys is commonly based on the premise that fallout is rapidly and strongly adsorbed by soil and sediment particles in most environments and that any subsequent lateral redistribution primarily reflects erosion and sedimentation.

Following validity checks and sample collection, soil redistribution rates are estimated on the basis of a comparison between the reference value and the inventories measured for individual sampling points using calibration models. Radionuclide inventories that are depleted relative to the reference value indicate erosion, whilst point inventories exceeding the reference value indicate deposition. Existing procedures for calibrating fallout radionuclide measurements to provide quantitative estimates of soil redistribution rates have largely been developed in tandem with $^{137}$Cs studies and can be divided into empirical relationships and theoretical models (Walling and He, 1999a). Although simple to use, empirical relationships (e.g., Bajracharya *et al.*, 1998) are constrained by a number of limitations on account of being derived from erosion plots that may not be wholly representative of catchment conditions. The theoretical approaches currently available comprise the proportional, profile distribution and mass balance models. Early versions of the proportional model (e.g., Martz and De Jong, 1991) are oversimplistic and fail to take into account various factors including the effects of the removal of freshly deposited fallout before its incorporation into the tillage horizon. Similarly, early versions of the profile distribution model (e.g., Zhang *et al.*, 1990) are hampered by a number of constraints including the failure to take account of the time-dependent nature of $^{137}$Cs fallout and the potential for its redistribution following deposition as fallout. Mass balance models provide a more rigorous accounting procedure (e.g., Yang *et al.*, 2000) by addressing the principal limitations of the proportional model. Walling and He (1999a) propose improved versions of the main types of $^{137}$Cs-based erosion models.

A number of key advantages are associated with the use of the $^{137}$Cs technique to assess soil redistribution rates. These include the provision of retrospective medium-term (~40 years) information on erosion rates and patterns that encompasses the sum of all erosive processes and that avoids the need for longer term monitoring programmes. The $^{137}$Cs technique can be applied in a wide range of environments and at different spatial scales (Wicherek and Bernard, 1995; Nagle *et al.*, 2000; Collins *et al.*, 2001b), typically involves only a single site visit thereby overcoming the sampling constraints of traditional monitoring methods and involves only minimal site disturbance. The soil redistribution estimates derived for individual sampling points can be extrapolated to larger areas and $^{137}$Cs analysis is nondestructive. The principal limitations of the $^{137}$Cs approach include the costs of analytical equipment and the difficulties experienced in interpreting medium term estimates of average soil redistribution rates in the absence of complementary information on land use patterns and intensity. Application of the approach is problematic in heavily gullied landscapes and in semi-arid areas (Chappell, 1999). Methodological uncertainties are associated with selecting the optimum coring strategy necessary for characterizing the variability of $^{137}$Cs inventories in reference locations (Sutherland, 1996) and on hillslopes (Sutherland, 1994). The global pattern of bomb-derived fallout, which results in reduced inventories in some parts of the world, hampers $^{137}$Cs measurements on samples collected in equatorial regions and the Southern Hemisphere. Existing calibration models require validation (Porto *et al.*, 2001).

The potential utility of unsupported $^{210}$Pb measurements in soil redistribution studies has only recently been explored (Walling and He, 1999b; Walling *et al.*, 2003). Unsupported $^{210}$Pb measurements afford an alternative to using the $^{137}$Cs technique in those parts of the world where low inventories pose measurement problems and provide a means of assembling retrospective longer term ($\sim$100 years) information. Analysis of $^{137}$Cs and $^{210}$Pb can be undertaken simultaneously and the two radionuclides can be employed conjunctively to provide a more detailed erosion history. However, existing calibration models for unsupported $^{210}$Pb measurements require further refinement and validation.

By virtue of its short half-life, $^{7}$Be provides an opportunity for investigating soil erosion rates and patterns at the event scale (Walling *et al.*, 1999a). Beryllium-7 measurements therefore address the problems associated with the derivation of short-term erosion estimates using either $^{137}$Cs or unsupported $^{210}$Pb data and permit the interpretation of erosion in relation to short-lived land use or hydrometeorological conditions. It is, however, important to recognize that the use of $^{7}$Be measurements is best suited to situations where significant erosion events are separated by $\sim$5 months in order to minimize the effect of previous erosion, otherwise it is necessary to take account of the temporal pattern of fallout and the sequence of erosion events (Walling *et al.*, 1999a).

Much of the existing work based on fallout radionuclide measurements has been associated with soil erosion studies and has therefore involved the exclusive assessment of particular sediment sources without consideration of their connectivity with river channels. However, radionuclide measurements can be used to assist the construction of catchment suspended sediment budgets and therefore offer a unique opportunity for assembling the information necessary for linking sediment sources and stores with estimates of sediment flux (Loughran *et al.*, 1992; Owens *et al.*, 1997). Alternatively, carefully designed soil coring programmes extending from hillslope summit to river channel can provide a basis for estimating the net contributions of sediment from different areas or land use to river channels.

(viii) Combined measurement procedures. Erosion is frequently catchment-wide during rainstorms and therefore encompasses several sediment sources. Because many measurement techniques are best suited to monitoring particular sediment sources, it is often necessary to employ a combination of available methods in order to provide a comprehensive assessment of sediment provenance. For example, Sutherland (1990) describes the combined use of erosion pins, Gerlach troughs, cross-profiling and field observations to evaluate sediment sources in a small tropical catchment in Kenya. Likewise, Fryirs and Brierley (1999) used sequential aerial photos, sedimentation surveys and cross-profiling to assess sediment sources in Wolumla catchment, Australia. The combined use of erosion measurement techniques is described by a host of other studies (e.g., De Jong *et al.*, 1999; Gobin *et al.*, 1999). The adoption of a range of measurement techniques, however, inevitably compounds logistical problems and costs and can preclude the simultaneous assessment of individual sediment sources.

*b The direct approach*: A range of techniques provide a direct means of documenting catchment suspended sediment sources by virtue of taking account of both sediment mobilization and delivery. These procedures avoid the need for inference or supportive information on sediment routing and yield.

(i) Erosion vulnerability indices. A variety of procedures available for evaluating the vulnerability of land to erosion and the efficiency of sediment delivery afford a direct means of assessing catchment suspended sediment sources. These procedures have commonly been developed to address erosion problems in drainage basins in the USA, where environmental problems concerning either forestry or fishery issues are reported. An example is provided by the Timber, Fish and Wildlife (TFW) index, which comprises rankings for the susceptibility of different areas of a catchment to erosion and the probability of mobilized sediment impacting upon fishery resources (Washington Forest Practices Board, 1994). Erosion vulnerability indices can be used to assist priority setting for sediment management strategies and afford valuable guidance for erosion measurement programmes. The wider applicability of many existing indices is, however, constrained by their catchment-specific nature, whilst the accuracy of surrogate measures of erosion is questionable. Application of erosion vulnerability indices is not cost-effective in larger catchments.

(ii) Sedigraphs and hysteretic loops. The characteristics of storm period hysteretic rating loops for suspended sediment concentration–discharge relationships have been tested as a basis for evaluating the provenance of fluvial suspended sediment. Anticlockwise loops have, for example, been interpreted in terms of sediment supply from channel sources (Klein, 1984). Clockwise hysteresis has also been attributed to the resuspension of sediment from channel sources during the rising limb of storm hydrographs (Bogen, 1980), but alternative explanations have been advocated including the exhaustion of sediment supply from surface (Doty and Carter, 1965) or subsurface (Carling, 1983) sources and reduced detachment of surface soil particles owing to the cessation of effective rainfall (Novotny, 1980).

It is therefore possible to explain similar hysteretic loops in terms of sediment supply from either surface or channel sources and additional information is clearly necessary for verifying sediment provenance (Peart and Walling, 1988). In a recent study of suspended sediment sources in the Peijbaye River basin, Costa Rica, Jansson

(2002) confirmed the problems associated with using hysteretic loops to infer sediment provenance and contended that the sedigraph-rainfall method, whereby the timing of rainfall and sediment concentration peaks is combined with information on storm water travel times, represents a valuable alternative method.

(iii) Sediment fingerprinting. In response to the problems associated with conventional indirect means of assessing catchment suspended sediment sources, sediment fingerprinting has attracted increasing attention as an alternative basis for obtaining such information. Sediment fingerprinting is founded on two main assumptions: first, that potential sediment sources can be discriminated on the basis of measurements of their geochemical properties, or fingerprints; and secondly, that comparison of the properties or fingerprints of suspended sediment with those of source material samples affords an opportunity for determining the relative importance of individual sources. Existing studies have confirmed that a range of properties can be successfully employed to fingerprint suspended sediment sources, including mineralogy (Hillier, 2001), mineral-magnetism (Dearing, 2000) and geochemistry (Lewin and Wolfenden, 1978), as well as environmental radionuclides (Olley *et al.*, 1993), organic substances (Brown, 1985), particle size (Kurashige and Fusejima, 1997) and stable isotopes (Douglas *et al.*, 1995). However, the use of an individual property or single-component fingerprint frequently introduces spurious source-sediment matches, with the result that no single property reliably distinguishes different sediment sources (Collins and Walling, 2002). The quest for a single diagnostic property is therefore considered to be unrealistic and inappropriate.

Given this problem, recent studies employing the fingerprinting approach have used several diagnostic properties in combination. By combining individual properties influenced by contrasting environmental controls and that therefore possess a substantial degree of independence, so called composite fingerprints afford a more reliable and consistent basis for distinguishing sediment sources on account of being more representative of the mixtures of catchment-derived material comprising suspended sediment samples. Composite fingerprints are used in combination with multivariate mixing models to provide quantitative estimates of suspended sediment provenance.

Quantitative composite fingerprinting techniques have been used to assess individual sediment source types classified in terms of surface soils under different land use and channel banks (Walling and Woodward, 1995; Slattery *et al.*, 1995; Collins *et al.*, 1997a; Russell *et al.*, 2001), or more simply as the surface and subsurface portions of river basins (Wallbrink and Murray, 1993). Alternatively, the fingerprinting approach has been adopted to investigate spatially defined sediment sources represented by geological units (Collins *et al.*, 1998; Walling *et al.*, 1999b) or tributary sub catchments (Collins *et al.*, 1996; Bottrill *et al.*, 2000) and to integrate estimates of spatial provenance and source type for larger drainage basins (Collins *et al.*, 1997b). Carefully designed suspended sediment sampling programmes enable information to be assembled on sediment sources over a range of temporal scales (see Figure 8).

A number of important advantages are associated with the use of the fingerprinting approach. Comparison of representative source material and suspended sediment samples provides a basis for determining spatially integrated

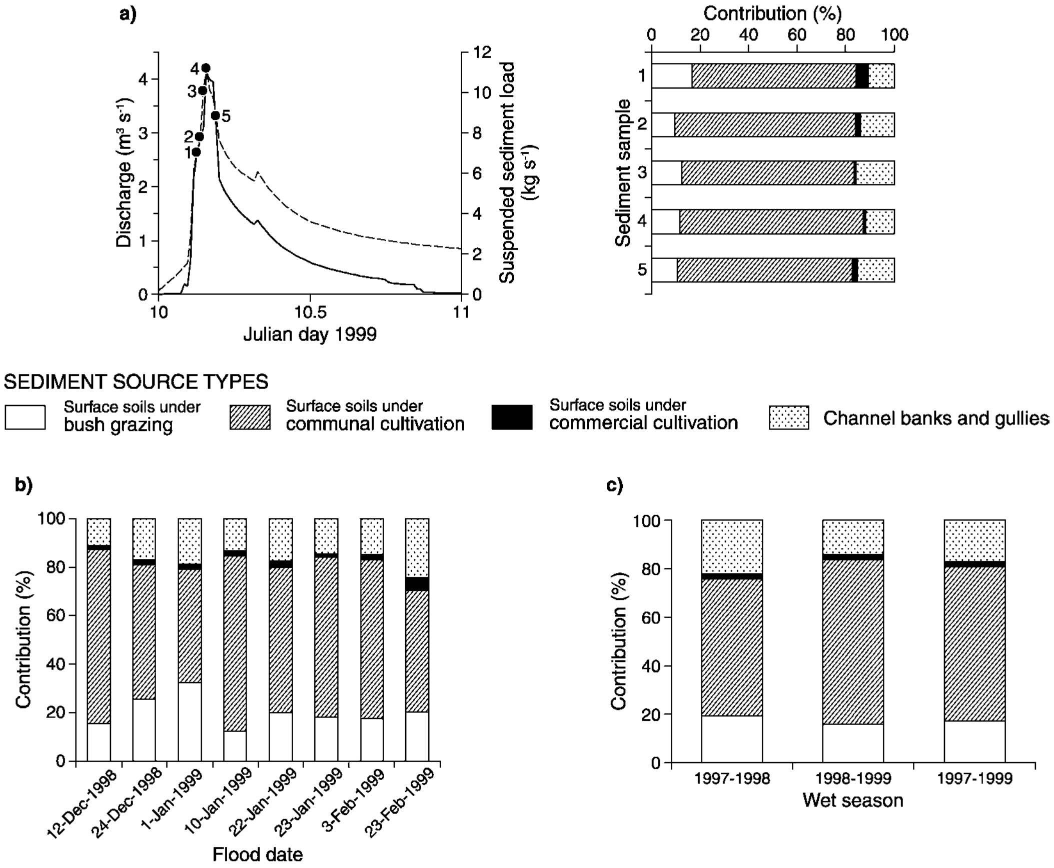

**Figure 8** Intra-storm (a), inter-storm (b) and seasonal (c) variations in the relative contributions from individual sediment source types in the Upper Kaleya catchment, Zambia
*Source*: adapted from Collins *et al.* (2001a).

estimates of sediment provenance, which conveniently avoids many of the sampling constraints and logistical problems hampering the indirect approach. Sediment fingerprinting is appropriate for investigating different types of sediment sources over a range of spatio-temporal scales and environments, and provides a means of simultaneously assessing the relative importance of individual sediment sources. By linking sources and sediment transport, fingerprinting procedures avoid the need to complement *in situ* erosion estimates with information on sediment routing. The fingerprinting approach readily lends itself to numerous catchment management scenarios.

Despite these important advantages, wider adoption of the fingerprinting approach as a conventional procedure for sediment sourcing studies continues to be hampered by a number of methodological uncertainties and problems. Generic guidelines for pre-selecting the most useful combinations of properties for discriminating sediment sources in different catchments are not available, although recent work has begun to address this issue (Collins and Walling, 2002). The approach is dependent upon the collection of representative samples of source material and suspended sediment. There are, at present, no guidelines for the optimum number of samples required to characterize sediment sources effectively using different properties. It is clearly important for appropriate checks, e.g., probability sampling to be incorporated into fingerprinting procedures, in order to address this problem. Collection of representative suspended sediment samples has been assisted by the recent development of a simple time-integrated sampler (Phillips *et al.*, 2000). Fingerprint property transformation during sediment delivery represents a potential problem requiring further attention (Collins *et al.*, 1997a; Walling and Collins, 2000) and a degree of uncertainty is associated with the numerical solutions provided by the current generation of multivariate sediment-mixing models (Rowan *et al.*, 2000). Notwithstanding these problems, the fingerprinting approach affords a highly valuable and effective means of investigating catchment suspended sediment sources by taking account of both the on-site and off-site controls governing sediment mobilization and delivery.

## 4 Data validation

Whilst sediment sourcing studies increasingly benefit from the advanced data processing procedures that can be adopted in association with available measurement techniques, investigators continue to direct insufficient attention towards data validation. Two main approaches can be used to verify data on suspended sediment provenance: namely, comparisons of source estimates and corroboration using independent information. The reliable comparison of sediment source data is frequently hampered by a number of potential problems including the contrasting geomorphic setting and duration of independent studies as well as the diversity and nonstandardization of the measurement techniques employed. Although a few studies have attempted to compare and validate suspended sediment source data for the same study area and duration, the reliability of such an exercise is compromised by numerous limitations. Different techniques are appropriate for measuring specific sediment sources over particular spatio-temporal scales and, most importantly, are characterized by contrasting intrinsic assumptions, procedures and accuracy. Sirvent *et al.* (1997) compared erosion estimates generated using erosion pins and profilometers for two plots in the Ebro basin, Spain, and concluded that the latter consistently exceed the former on account of reduced accuracy. Benito *et al.* (1991) reported similar findings. A number of studies have concluded that erosion estimates based on volumetric techniques (e.g., erosion pins and profilometers) typically exceed those associated with the use of collector devices (e.g., Gerlach troughs) on account of the former measuring gross and the latter measuring net erosion, respectively (Takei *et al.*, 1981; Rogowski *et al.*, 1985; Sala, 1988; Evans, 1995). The comparison of sediment sourcing techniques is clearly fraught with difficulty.

The validation of sediment source data on the basis of independent information appears to offer a reasonably reliable means of bypassing these uncertainties. For example, Collins *et al.* (1998) successfully verified fingerprinting estimates of the spatial provenance of contemporary suspended sediment fluxes in the Exe and Severn River basins, UK. The approach adopted involved testing the consistency of the fingerprinting data using a combination of flood routing times, storm-period rain gauge records and tributary suspended sediment yields. A number of factors can, however, compromise the direct comparability of such data sets including the effects of sediment storage and remobilization in larger drainage basins. Alternatively, Porto *et al.* (2001) used information on suspended sediment yield from the outlet of a small (1.38 ha) catchment in southern Italy to validate estimates of soil erosion upstream based on $^{137}$Cs measurements. This approach is, however, clearly restricted to small catchments where a sediment delivery ratio close to 1.0 can be assumed and is dependent upon careful examination of the temporal consistency of the two data sets employed.

Data validation should undoubtedly be afforded greater emphasis in studies of suspended sediment sources. It is, however, important that comparisons of the information generated by independent studies or different techniques and verification procedures using alternative information lend due consideration to the principal limitations involved. The fact that reliable data validation requires independent information is perhaps the most important factor compromising the cost–benefit of individual sediment sourcing techniques.

## IV Modelling catchment suspended sediment sources

A range of increasingly complex models can be used to simulate sediment mobilization and delivery rates. Traditionally, simplistic empirical relationships for predicting soil erosion rates, e.g., Universal Soil Loss Equation/Revised Universal Soil Loss Equation (USLE/RUSLE) (Renard *et al.*, 1991) could be used in conjunction with estimated sediment delivery ratios and sediment yield data as a means of determining channel bank erosion by difference (Peart and Walling, 1988). Spatially distributed models of soil erosion and sediment delivery are, however, now increasingly used in response to the emergence of more sophisticated technology and computational (e.g., cellular automata, neural network, genetic algorithm) procedures (Brooks and McDonnell, 2000). Distributed models can be based on either a semi-empirical approach involving the combined use of the USLE/RUSLE and distributed information on drainage networks, routing factors or sediment delivery ratios (Bradbury *et al.*, 1993; Fraser *et al.*, 1996; Pilotti and Bacchi, 1997; Van Rompaey *et al.*, 2001) or complex physically based process descriptions, e.g., Water Erosion Prediction Project (WEPP) (Nearing *et al.*, 1989), European Soil Erosion Model (EUROSEM) (Morgan *et al.*, 1994), Système Hydrologique Européen (SHE/SHESED) (Bathurst *et al.*, 1995), Limburg Soil Erosion Model (LISEM) (De Roo *et al.*, 1996) and Ephemeral Gully Erosion Model (EGEM) (Nachtergaele *et al.*, 2001).

Although useful for simulating sediment mobilization and delivery, the output from distributed models frequently represents integrated response and must therefore be further scrutinized and processed in order to assess the relative importance of individual sediment sources. Existing models frequently incorporate only a selection of potential sediment sources or even an individual source. The availability of reliable information on the spatial and temporal variability of sediment mobilization and delivery constrains the meaningful evaluation and validation of distributed models. Existing work has thus largely focused on ensuring that distributed models are theoretically acceptable as opposed to consistent with field data (Beven, 2002).

Highly parameterized distributed models therefore remain largely untested. The use of the most commonly available information, i.e., sediment yield data, permits validation of integrated basin response but precludes verification of internal performance. It is obviously possible to simulate basin output in terms of incorrect compensating internal behaviour. There are, nevertheless, a few examples of validating distributed predictions of soil redistribution using $^{137}$Cs measurements (e.g., Chappell, 1996; He and Walling, 1998).

A number of more general problems are associated with distributed modelling *per se* (Brooks and McDonnell, 2000; Beven, 2002; Beven and Feyen, 2002). The accurate representation of land surfaces continues to pose problems, but remains critical because variations in elevation are important in governing sediment mobilization and redistribution. Numerous uncertainties exist in assuming that Digital Elevation Model (DEM)-based hydrological modelling is reliable, because DEMs comprise artefacts, which must be carefully scrutinized (Wise, 2000). Improved process representation and inclusion are required. Specific areas warranting attention include the effects of scale and uncertainties in accounting for the spatial variability of precipitation, the representativeness of runoff flow paths or the occurrence of ephemeral gully erosion (Garen *et al.*, 1999). Existing models need to include more small-scale processes, especially whilst predicting change over a larger temporal or spatial resolution. Parameter and predictive uncertainty introduce equifinality (Beven, 2002), which must be explicitly recognized. Despite such problems, spatially distributed models of catchment erosion and sediment delivery afford a useful means of predicting the erosive behaviour of river basins under changing environmental or management scenarios.

## V Historical suspended sediment sources

Longer term information on suspended sediment sources represents an important data requirement for a number of reasons. Such estimates are essential for reconstructing historical catchment erosion patterns and assisting the interpretation of longer term sediment yield records in terms of the impact of past environmental change. Provision and examination of historical data sets will inevitably serve to support more reliable forecasts of the potential perturbations in sediment sources likely to result from climatic and land use change in the future. Equally, the capacity to manage current and predicted sediment-related environmental problems more effectively depends, in part, upon an improved understanding of the consequences of historical climatic trends and anthropogenic activity on sediment mobilization and routing in drainage basins.

The numerous problems associated with many measurement techniques mean, however, that monitoring programmes are typically short-duration (Higgitt, 1993), yielding discontinuous data records that are inadequate for reconstructing historical patterns of suspended sediment provenance. Existing studies of sediment sources using the indirect approach provide, at best, data encompassing periods of only a few years to decades. Fanning (1994), for instance, reported the use of erosion pins to investigate soil loss over a ten year study period in a small arid rangeland catchment, Australia, whilst Vandaele *et al.* (1996) used sequential aerial photos taken in 1947 and 1991 to determine longer-term soil redistribution patterns in a field near

Leuven, Belgium. Boardman (1991) describes a monitoring programme aimed at recording the extent and magnitude of soil erosion on the South Downs, UK, over a ten-year period. Such studies fall considerably short of the requirement for longer-term information on catchment suspended sediment sources.

Sediment fingerprinting affords a convenient basis for addressing the temporal shortcomings of conventional sediment source monitoring programmes, by using the sediment quality profiles preserved in a variety of depositional sinks as integrated records of proxy historical erosion data. This particular application of the fingerprinting approach is founded upon a comparison between the properties, or fingerprints, of historical sediment deposits and contemporary catchment source materials. Much attention has focused on the use of lake sediments to reconstruct suspended sediment sources over the past $10^2$–$10^3$ years (Oldfield and Clark, 1990). Radiometric (Wasson *et al.*, 1987), mineral-magnetic (Foster *et al.*, 1998; Oldfield *et al.*, 1999) and geochemical (Jones *et al.*, 1991) properties, as well as combinations of properties (Huang and O'Connell, 2000) have proved useful for this purpose. In a recent example, De Boer (1997) reported the use of mineralogy and geochemistry profiles in lake sediment cores from Stony Creek, Western Canada, to reconstruct changes in sediment source types over the past 100–150 years. Kelley and Nater (2000) determined the spatial provenance of a sectioned core from Lake Pepin, Minnesota, in terms of the relative contributions from individual tributary subcatchments.

A number of studies have also investigated the potential for using the geochemical profiles preserved in floodplain or estuary deposits and channel fill sequences to

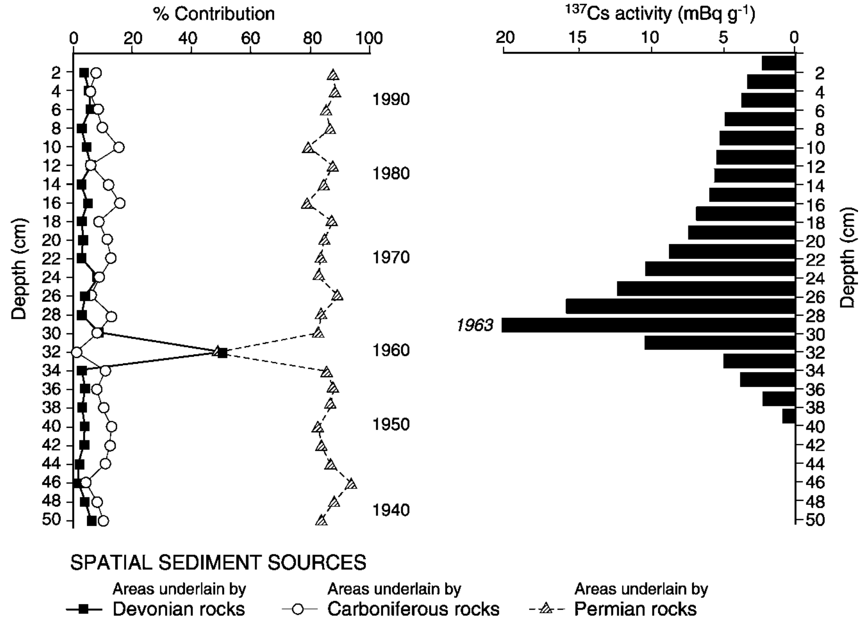

**Figure 9** Longer-term variations in the spatial provenance of suspended sediment fluxes in the Exe basin, UK
*Source*: adapted from Collins *et al.* (1997c).

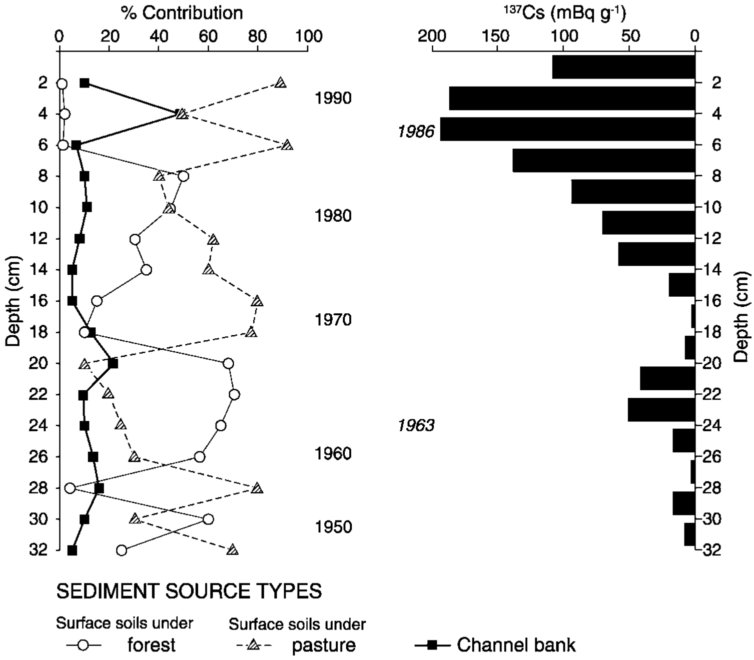

**Figure 10** Longer-term variations in the relative contributions from individual sediment source types in the Upper Severn catchment, UK
*Source*: adapted from Collins *et al.* (1997d).

reconstruct longer-term suspended sediment sources (Yu and Oldfield, 1989; Foster *et al.*, 1998; Owens *et al.*, 1999; Rowan *et al.*, 1999; Owens and Walling, 2002). Collins *et al.* (1997c), for example, used a composite fingerprinting technique in combination with a $^{137}$Cs core chronology to investigate the longer term spatial provenance of suspended sediment in the Exe basin, UK. The results provided clear evidence for a perturbation in the typical spatial source of suspended sediment owing to an increased contribution from the Devonian rocks in the north of the catchment, resulting from a series of extreme precipitation events on Exmoor in 1960 (see Figure 9). Collins *et al.* (1997d) used a similar approach to investigate longer term sediment source types in the Upper Severn catchment, UK (see Figure 10).

Sediment profiles preserved in caves have been used as a means of assembling information on longer term sediment sources in areas where environmental change, e.g., glaciation, has reworked or removed sediment deposits from the wider environment (Bottrell *et al.*, 1999; Woodward and Bailey, 2000). Woodward *et al.* (2001) report the use of a quantitative composite fingerprinting technique to investigate the provenance of historical slackwater deposits in a rockshelter in the Pindus Mountains, Greece.

Employing the fingerprinting approach to evaluate longer term suspended sediment sources must, however, be qualified in relation to a number of potential problems and limitations. A reliable core chronology (e.g., using $^{137}$Cs or unsupported

$^{210}$Pb measurements) must be established. The selection of representative sediment coring sites is difficult because the spatial variability of geochemical properties in sediment deposits typically exceeds downcore variability (Foster and Charlesworth, 1994; Macklin *et al.*, 1994) because of natural sorting and selective deposition and the resulting nonsynchroneity of core profiles (Oldfield *et al.*, 1999). It is therefore advisable to collect and measure a number of sediment cores. Parameter transformation, whereby downcore variations in fingerprint property concentrations reflect physico-chemical translocation and pedogenesis as opposed to fluctuations in sediment provenance represents a potential problem (Collins *et al.*, 1997d). Equally, properties characterized by marked temporal patterns in their release to the environment or *in situ* decay (e.g., $^{137}$Cs) cannot be used as fingerprint properties on account of their downcore variations corresponding with such behaviour rather than changes in sediment sources. The findings based on floodplain cores reflect the provenance of suspended sediment during overbank floods only, but floodplain deposits should, nevertheless, be more generally representative of the sediment transported by a river because floods causing overbank inundation typically account for a significant proportion of the total suspended sediment flux.

## VI Perspective

Reliable confirmation of the nature and relative significance of catchment suspended sediment sources represents an important prerequisite to understanding fluvial sediment delivery systems and for assisting the development of targeted erosion management and pollution control strategies. Documenting the provenance of fluvial suspended sediment is, nevertheless, highly problematic.

Catchment suspended sediment sources can be documented using indirect and direct approaches. Given the spatial and temporal complexity of sediment mobilization and delivery, investigations of suspended sediment provenance are typically constrained by problems of representativeness and cost. The scope for employing many techniques of erosion measurement is therefore especially restricted. Although recent advances in data acquisition afforded by PEEPs, remote sensing or GPS systems and digital photogrammetry have helped to reduce such problems, these measurement techniques take no account of the off-site factors governing source–river coupling and the uncertainties in relating estimates of sediment mobilization *in situ* and sediment transport in river channels without supportive information on sediment routing. In the absence of information on the catchment sediment budget, the provenance of suspended sediment loads can only be inferred on the basis of upstream erosion data. The erosion of suspended sediment sources is often simultaneous during rainstorms and the individual portions of a catchment can be expected to release fine material at different rates in response to corresponding variations in the magnitude of the factors of resistance governing sediment mobilization and transfer. It is therefore frequently necessary to assess the simultaneous relative contributions from a number of potential sediment sources. Clearly, this requirement further compounds the sampling problems and costs associated with the measurement techniques underpinning an indirect approach to sediment source assessment. Consequently, it is typically only viable to target the monitoring of a particular sediment source and the contribution from additional sources must therefore be estimated.

Because of the numerous problems associated with the conventional indirect approach to investigating catchment suspended sediment sources, sediment fingerprinting has attracted increasing attention as an alternative means of assembling such information. Sediment fingerprinting uses a range of geochemical properties to link catchment source material and suspended sediment samples and therefore circumvents the need for complementary information on sediment delivery. Many of the sampling constraints and operational difficulties hampering erosion measurements are avoided and the simultaneous relative significance of a number of suspended sediment sources is easily confirmed. Source fingerprinting procedures afford a useful means of investigating different types of sediment sources in numerous environments and are appropriate for addressing a range of catchment management issues. Additionally, and perhaps uniquely, the fingerprinting approach can be used to reconstruct longer-term changes in suspended sediment sources. Sediment fingerprinting must clearly be seen as a highly attractive alternative to the traditional indirect approach to establishing catchment suspended sediment sources.

The prospects for advancing existing understanding of catchment suspended sediment sources appear reasonably promising. Technological progression is likely to continue improving the temporal and spatial resolution of erosion measurement procedures based on surveying, remote sensing or photogrammetric techniques. Reliable interpretation of the probable sources of suspended sediment transport in terms of the data acquired by such means will, however, continue to require supportive information. Recent advances in sediment budgeting should prove useful in this respect, but place additional and potentially exhaustive demands on resources. By virtue of this important shortcoming of an indirect approach to sediment sourcing, geomorphologists should endeavour to apply sediment fingerprinting more widely. Although its wider adoption as a conventional methodology is clearly dependent upon the development of more generic procedures, the fingerprinting approach represents a highly valuable tool for investigating suspended sediment sources. Scope remains for exploiting this potential.

The spatial heterogeneity of the on-site and off-site factors governing sediment mobilization and delivery necessitate the use of distributed modelling. Progress in computing and model development have, however, exceeded advances in data collection methods and it is commonly neither financially nor technically viable to assemble the input or validation data required for existing models. Recent advances in digital data collection techniques are helping to resolve these problems, but there is considerable scope for exploiting the potential afforded by sediment fingerprinting. In addition, attention should be directed towards improving process-based representations of bank erosion and sediment remobilization from secondary sediment sources as well as the evaluation of soil erodibility coefficients in relation to measurable soil properties. Distributed models must become more user-friendly in order to reduce training requirements. Model output frequently needs to be partitioned in order to reveal the relative importance of individual sediment sources.

Future work aimed at assembling information on suspended sediment sources should place greater emphasis on data validation and reconstruction of longer-term trends. The scientific credibility of sediment sourcing studies will undoubtedly benefit in this manner. Detailed examination of the relative importance of primary and secondary sediment sources is required as a means of further elucidating the complexity of sediment mobilization and delivery in river basins. There is considerable scope for integrating existing measurement and modelling techniques. An integrated approach will enable fluvial geomorphologists to continue addressing important scientific and management agendas.

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