PROVENANCE OF INTERSTITIAL SEDIMENT RETRIEVED FROM SALMONID SPAWNING GRAVELS IN ENGLAND AND WALES:

A Reconnaissance Survey Based on the Fingerprinting Approach

R&D Technical Report W2-046/TR3

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 ISBN 1844320588

Dissemination Status
Internal: Released to Regions
External: Released to Public Domain

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This report describes the findings of a reconnaissance investigation, based on the use of the fingerprinting approach. The study aimed at assembling information on the relative importance of surface and channel/subsurface sources in accounting for the provenance of interstitial fine sediment samples retrieved from the salmonid spawning gravels in 18 rivers in England and Wales. The report will be of interest to Agency staff and others involved in the management of riverine salmonid fisheries.

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EXECUTIVE SUMMARY

The siltation of spawning gravels has been increasingly cited as an important cause of the declining success of salmonid fisheries reported for many years in England and Wales. Existing remedial measures, including gravel cleaning and the use of egg boxes for restocking, typically yield short-term benefits and are constrained by cost and practical difficulties. It is therefore generally recognised that programmes aimed at preventing or reducing siltation afford a more appropriate and sustainable management strategy for addressing the problem.

The implementation of effective strategies for the prevention or reduction of spawning gravel siltation is heavily dependent upon an understanding of the source of the increased fine sediment loadings in those river basins where the siltation of salmonid spawning gravels represents an environmental problem. Without reliable information on sediment provenance, the resources available for preventing or reducing the siltation of spawning gravels cannot be properly targeted.

Assembling accurate information on catchment sediment sources represents a difficult task, because of the limitations and uncertainties associated with traditional measurement and monitoring procedures. Due to these constraints, the fingerprinting approach is increasingly recognised as an alternative indirect method for establishing the source of the sediment transported by a river.

Given the need to develop sediment control strategies for salmonid spawning gravels, this report presents the findings of a reconnaissance investigation, based on the use of the fingerprinting approach, aimed at assembling information on the relative importance of surface and channel/subsurface sources in accounting for the provenance of interstitial fine sediment samples retrieved from the salmonid spawning gravels in 18 rivers in England and Wales.

The findings verify the utility of the fingerprinting approach for investigating the source of interstitial fine sediment accumulating in salmonid spawning gravels. The primary source of the interstitial sediment collected from the study rivers was found to vary regionally in response to a number of controls. For example, channel banks are important sediment sources in the south-west of England and south Wales, where river channels are heavily incised and the trampling and degradation of channel margins of livestock is common. Surface sources are more important in the chalklands of southern England, where the widespread cultivation of autumn sown cereals and the absence of hedges combine to increase both the rates of topsoil erosion and the efficiency of sediment transfer to the stream network. Similarly, the pressure of grazing and tourism on the open upland landscapes of the study rivers of northern England and mid Wales encourage sediment production from surface soils, whilst mixed farming promotes soil loss from cultivated and uncultivated areas in the study catchments of north Wales.

Further work is required to provide a more rigorous assessment of countrywide variations in sediment sources. However, it is important that the implications of these preliminary findings should be recognised by the authorities and stakeholders responsible for developing strategies for controlling and reducing the degradation of salmonid spawning gravels by siltation. Control of sediment mobilisation from surface sources will clearly require a different approach to control of bank erosion and degradation.

KEY WORDS
Salmon, trout, spawning, gravels, redds, sediment, siltation, land use.

1 INTRODUCTION

Siltation of spawning gravels has frequently been cited as one of the principal factors responsible for the declining success of salmonid fisheries in a number of rivers throughout England and Wales (Turnpenny and Williams, 1980; Olsson and Persson, 1988; Acornley and Sear, 1999). River bed siltation degrades benthic habitats and has been shown by a number of field (Lisle, 1989; Platts *et al.*, 1989; Sear, 1993) and laboratory (Beschta and Jackson, 1979; Diplas and Parker, 1992) studies to have a detrimental impact upon spawning redds. For example, Heaney *et al.* (2001) demonstrated that a 10% loading of fine sediment (<2 mm) reduced egg-to-fry survival from 32% to 9%, whilst a 15% loading caused a mortality rate of 97%.

Gravel beds supporting salmonid fisheries naturally exhibit a bimodal grain size distribution consisting of a coarse framework and fine sediment, which fills the interstitial spaces. The presence of elevated quantities of fine interstitial sediment, however, has serious consequences for the aquatic habitat, because sediment composition affects two critical properties of spawning gravels, permeability and porosity (Carling and McCahon, 1987).

Permeability controls the delivery rate of dissolved oxygen and the subsequent removal of carbon dioxide and metabolic waste. Both of these factors strongly influence egg-to-hatching success and are adversely affected by the excessive accumulation of fine interstitial sediment (Hausle and Coble, 1976; Iwamoto *et al.*, 1978; Carling, 1985). Although salmonids naturally remove fine-grained sediment during redd construction, evidence for the efficiency of this process remains contradictory. Crisp and Carling (1989), for example, found no significant reduction in the percentage of fines (<1 mm) in redds compared to the surrounding gravel bed, whilst Kondolf *et al.* (1993) reported the opposite. Furthermore, redd construction commonly causes kinematic sieving which permits fines to sink deeper into the nest, resulting in the siltation of eggs at the basal interface (Middleton, 1970; Rosato *et al.*, 1986).

Porosity is an important factor controlling the intragravel movement and eventual emergence of alevins (Phillips *et al.*, 1975; Crisp, 1993). Siltation causes smothering and concretion of the spawning substrate, thereby preventing the emergence of fish into the overlying water column. The accumulation of high quantities of fine interstitial sediment in the gravel bed matrix also reduces the numbers and diversity of benthic invertebrates, which represent an important food source for salmonids (Scullion, 1983; Sear, 1993).

A range of remedial measures is currently employed to counteract the detrimental impact of river bed siltation upon salmonid spawning. These include gravel substrate cleansing, egg box installation and artificial re-stocking. Gravel cleansing or restoration commonly involves tractor rotavating and either high pressure jet or pump washing (Reeves *et al.*, 1991; Shackle *et al.*, 1999; Heaney *et al.*, 2001). Secondary siltation is, however, frequently experienced due to the disturbance of the channel during these gravel cleaning operations. Alternatively, egg boxes are being installed to assist spawning success rates in the upper reaches of several important salmonid rivers and these are often employed in association with artificial re-stocking programmes. Elsewhere, clean gravel deposits have been artificially introduced into stream channels as a means of improving spawning habitat quality. Such remedial actions, are, nevertheless, typically short-term, due to the associated prohibitive financial costs, logistical difficulties and high demands on labour and time.

It is now recognised that a programme of prevention rather than cure is required to address the spawning gravel siltation problem. In order to prevent the accumulation of elevated levels of fine interstitial sediment in the bed gravels of salmonid rivers, the key factors responsible for increased delivery of fine sediment and thus siltation rates in river catchments must be identified and appropriate management strategies implemented. A number of factors are currently held responsible for accelerated siltation rates in many of the rivers supporting salmonid fisheries in England and Wales (Shackle *et al.*, 1999). These include changes in agricultural practices such as a reduction in the use of water meadows which act as natural sediment traps, an increase in the area of arable cultivation and the shift from spring to autumn sowing of cereals which causes the soil to be compacted and smoothed prior to the winter rains, further increasing erosion; disturbances caused by channel maintenance works; a reduction in the frequency of natural flushing flows due to increased river regulation; reduced flows due to over-abstraction; and a decline in the cleaning of river beds e.g. harrowing. Yet, despite the numerous inferences made regarding, in particular, the importance of land use change, there has, to date, been no extensive survey of the origin of the fine-grained sediment causing the degradation of spawning gravels. Potential sources of interstitial fine sediment might include cultivated or grazed portions of river basins experiencing soil erosion or eroding channel banks. Information on the origin of interstitial fine sediment is, nevertheless, essential for underpinning the implementation of appropriate catchment management strategies which target control measures to those sources responsible for increased sediment mobilisation and subsequent sediment delivery to stream channels (Scrivener and Brownlea, 1989; O ’Connor, 1998; Shackle *et al.*, 1999; Heaney *et al.*, 2001). Thus, for example, efforts directed at controlling bank erosion and trampling of river banks by livestock could be misdirected, if the primary source of the increased sediment loading was cultivated fields.

Recent assessments of salmonid fish stocks undertaken by the Agency in 1997 and 2001 revealed that spawning levels in many rivers are below the critical threshold necessary to maintain healthy fisheries. Consequently, as part of its ongoing R&D programme, the Agency has undertaken a national survey of the spawning gravel siltation problem in England and Wales, as part of its National Salmon Management Strategy. In recognition of the urgent need for accurate and reliable information on the provenance of fine-grained interstitial sediment in spawning gravels, a key component of this research programme has involved a reconnaissance survey, based on the use of the sediment fingerprinting approach, to assemble such data for 18 important salmonid rivers. This comprises an investigation of the relative importance of surface soils under different land use and channel banks as the source of fine interstitial sediment collected from salmonid spawning gravels during an extensive river bed basket sampling programme conducted by the Agency. The principal findings are outlined in this report.

2 STUDY RIVERS

Interstitial sediment samples were collected from salmonid spawning gravels in a total of 18 rivers (see Figure 2.1). These catchments were selected to be representative of important salmonid rivers throughout England and Wales which are reported to be experiencing problems associated with the siltation of spawning gravels. For convenience, the study catchments can be divided into those located in the south-west, south and north of England and those in south/mid and north Wales.

2.1 Study Rivers in South-West England

Eight rivers (see Figure 2.1) were selected in south-west England, where there is serious concern regarding the declining spawning success of salmonids. Although the river Camel has consistently been amongst the most productive fisheries for salmon and sea trout in the south-west of England, a survey of juvenile salmon and trout fish stocks in 1997 revealed a considerable decline compared to the corresponding results for 1994 (Environment Agency, 2000a). Likewise, although the rivers Fal and Fowey have historically represented important spawning areas for salmon, brown trout and sea trout, recent surveys of these watercourses revealed declining stocks of such fish (Environment Agency, 2000b, 2000c). Similar problems are reported for the rivers Lynher, Plym, Tamar, Tavy and Yealm, which have traditionally supported successful salmonid fisheries along their entire courses (Environment Agency, 2000d). In response to these problems, some spawning gravel cleaning has already been initiated in the Lynher and Plym catchments (Environment Agency, 2000d).

2.2 Study Rivers in Southern England

The study rivers in the south of England were the Itchen, Kennet and Test (see Figure 2.1). Gravel bed siltation is widely recognised as an important factor responsible for a serious decline in the numbers of salmon and brown trout in both the Itchen and Test (Environment Agency, 2000e) and of the latter in the Kennet (Environment Agency, 2000f). Consequently, the Itchen and Test are now artificially stocked with rainbow trout and the Agency is working with the Centre for Environment, Fisheries and Aquaculture Science (CEFAS) to promote the use of salmonid egg boxes in important spawning and nursery areas along these rivers. In addition, the Agency is collaborating with the Wild Brown Trout Society on a spawning habitat enhancement project comprising gravel cleaning, river shallowing and bank narrowing, whilst attention is also being directed towards the identification of key siltation pathways (Environment Agency, 2000e).

2.3 Study Rivers in Northern England

Spawning gravel siltation is increasingly recognised as a principal factor contributing to recent declines in the local populations of salmon, sea trout and brown trout in the rivers Esk and Ribble (Environment Agency, 1999a, 1999b). Such decline is a major cause for concern, because these rivers have traditionally supported two of the best salmonid fisheries in northern England (Environment Agency, 1999a, 1999b). In response to the siltation problem in the Ribble valley, the Agency is working with local angling clubs and the Ribble Fisheries Association to clean spawning gravels and to introduce fresh gravels downstream of reservoirs (Environment Agency, 1999b). Because of declining natural fish populations, some artificial re-stocking is now undertaken in the river Ribble (Environment Agency, 1999b).

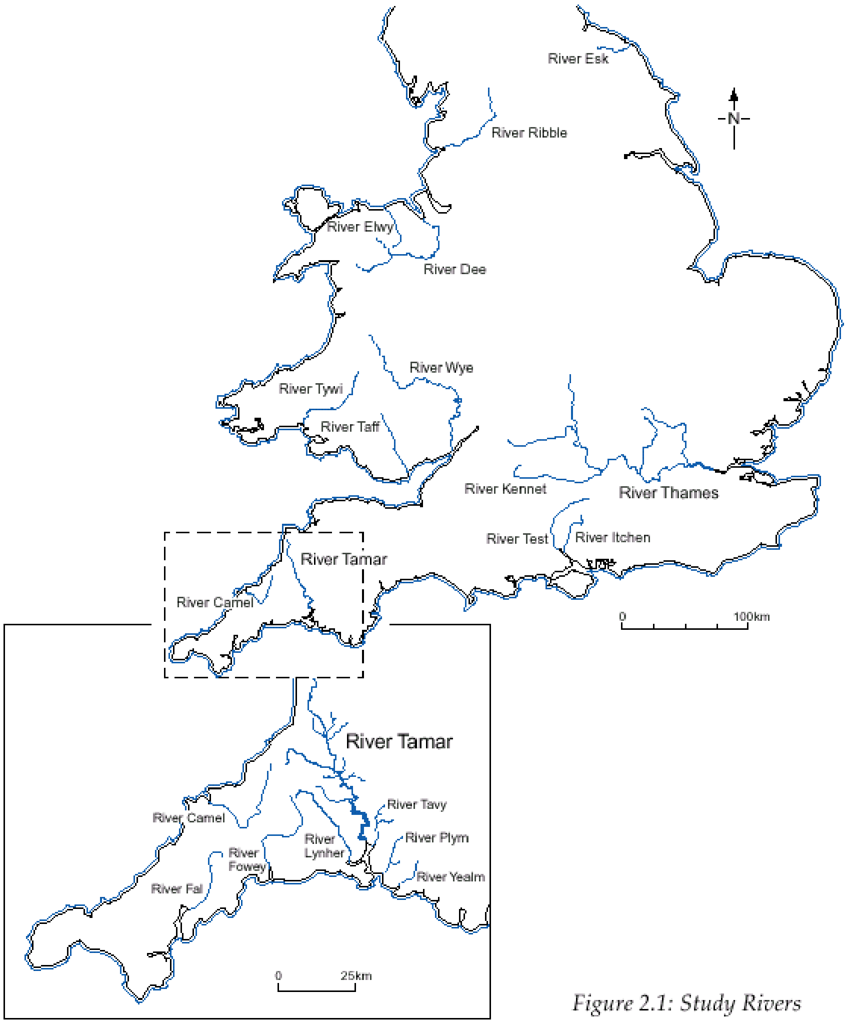

Figure 2.1: Study Rivers

2.4 Study Rivers in South/Mid Wales

Gravel bed siltation is also reported as having a detrimental impact upon the spawning success of salmonids in several rivers of south and mid Wales, where sharp declines in juvenile trout and salmon populations have been consistently recorded during the 1990s (e.g. Environment Agency, 1999c). Consequently, the rivers Taff, Tywi and Wye (see Figure 2.1) were included in the reconnaissance survey, in order to represent the premier salmonid fisheries of this region.

2.5 Study Rivers in North Wales

The rivers Dee and Elwy were selected to represent salmonid rivers in northern Wales experiencing the detrimental impact of spawning gravel siltation (see Figure 2.1). Local natural salmonid stocks have been below target in four of the last six years (Environment Agency, 1999d, 1999e) and are now closely monitored, e.g. by the Dee Stock Assessment Programme (DSAP) (Environment Agency, 1999d).

3 METHODOLOGY

3.1 The Approach

The procedure employed by this investigation comprised two key stages:

a) An assessment of the particle size composition of the interstitial sediment recovered from the bed gravels in each study catchment.
b) A reconnaissance sediment fingerprinting exercise to establish the provenance of the samples of interstitial sediment collected from each study catchment.

3.2 Collection of the Samples of Interstitial Fine Sediment

Representative samples of interstitial fine sediment were collected from salmonid spawning gravels within each study river during a national fieldwork programme conducted by the Agency over the period 1999-2000. This exercise was based upon the use of retrievable sampling baskets designed by the Department of Geography at the University of Exeter, which were inserted in artificial redds constructed in the river bed at representative locations, in order to quantify the amount of fine sediment accumulating within the interstices of the bed gravel and to obtain representative samples of that sediment for subsequent use in a source fingerprinting investigation. Further discussion of the design, installation and operation of the sampling baskets is beyond the scope of this report but it is important to note two aspects. First, the baskets were filled with representative clean framework gravel from which fine sediment had been removed. Any fine sediment subsequently recovered from the basket after removal from the bed therefore represented fine sediment moving into or through the gravel framework. Since it has been argued that salmon naturally clean bed gravels during redd construction, the installation of a basket containing cleaned gravel into an artificial redd provides a direct measure of the accumulation of fine sediment in a redd after its construction and thus of the potential for ingress of fine interstitial sediment to impact upon the incubating eggs. Secondly, the sampling baskets incorporated an outer fabric sleeve which could be raised around the outside of the basket prior to its removal from the gravel, in order to prevent loss of the fine interstitial sediment that had accumulated within the trap after its emplacement (cf. Sear, 1993). The location of the sampling sites and the number of samples of interstitial fine sediment (total n =141) retrieved from each study river are summarised in Table 3.1.

Table 3.1: The location and number of interstitial sediment samples collected from each study catchment

Catchment	Tributary	Sampling site	NGR	No. of samples
Camel	Allen	Trehanick	SX066791	3
	main stem	Kenningstock	SX096807	3
Dee	Alyn	Burton	SJ358568	4
	Ceiriog	Graig	SJ233378	4
	Llafar	Pont-y-Llafar	SH893324	1
Elwy	main stem	Llangernyw	SH878674	2
Esk	main stem	Lealholm	NZ764076	3
	main stem	Glaisdale	NZ781055	3
	main stem	Grosmont	NZ826055	3
	main stem	Sleights	NZ863078	3
Fal	main stem	Tregony	SW922450	3
	main stem	Golden Mill	SW929468	5
Fowey	Cardinham	Margate Wood	SX101664	3
	Warleggan	Pantersbridge	SX158676	3
	main stem	Ashford	SX202661	3
	St. Neot	Pengelly	SX185654	1
Itchen	main stem	Lower Itchen Fishery	SU466175	6
	main stem	Winchester College	SU483288	6
Kennet	main stem	Freedmans Marsh	SU323635	4
	main stem	Eddington Mill	SU341693	4
	Lambourn	Welford	SU414726	4
Lynher	Deans Brook	Villaton	SX382623	3
	main stem	Bathpool	SX286749	3
Plym	Meavy	Clearbrook	SX526665	3
	main stem	Bickleigh	SX526618	3
Ribble	main stem	Manor Bridge	SD807727	1
	Long Preston Beck	Long Preston	SD841580	1
	main stem	Selside	SD793759	1
	Tems Beck	Giggleswick	SD811632	1
	main stem	Halton Bridge	SD852552	1
Taff	main stem	Hawthorn	ST088881	4
Tamar	Inny	Penpont Finches Bridge	SX260815	3
	Lyd	Foxcombe	SX477874	3
		Sydenham	SX429838	3
	Ottery	Canworthy Water	SX229917	3
	main stem	Crowford	SX289994	3
Tavy	main stem	Brookmill	SX477733	3
	main stem	Iron Bridge	SX511786	2
	Walkham	Grenofen	SX488709	3
Test	main stem	Bossington Dairy Bridge	SU337306	6
	main stem	Broadlands	SU356165	3
Tywi	Cennen	Glan-Cennen	SN619181	6
Wye	Marteg	Moelfre	SO002753	5
Yealm	Piall	Great Stert	SX599576	3
	main stem	Lotherton	SX595538	3
				Total = 141

3.3 Assessing the Grain Size Composition of Interstitial Fine Sediment Collected from Bed Gravels

Following collection and drying,all interstitial sediment samples were gently disaggregated and sieved through a 125µm mesh by Agency staff. This sediment source investigation focused upon fine-grained sediment (i.e. clay and silt), because research has demonstrated its important influence on gravel permeability and porosity (Crisp, 1993). Furthermore, due to the selectivity of drainage basin sediment delivery processes, coarser particles (>125µm) mobilised from catchment hill slopes are unlikely to reach river channels (Walling and Moorehead, 1989; Slattery and Burt, 1997; Walling *et al.*, 2000).

Any attempt to determine the relative importance of both surface and subsurface sources of interstitial sediment must therefore focus on the fine, rather than the coarse, fractions. Examination of the provenance of coarser material would effectively exclude surface soils as a potential source of interstitial sediment, because of the preferential deposition of coarse-grained particles during sediment transfer between distal areas of erosion on the catchment slopes and river channel. Consequently, coarser interstitial sediment is likely to be almost exclusively derived from the erosion of more proximal sources, such as channel banks or margins and upstream channel deposits. Although the findings of many investigations indicate that the <63µm fraction accounts for most of the eroded material delivered to river channels from surface sediment sources, this study selected a larger size fraction (<125µm) as a means of ensuring that the potential for supply of the coarser fractions of the fine interstitial sediment from proximal sediment sources was taken into direct consideration. Furthermore, use of the <125µm, as opposed to the <63µm fraction, reduced sample sieving times. In addition, there is some evidence to suggest that the <125µm fraction is most responsible for reducing the oxygen supply to fish embryos incubating in spawning gravels and is therefore most important from a fisheries perspective (Nicholls, 2000).

Because grain size composition is a fundamental sediment property which can also be employed as a useful preliminary indicator of the potential links between catchment sediment sources and interstitial sediment, the absolute particle size composition of all sediment samples was measured using a Malvern Mastersizer MS20 laser diffraction granulometer (see Plate 3.1). This analysis followed pre-treatment with hydrogen peroxide to destroy the organic fraction and chemical dispersion with sodium hexametaphoshate (McManus, 1988). Values of specific surface area ($m^2\ g^{-1}$) were calculated for individual samples using the particle size distribution and assuming spherical particles (cf. Figures 3.3 - 3.5).

Plate 3.1: The laser diffraction granulometer.

Table 3.2 presents a summary of the particle size characteristics of the interstitial sediment samples collected from each study river. Although three or more samples are available for most sampling sites, there are inevitably some instances where fewer samples were collected (e.g. for each site in the river Ribble). A degree of caution is therefore required when interpreting the representativeness of the particle size data for these particular sites, although it is important to note that a minimum of five samples was collectively available for each study catchment. Mean d_{50} values range from 7.42µm (river Dee at Burton) to 53.01µm (river Ribble at Giggleswick), whilst the mean percentage <2µm varies between 4.24% (river Fowey at Ashford) and 10.77% (river Dee at Burton), indicating that clay-sized material typically represents only a small proportion of the interstitial sediment samples. Values for the mean percentage of <63µm particles in the samples from individual sampling sites range from 48.98% (river Ribble at Manor Bridge) to 88.96% (river Elwy at Llangernyw). Clay-and silt-sized materials therefore consistently comprise a greater proportion of the interstitial sediment samples from the study catchments than the 63-125µm (i.e. sand-sized) fraction. The only exception is the river Ribble at Manor Bridge, where 63-125µm material represents 51.02% of the single interstitial sediment sample retrieved from this particular location. Overall, approximately 76% of the interstitial sediment sampled in all of the study catchments is <63µm and 24% is 63-125µm material. These data indicate that the interstitial sediment samples collected for this investigation can be meaningfully compared with both catchment surface and subsurface source materials, thereby underpinning the use of the fingerprinting approach.

Table 3.2: Summary of the particle size composition of the interstitial sediment samples (<125µm) collected from each study catchment

Catchment	Tributary	Sampling site	No. of samples	Mean d_{50} (µm)	Mean % <2 µm	Mean % <63 µm	Mean % >63 µm
Camel	Allen	Trehanick	3	20.93	4.67	75.11	24.89
	main stem	Kenningstock	3	19.82	5.76	77.28	22.72
Dee	Alyn	Burton	4	7.42	10.77	87.00	13.00
	Ceiriog	Graig	4	11.43	6.23	88.00	12.00
	Llafar	Pont-y-Llafar	1	12.76	5.71	86.93	13.07
Elwy	main stem	Llangernyw	2	12.60	6.45	88.96	11.04
Esk	main stem	Lealholm	3	8.55	9.99	87.06	12.94
	main stem	Glaisdale	3	9.59	8.77	86.83	13.17
	main stem	Grosmont	3	9.66	8.92	86.50	13.50
	main stem	Sleights	3	9.88	8.76	84.67	15.33
Fal	main stem	Tregony	3	28.23	6.45	70.77	29.23
	main stem	Golden Mill	5	25.68	6.04	71.77	28.23
Fowey	Cardinham	Margate Wood	3	12.25	5.84	83.95	16.05
	Warleggan	Pantersbridge	3	23.99	6.74	71.28	28.72
	main stem	Ashford	3	33.71	4.24	64.18	35.82
	St. Neot	Pengelly	1	12.72	6.04	83.47	16.53
Itchen	main stem	Lower Itchen Fishery	6	11.61	9.69	83.12	16.88
	main stem	Winchester College	6	19.17	10.69	79.90	20.10
Kennet	main stem	Freedmans Marsh	4	45.35	5.79	54.47	45.53
	main stem	Eddington Mill	4	31.25	7.96	71.09	28.91
	Lambourn	Welford	4	29.49	8.26	70.11	29.89
Lynher	Deans Brook	Villaton	3	14.28	7.40	79.90	20.10
	main stem	Bathpool	3	20.03	7.34	75.58	24.42
Plym	Meavy	Clearbrook	3	14.61	5.80	82.92	17.08
	main stem	Bickleigh	3	21.32	7.77	73.89	26.11
Ribble	main stem	Manor Bridge	1	31.31	4.33	48.98	51.02
	Long Preston Beck	Long Preston	1	33.99	7.23	62.21	37.79
	main stem	Selside	1	35.74	6.46	65.40	34.60
	Tems Beck	Giggleswick	1	53.01	8.41	61.43	38.57
	main stem	Halton Bridge	1	40.26	5.48	56.10	43.90
Taff	main stem	Hawthorn	4	11.16	8.35	79.79	20.21
Tamar	Inny	Penpont Finches Bridge	3	25.93	5.98	69.73	30.27
	Lyd	Foxcombe	3	15.97	7.21	79.67	20.33
		Sydenham	3	18.40	7.93	75.32	24.60
	Ottery	Canworthy Water	3	13.27	7.23	83.70	16.30
	main stem	Crowford	3	20.15	7.48	74.74	25.26
Tavy	main stem	Brookmill	3	16.76	6.27	78.76	21.24
	main stem	Iron Bridge	2	30.72	6.97	66.20	33.80
	Walkham	Grenofen	3	18.12	5.06	76.29	23.71
Test	main stem	Bossington Dairy Bridge	6	18.27	9.38	81.30	18.70
	main stem	Broadlands	3	21.69	9.03	74.67	25.33
Tywi	Cennen	Glan-Cennen	6	35.86	5.78	64.06	35.94
Wye	Marteg	Moelfre	5	12.62	6.37	88.69	11.31
Yealm	Piall	Great Stert	3	16.20	6.99	80.66	19.34
	main stem	Lotherton	3	12.16	6.66	84.10	15.90

3.4 Fingerprinting the Source of Interstitial Sediment

3.4.1 The basis of the fingerprinting technique

The basis of using the fingerprinting approach to determine the provenance of fine-grained interstitial sediment in spawning gravels is summarised in Figure 3.1. Precipitation and runoff cause the erosion of sediment from surface and subsurface sediment sources within a catchment and some of the mobilised material is subsequently routed to the river channel where it contributes to the suspended sediment load. Due to a number of factors, including flocculation, velocity fluctuations and intra-gravel flows, a small proportion of the suspended load settles to the river bed and infiltrates the coarser gravel bed matrix (Frostick *et al.*, 1984; Lisle, 1989; Droppo and Stone, 1994). The physical and chemical properties of this interstitial sediment directly reflect its provenance. Sediment fingerprinting takes account of this natural sediment delivery system and involves two critical stages: firstly, the characterisation of potential sediment sources and the interstitial fine sediment recovered from the gravel beds using a range of physical and chemical properties or fingerprints, and secondly, comparison of these fingerprints to determine the relative contributions from the individual sources to the interstitial sediment (Walling *et al.*, 1993, 1999; Walling & Woodward, 1995; Collins *et al.*, 1996, 1997a, 1998, 2001; Russell *et al.*, 2001). The first stage is dependent upon the selection of a suite of diagnostic properties, which are capable of discriminating potential sediment sources in an unequivocal manner. A quantitative sediment mixing model is normally employed during stage two.

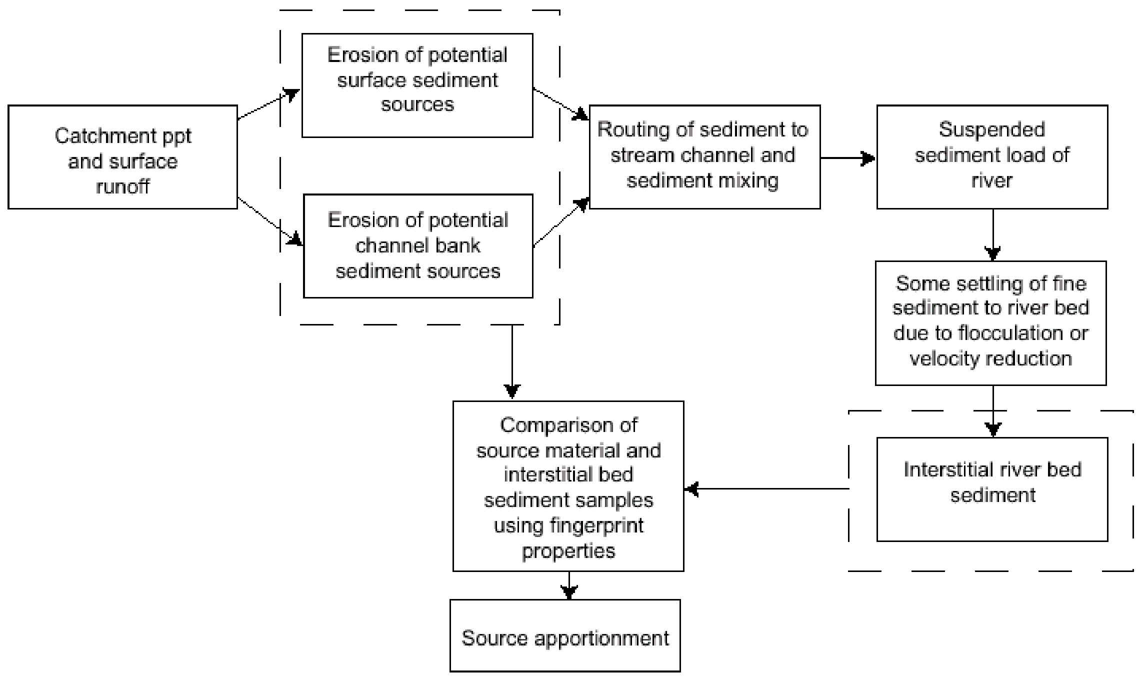

Figure 3.1: The basis of employing the fingerprinting approach to establish the provenance of interstitial fine sediment recovered from spawning gravels

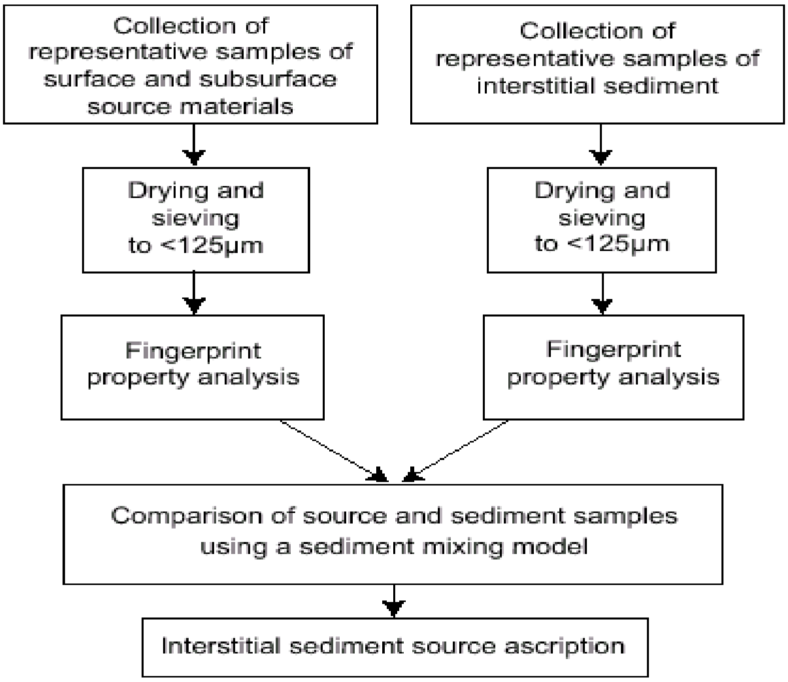

Figure 3.2: The procedure for using the fingerprinting approach to establish the provenance of interstitial fine sediment

Use of the fingerprinting approach offers a number of advantages for determining the provenance of fine-grained interstitial sediment.In the first instance,sediment fingerprinting overcomes many of the sampling constraints, operational problems and uncertainties associated with the use of traditional measurement and monitoring techniques currently available for establishing sediment origin through direct means, including deployment of erosion pins, runoff troughs and profilometers (Peart & Walling, 1988; Loughran & Campbell, 1995). Secondly, sediment fingerprinting can be used simultaneously to assess the relative contributions from a number of potential sources. To date, the approach has been successfully employed to determine the relative importance of different categories of sediment source over a variety of temporal scales. For example, it has proved possible to establish the relative contributions from either individual source types (surface soils under different land use and channel banks) or spatial sources (contrasting geological zones or tributary sub-catchments) to the contemporary sediment flux of rivers (Walling & Woodward, 1995; Collins *et al.*, 1997b, 1998; Walling *et al.*,1999; Bottrill *et al.*, 2000) and to longer-term sediment deposits collected from river floodplains (Collins *et al.*, 1997c, 1997d) or lakes (Foster & Walling, 1994). Given such success, the fingerprinting approach would appear to offer considerable potential for investigating the provenance of fine-grained interstitial sediment in salmonid spawning gravels.

3.4.2 Using sediment fingerprinting

Figure 3.2 summarises the key stages comprising the use of the fingerprinting approach to quantify the relative contributions from individual source types to the samples of fine-grained interstitial sediment retrieved from salmonid spawning gravels.

Collection of catchment source material samples

Source material sampling was stratified to encompass the principal potential surface and subsurface sediment sources identified within each study catchment, because this investigation was primarily concerned with assessing the relative importance of surface and channel bank erosion as the provenance of the interstitial sediment collected from salmonid spawning gravels. All samples were collected with a stainless steel trowel. In the case of surface source material collected from different land use categories, sampling involved the collection of top soil (upper 2cm) susceptible to erosion and subsequent transport to the river, whilst for channel banks (i.e. subsurface sediment sources) sample collection was directed to the faces of erosion scars supplying sediment to the adjacent stream. Because the study involved a total of 18 catchments, this sampling programme was necessarily undertaken at a reconnaissance level. Replicate source material samples were, nevertheless, collected in order to characterise the geological and pedological variability of each source and therefore to ensure the representativeness of the corresponding fingerprint property data sets. Table 3.3 summarises the sample numbers (total n = 672) collected from each potential sediment source within each study catchment.

Table 3.3: The total number of samples collected from each potential sediment source within each study catchment

Catchment	Sediment source					
	Moorland	Rough pasture	Woodland/ forest	Cultivated	Pasture	Channel banks
Camel	-	8	11	10	10	10
Dee	-	-	7	9	7	8
Elwy	-	-	8	7	-	7
Esk	10	-	8	10	7	11
Fal	-	-	10	10	10	10
Fowey	10	-	10	10	10	9
Itchen	-	-	10	10	10	10
Kennet	-	-	10	10	10	10
Lynher	-	-	9	8	9	8
Plym	8	-	7	7	-	8
Ribble	9	-	8	8	-	8
Taff	-	-	11	11	-	10
Tamar	-	-	11	11	9	12
Tavy	8	-	8	9	-	9
Test	-	-	10	10	10	10
Tywi	-	10	10	10	-	10
Wye	-	-	10	10	-	10
Yealm	8	-	7	8	8	8
						Total = 672

Laboratory analysis of fingerprint properties

Samples of interstitial sediment were initially returned to Agency offices and dried and sieved, before being forwarded to the University of Exeter. Upon arrival at the laboratory in the Department of Geography at the University of Exeter, all source material samples were oven dried at 40ºC. Prior to laboratory analysis, the source material samples were disaggregated using a pestle and mortar and screened through a 125µm sieve in order to provide comparability with the interstitial sediment samples. During this exercise, the replicate samples collected for each source category within each study catchment were bulked into single composite samples and thoroughly mixed. This yielded a total of 80 bulked source material samples for fingerprint property analysis. Interstitial sediment samples were not bulked in the same manner, so that potential differences in the origin of interstitial sediment collected from different sampling sites associated with a particular river were taken into consideration.

A wide range of mineralogic, mineral-magnetic, geochemical, radiometric, organic and isotopic properties has been employed in sediment fingerprinting investigations (Collins, 1995; Walling & Collins, 2000). Many early studies were based upon single-component fingerprints, but problems of representativeness were frequently experienced with such an approach. For example, the use of an individual property frequently introduces spurious source-sediment matches, with the result that no single diagnostic property can reliably distinguish a number of potential sources (Yu & Oldfield, 1989; Walling *et al.*, 1993; Collins, 1995). As a means of addressing this problem, work at the University of Exeter has favoured the use of composite fingerprints, comprising a range of different fingerprint properties. Composite fingerprints maximise the effectiveness of the fingerprinting approach by using individual properties influenced by differing environmental controls and which are therefore characterised by a substantial degree of independence. Such an approach ensures that in combination, the properties afford reliable sediment provenance discrimination and allow more sources to be distinguished. On the basis of this reasoning, the composite fingerprints employed in recent studies have comprised different combinations of mineral-magnetic, geochemical, radiometric and organic properties (Walling *et al*., 1993, 1999; Walling & Woodward, 1995; Collins *et al*., 1996, 1997a, 1998, 2001).

The reconnaissance nature of this study precluded the use of such an extensive suite of fingerprint properties. As a result, based on previous experience at the University of Exeter and in view of the emphasis on distinguishing surface and subsurface sediment sources within the study areas, the properties employed in this investigation comprised a combination of organic (C, N) and radiometric (^{137}Cs, unsupported ^{210}Pb, ^{226}Ra) properties.

Organic constituents are commonly preferentially associated with surface materials and therefore provide a useful means of discriminating top soil and channel bank sediment sources (Walling & Kane, 1984; Walling et al., 1993; Peart, 1993, 1995). Land use practices can also cause appreciable differences in the concentrations of organic substances in surface soils because, for example, repeated tillage lowers the organic matter content of arable soils compared to pasture or woodland, whilst channel banks frequently exhibit lower organic matter concentrations than top soil.

Fallout radionuclides (i.e. ^{137}Cs and unsupported ^{210}Pb) are partcularly useful as sediment fingerprints because their labelling is consistent over large areas and their environmental behaviour, whilst effectively independent of lithology and pedology, is strongly influenced by land use (Walling & Woodward, 1992; Loughran & Campbell, 1995). Fallout radionuclide concentrations are typically lower in cultivated than uncultivated topsoil, because tillage mixes fallout evenly within the plough layer, whilst channel banks frequently exhibit very low concentrations because their vertical surfaces result in only limited receipt of such substances. Consequently, fallout radionuclides have proved extremely useful for distinguishing individual sediment source types (Walling & Woodward, 1992; He & Owens, 1995). Ra-226, a naturally occurring geogenic radionuclide was also employed, since its measurement was necessary in order to determine unsupported ^{210}Pb activity and because it has proved useful in discriminating potential sediment sources.

Concentrations of C and N in the catchment source material and interstitial sediment samples were determined using a CE Instruments NA2500 elemental analyser, shown in Plate 3.2. Fallout radionuclide concentrations were measured by gamma spectrometry using high-resolution N-type HPGe detectors linked to a multi-channel analyser and PC data collection system (see Plate 3.3). Count times were typically 80,000s. Radiometric measurements followed the procedures described by Joshi (1987) and Walling & Quine (1993).

Plate 3.2: The elemental analyser

Plate 3.3: The gamma spectrometry laboratory

Data processing

The sediment mixing model

Following the laboratory analysis, the fingerprint properties of the source material and interstitial sediment samples from each study catchment were compared using the quantitative multivariate sediment mixing model described by Collins *et al*. (1997a). This mixing model assumes that the fingerprint property concentrations in any given sample of interstitial sediment reflect the corresponding concentrations in the original sources and the relative contributions of these sources to that sample. The sediment mixing model must satisfy two linear constraints:

a) The relative contribution from each potential source of interstitial sediment must lie in the range 0 to 1, i.e.:

$$0 \leq P_s \leq 1 \tag{1}$$

b) The sum of the relative contributions from all potential sources of interstitial sediment must equal 1, i.e.:

$$\sum_{s=1}^{n} P_s = 1 \tag{2}$$

A set of linear equations (see Equation 3) is established to compare the concentration of each individual fingerprint property measured in the source material and interstitial sediment samples for each study catchment. Because each set of linear equations is over-determined, optimised estimates of the relative contributions from individual sediment sources are established by minimising the sum of squares of the weighted relative errors, viz.:

$$\sum_{i=1}^{n} \left\{ \left(C_i - \left(\sum_{s=1}^{m} P_s S_{si} Z_s O_s \right) \right) / C_i \right\}^2 W_i \tag{3}$$

where:

C_i = concentration of fingerprint property ($_i$) in the interstitial sediment sample

P_s = the optimised percentage contribution from source category ($_s$)

S_{si} = concentration of fingerprint property ($_i$) in source category ($_s$)

Z = particle size correction factor for source category ($_s$)

O = organic matter content correction factor for source category ($_s$)

W_{i} = tracer specific weighting

m = number of sediment source categories

n = number of fingerprint properties

Running the sediment mixing model

The mixing model was executed using the Solver spreadsheet optimisation tool within Excel for Windows. A single value was used to represent the concentration of each individual fingerprint property within each sediment source category under scrutiny. This value, provided by laboratory analysis of the composite sample for each sediment source, reflects a mixture of discrete samples collected from a range of sampling points representative of each source potentially contributing to the interstitial sediment within a given study catchment and can thus be viewed as representative of that source.

Preliminary mixing model iterations attempted to discriminate between the fingerprint property concentrations measured for individual land use categories (i.e. surface sediment sources) and channel banks (i.e. subsurface sediment sources) within the study catchments. However, this approach proved unsuccessful.This was not unexpected, as previous experience with the fingerprinting approach has consistently demonstrated that a greater number of geochemical properties would normally be required to discriminate individual sediment source types classified on this basis (cf. Collins, 1995; Collins *et al.*, 1998; Walling & Collins, 2000). In consequence, the fingerprint property data for the surface soils under different land use within each study catchment were averaged to provide a single mean value representative of all potential surface sediment sources. This value was subsequently used with the corresponding value for channel banks in the mixing model, in order to quantify the relative contributions from surface and subsurface sediment sources. Careful examination of the raw fingerprint property data sets ensured that only those properties characterised by different values for surface and subsurface sediment sources within a given study catchment were included in the corresponding mixing model iterations. Other properties were removed because they fail to afford a means of discriminating the potential sediment sources under scrutiny and may therefore contribute to spurious source apportionment.

The particle size correction factor

Due to the well-documented relationship between grain size composition and the concentration of many chemical constituents of soil and sediment (Horowitz, 1991), there is a need to take account of potential differences in the particle size characteristics of source and interstitial sediment samples. In the absence of such consideration, it is impossible to compare directly values for the fingerprint properties of source and sediment samples. Figures 3.3 –3.5 compare the typical absolute particle size composition of the source and interstitial sediment samples collected from each study catchment. In some instances, interstitial sediment is finer than the corresponding catchment source material samples. For example, in the case of the Dee study catchment (see Figure 3.3b), interstitial sediment is typically characterised by a silt-clay ratio of 10.1,a d_{50} of 9.8µm and a specific surface area is 0.4910m^2 g^{-1}, whilst the corresponding values for local source materials are 11.5,11.2µm and 0.4399m^2 g^{-1}, respectively. Similarly,the typical interstitial sediment sample retrieved from the Taff study catchment is characterised by a silt-clay ratio of 8.6,a d_{50} of 11.2µm and a specific surface area of 0.4829m^2 g^{-1}, compared with values of 8.8,19.1µm and 0.4014m^2 g^{-1} for the typical catchment source material sample (see Figure 3.4f). In most cases, however, interstitial sediment is coarser than the upstream catchment source materials. For instance, the sediment source samples from the Elwy study catchment are typically characterised by a silt-clay ratio of 10.3,a d_{50} of 8.7µm and a specific surface area of 0.5028m^2 g^{-1}, whilst the equivalent values for interstitial sediment are 12.8,12.6µm and 0.4139m^2 g^{-1}, respectively (see Figure 3.3c). Similarly, source materials from the Tavy study catchment are typically characterised by a silt-clay ratio of 9.3,a d_{50} of 17.3µm and a specific surface area of 0.4218m^2 g^{-1}, compared to equivalent values of 11.5,20.8µm and 0.3464m^2 g^{-1} for the interstitial sediment samples (see Figure 3.5b).

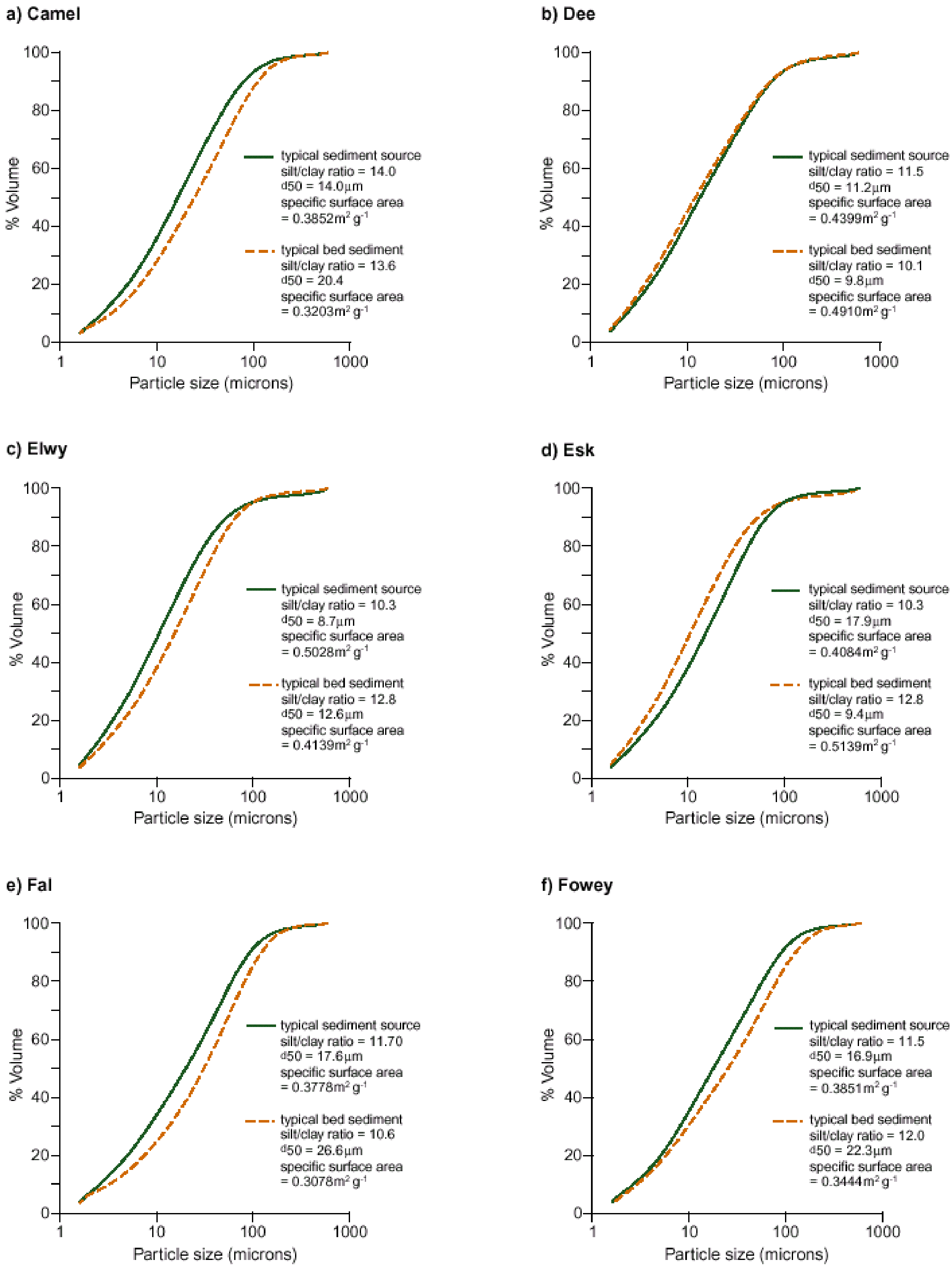

Figure 3.3: Comparison of the typical absolute particle size composition of source material and interstitial sediment samples

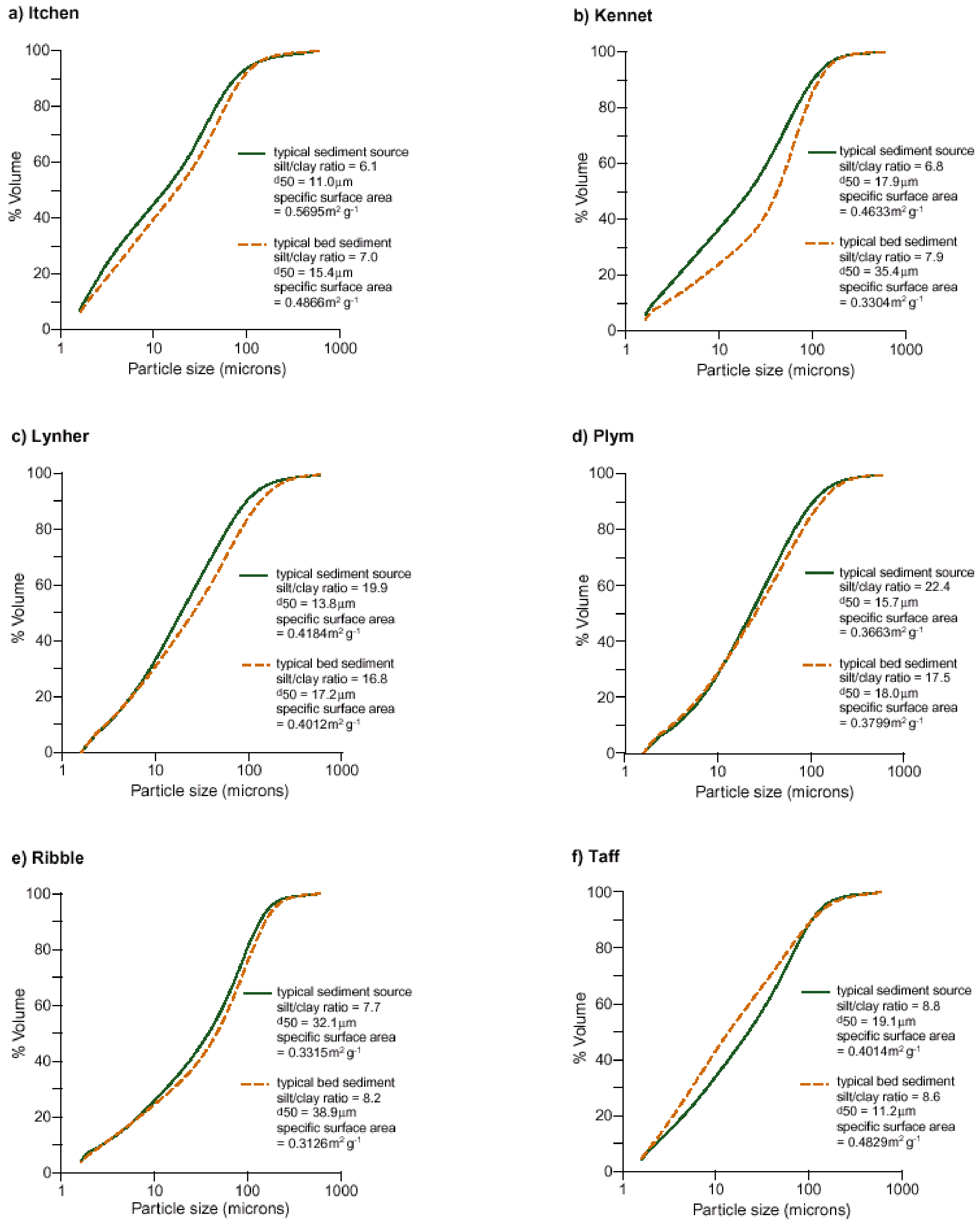

Figure 3.4: Comparison of the typical absolute particle size composition of source material and interstitial sediment samples

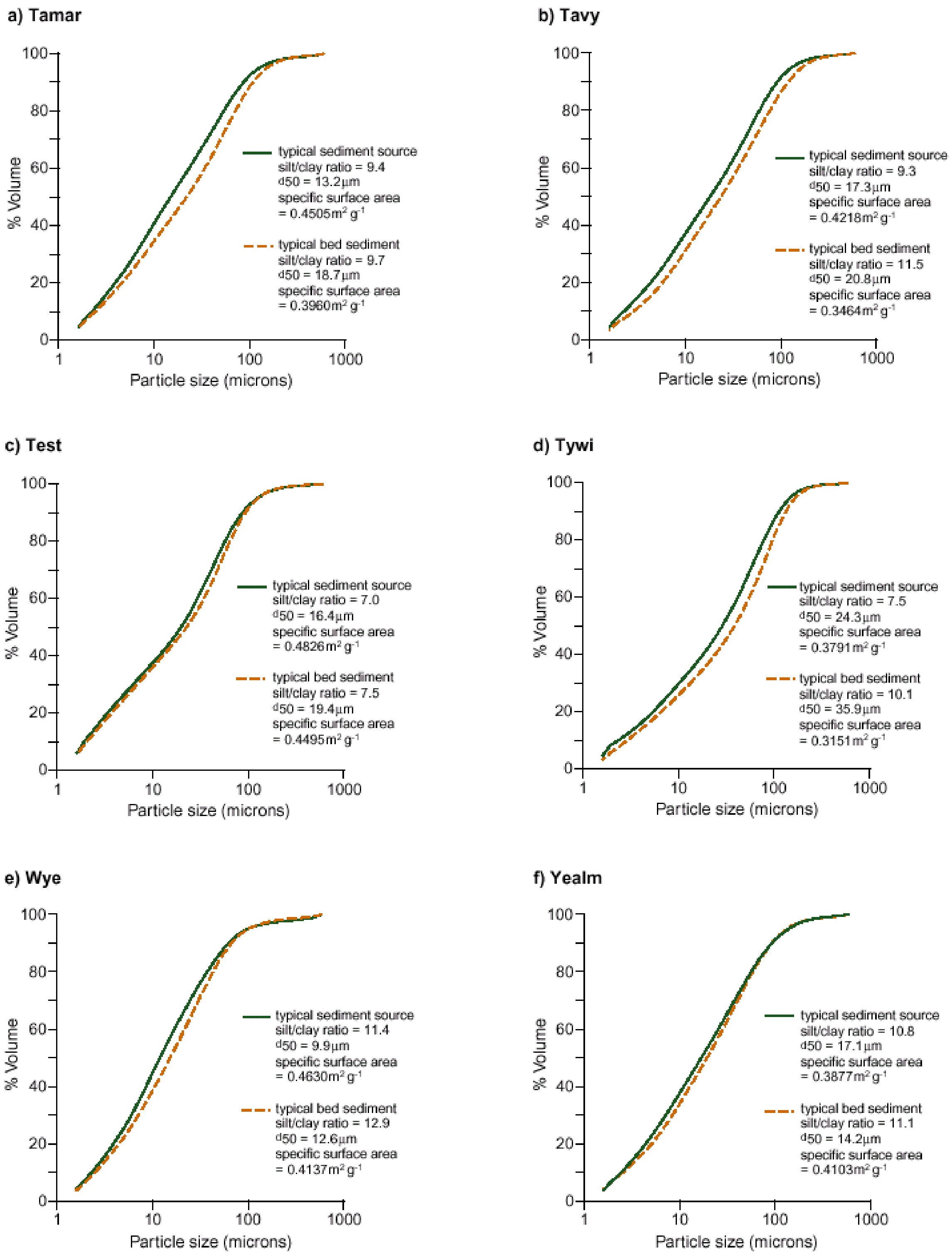

Figure 3.5: Comparison of the typical absolute particle size composition of source material and interstitial sediment samples

Although the influence of contrasts in particle size between the interstitial sediment and source material samples is partly addressed by restricting all analysis to material <125µm in diameter, a further correction factor is incorporated into the mixing model to compensate for differences in the grain size composition of this particular fraction of the source and interstitial sediment samples. The correction factor is based upon the ratio of the specific surface area (m^2 g^{-1}) of each individual interstitial sediment sample to the corresponding value for each source grouping (Collins *et al.*, 1997a). Specific surface area is employed because it represents one of the most useful surrogate measures of grain size composition and is widely understood to exert a powerful influence upon element concentrations (Horowitz, 1991). Although this approach does not take account of the precise relationship between specific surface area and values for each fingerprint property (cf. Russell *et al.*, 2001), it does, nevertheless, afford a convenient and effective means of permitting a meaningful comparison between source and interstitial sediment samples.

The organic matter correction factor

A similar procedure is also incorporated into the mixing model to take account of the potential influence of organic matter content upon fingerprint property concentrations (Horowitz, 1991). This correction factor utilises organic carbon content and is calculated in the same manner as the particle size correction (Collins *et al.*, 1997a). However it is important that the inclusion of this factor in combination with the particle size correction should be checked carefully, for each individual study catchment, in order to ensure that over-correction of the fingerprint property data is avoided (Collins *et al.*, 1997a). In this particular investigation, a combination of both correction factors was found to improve the comparability of the fingerprint property concentrations measured for the source material and interstitial sediment samples collected from seven of the eighteen study catchments. The mixing model iterations for the remainder of the study areas only included the particle size correction.

The fingerprint property weighting factor

The varying levels of precision associated with measurements of the five fingerprint properties are taken into account by the mixing model iterations using tracer specific weightings. These are calculated using the inverse of the square root of the variance associated with a set of standardised replicate laboratory measurements for each individual substance (Collins *et al.*, 1997a).

3 RESULTS

4.1 Study Rivers in South-West England

4.1.1 River Camel

Figure 4.1a presents the mean relative contributions of surface and subsurface sources to the interstitial sediment samples collected from the Camel study catchment.Channel bank erosion is the most important source of the interstitial sediment affecting local spawning gravels, contributing 97% of this sediment. Localised bank erosion is promoted by a number of factors, including ditching in the moorland areas of the upper Camel and widespread poaching and degrading of channel margins by livestock (Environment Agency, 2000a). The former problem can be readily observed near Trekeek (NGR SX113867) and the latter at both Slaughterbridge (NGR SX109855) and Fenteroon Bridge near Pencarrow (NGR SX104826). Erosion of top soils within the Camel study catchment contributes only 3% of the interstitial sediment sampled from this particular river. The cultivation of potatoes, brassicas and daffodils exposes bare soils on local steep slopes to the risks of water erosion, whilst poaching of surface soils by sheep and cattle increases the erosion of areas beneath pasture. Surface soil erosion is particularly evident in the Allen valley near Trehanick (NGR SX064795) and along the main stem of the Camel near Camelford (NGR SX098823).

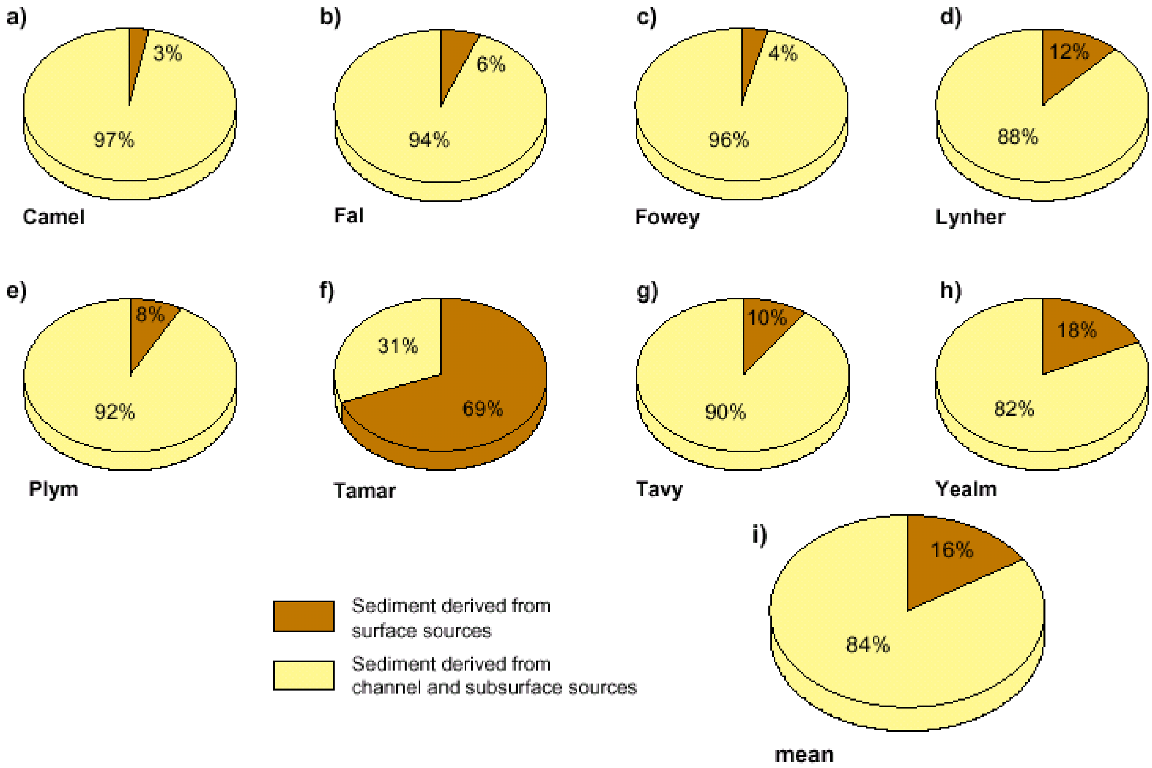

Figure 4.1: The typical provenance of interstitial sediment samples collected from study catchments in south-west England

In response to these problems of surface and subsurface erosion, the Agency is working with the Cornwall Farming and Wildlife Advisory Group (FWAG) to produce whole farm plans as a means of improving land management over extensive areas of the Camel valley. Much emphasis is currently being placed on collaborative fencing projects aimed at reducing the poaching of channel banks and the results of this sediment fingerprinting investigation clearly confirm the need to continue focusing attention upon minimising the erosion of subsurface sediment sources (i.e. river banks) within the Camel study area.

4.1.2 River Fal

Figure 4.1b provides information on the mean relative contributions of surface and subsurface sediment sources to the samples of interstitial sediment collected within the Fal study catchment. Channel bank erosion again represents the dominant source of interstitial sediment (94%), whilst topsoil erosion is of limited significance (6%). Widespread channel bank erosion occurs as a result of trampling by livestock and can be readily observed near Golden Mill (NGR SW928467). In addition, highway drainage is responsible for accentuating the disturbance of channel margins (Environment Agency, 2000b).

The erosion of surface sediment sources is caused by the exposure of soils on steep slopes to rainsplash, sheetwash and rilling by the cultivation of potatoes, brassicas, daffodils, wheat and barley, by overgrazing in moorland areas and during land disturbance caused by local forestry and mining activities (Environment Agency, 2000b). Steep roads in the upper Fal catchment provide efficient connectivity between catchment hill slopes and the river channel and therefore route the topsoil mobilised by erosion to the stream network.

These sediment fingerprinting data indicate that, if siltation problems on the river Fal are to be tackled effectively, the local Salmon Action Plan should, in particular, target the reduction of channel bank erosion. Such findings provide clear scientific support for the local collaborative channel margin fencing and reed bed regeneration projects currently being promoted by the Agency.

4.1.3 River Fowey

The results of the sediment fingerprinting exercise in the Fowey study catchment are shown in Figure 4.1c. Channel banks supply 96% and surface sources 4% of the interstitial sediment sampled from salmonid spawning gravels within this particular study area. The importance of channel bank erosion is consistent with the findings of a recent river habitat survey conducted by the Agency, which recorded severe poaching problems at 40% of the sites investigated along the river Fowey (Environment Agency 2000c). Such erosion is widespread because of channel margin trampling by livestock, ditching activities in the upper Fowey on Bodmin Moor and natural channel bank erosion and collapse during high magnitude flood events. Examples of severe bank erosion can be found near Trezibbet (NGR SX201754), Golitha Falls (NGR SX229689) and Warleggan (NGR SX147689). With respect to the severity of channel bank erosion in the Fowey study area, the fingerprinting estimates again provide clear support for the ongoing remedial action afforded by a number of local initiatives including fisheries fencing projects, the Bodmin Moor Project and various Countryside Stewardship Schemes (Environment Agency, 2000c). In addition, the importance of channel/subsurface erosion demonstrated by the sediment fingerprinting survey also underpins local work by the Agency and Cornwall FWAG aimed at promoting the development of permanent grassland swards along the Fowey riparian corridor.

Surface soil erosion also occurs in the Fowey catchment due to the exposure and mobilisation of topsoil as a result of overgrazing on Bodmin Moor and the increasing cultivation of crops, including wheat, in the lower reaches of the Fowey study area, e.g. near Redgate (NGR SX223683). In response to such erosion, the Agency is currently working in partnership with Cornwall FWAG to promote the adoption of whole farm plans and the development of riparian wetlands as means of reducing sediment delivery to the Fowey channel. Furthermore, a collaborative scheme between the Agency, the Fowey River Association, Cornwall County Council and the Highways Agency is addressing the potential for the localised siltation of spawning habitats in the upper Fowey resulting from improvements to the A30. However, the fingerprinting data clearly suggest that in relation to the siltation of spawning gravels, more attention and resources should be directed towards controlling channel margin, rather than topsoil, erosion.

4.1.4 River Lynher

Figure 4.1d summarises the typical relative contributionsfrom the erosion of surface soils and channel banks to the interstitial sediment samples collected from the Lynher study catchment. Erosion of topsoil contributes 12%, reflecting the impact of local land use intensification and change, e.g. in the Deans Brook portion of this particular study area (Environment Agency, 2000d). Changes in Deans Brook have primarily involved an expansion of the area of arable farming, which exposes surface soils to water-induced erosion during sowing periods in the autumn and spring. However, increased stocking levels are responsible for accentuating the erosion of surface soils beneath pasture in the headwater areas of the river Lynher, whilst woodlands supply sediment to the stream channel due to the erosion of footpaths and tracks associated with this land use category, e.g. near Rowse (NGR SX831646) and disturbances associated with with forestry management activities in the upper Lynher, e.g. at the Havana Plantation (NGR SX220790). The erosion of channel beds, nevertheless, represents the dominant source of the interstitial sediment collected from local salmonid spawning habitats, contributing 88%. Bank erosion is promoted by livestock degradation and natural channel erosion during flood flows and examples are found near Trebartha (NGR SX263777) and Rowse (NGR SX381646).

With respect to catchment management, the fingerprinting data demonstrate that channel habitat conservation works, undertaken under the Auspices of the Lynher project, involving both the Agency and Cornwall FWAG, should target the control of both surface and channel/subsurface erosion if the siltation of salmonid spawning gravels is to be reduced. In this respect, the project is already correctly addressing the need to reduce sediment delivery from both slopes and channel margins by promoting channel bank fencing, as well as the sowing of cover crops in arable fields.

4.1.5 River Plym

The typical mean relative contributions from the erosion of surface soils (8%) and channel banks (92%) in the Plym study catchment are presented in Figure 4.1e. Overgrazing by sheep and beef cattle on Dartmoor encourages the erosion of topsoil beneath moorland and pasture, whilst material eroded from surface soils in the plantation forests around Burrator Reservoir (NGR SX550690) is easily routed to the stream channel along the steep roads passing through this portion of the catchment. Bank erosion is observed at many locations, including Hoo Meavy (NGR SX525657) and Cavador Bridge (NGR SX555647), reflecting a combination of natural erosion during floods and channel margin disturbances by livestock.

In accordance with this information, the local Salmon Action Plan should primarily target the reduction of channel bank erosion, whilst also encouraging the use of some resources to control the erosion and delivery of topsoil in specific locations.

4.1.6 River Tamar

The mean results of the sediment source ascription undertaken for the Tamar study catchment are illustrated in Figure 4.1f. In contrast to the other study areas in south-west England, the results suggest that surface sources are dominant and that both surface and subsurface sources are important contributors to the siltation of local spawning habitats, contributing 69% and 31% respectively. A number of factors combine to account for the greater significance of topsoil erosion within this particular river basin. Stocking densities are amongst the highest in the UK in this area, thereby subjecting surface soils beneath pasture to severe poaching and subsequent erosion during rainstorms. Evidence for such problems can be found, for example, in the upper Tamar near Whitstone (NGR SX724983), in the Ottery tributary sub-catchment near Hendra (NGR SX205926), in the Lyd sub-basin near Lydford (NGR SX498855) and in the Inny sub-catchment near Tregunnon (NGR SX244827). Arable cultivation is more widespread in the areas drained by the river Tamar, especially in the Ottery and Inny sub-catchments, due to the much reported local agricultural land use change over recent years from pasture to arable cultivation of autumn-sown cereals (Environment Agency, 2000d). Such farming frequently results in accelerated soil erosion and sediment delivery to river channels during autumn and winter, especially in areas like the Tamar valley, where steep slopes are common and such sediment mobilisation and transfer coincides with the salmonid spawning season. Furthermore, connectivity between the Tamar channel network and hill slopes supporting arable farming, grazing or forestry/woodland is enhanced by the local road network, thereby accentuating the efficient delivery of sediment mobilised from surface sources to downstream watercourses. An example of such hill slope – channel coupling is found in the Lyd sub-catchment near Foxcombe (NGR SX478874).

The erosion of channel banks, nevertheless, also represents a significant source of the interstitial sediment samples collected from this particular study area. Examples of severe bank erosion are commonplace, including the upper Tamar near Crowford (NGR SX288988), along the Ottery tributary near Hendra (NGR SX203924), in the Lyd sub-basin near Sydenham (NGR SX441834) and along the Inny tributary near Trerithick (NGR SX244819). In many cases, banks collapse into the adjacent watercourse as a result of severe undercutting and destabilisation during high magnitude flood events.

These fingerprinting data demonstrate that, although the Agency is collaborating with the West Country Rivers Trust on the Tamar 2000 SUPPORT Project (**SU**stainable **P**ractices **P**roject **O**n the **R**iver **T**amar) to promote fencing of the riparian zone as a means of reducing bank erosion, increased attention should also focus on reducing soil erosion and attenuating sediment delivery from catchment hill slopes. Without the implementation of control measures targeting the reduction of surface soil erosion, spawning gravel siltation is likely to remain a serious problem for salmonid fisheries in the Tamar study area.

4.1.7 River Tavy

Figure 4.1g examines the mean relative importance of surface and subsurface sources of interstitial sediment collected from salmonid spawning habitats in the Tavy study catchment. As with the majority of the study areas in south-west England, channel bank erosion is dominant, contributing 90% of the sediment, whilstr surface soil erosion contributes 10%. Bank erosion is common throughout the study catchment and can be seen, for example, at Mary Tavy (NGR SX507789, Plate 4.1), Harford Brifge (NGR SX505768) and Hillbridge (NGR SX532804). Both moorland and improved pasture areas are widely poached due to grazing pressures, and topsoil in the upper Tavy on Dartmoor experience erosion due to the use of footpaths by tourists and ramblers. Roads and footpaths frequently provide linkages between eroding hill slopes and the channel network.

Plate 4.1: Channel bank erosion at Mary Tavy in the Tavy study catchment

4.1.8 River Yealm

For the interstitial sediment samples retrieved from the Yealm study catchment (see Figure 4.1h), eroding channel banks represent the dominant sediment source (82%), although eroding catchment topsoil also contributes a significant proportion (18%). Numerous examples of acively eroding channel banks can be found along the Yealm channel, including near Piall Bridge (NGR SX596605) and Popple's Bridge (NGR SX598544). The appreciable contribution from eroding surface soils reflects the severe poaching of moorland and pasture soils in the upper Yealm and the widespread soil loss experienced from the arable fields which dominate the lower portions of the study area. Footpaths and roads route sediment mobilised on local hill slopes to the channel network.

4.1.9 Summary

Overall, the mean relative contributions from surface and channel/subsurface sources of interstitial sediment for the study catchments in south-west England are 16% and 84% respectively, (see Figure 4.1I). These results emphasise that ctchment management plans dealing with salmonid spawning gravel siltation in this particular region need to concentrate upon the control of channel bank erosion. Similar findings have been reported by Nicholls (2000) for the neighbouring Torridge catchment. However, because surface soil erosion also contributes a significant proportion of interstitial sediment in the study catchments of south-west England, this source should not be ignored and local Salmon Action Plans must also endeavour to control the mobilisation and subsequent delivery of topsoil to river channels.

4.2 Study Rivers in Southern England

4.2.1 River Itchen

Figure 4.2a examines the mean mixing model results for the provenance of the interstitial sediment samples collected from the Itchen study catchment. Erosion of surface soils clearly represents the principal source (97%) of the sediment recovered from local spawning habitats. Much of this sediment is likely to originate from the extensive tracts of arable land which are used for growing wheat, barley and oilseed rape. The cultivation of fields for such crops permit the detachment of surface soils during rainstorms and the subsequent transport of sediment particles along the wheelings and footpaths in arable fields. In contrast, channel bank erosion contributes only 3% of the interstitial sediment sampled from the Itchen study catchment. Bank erosion is less significant because easily eroded well-defined vertical channel banks do not develop in the local geology, the channel margins are frequently protected by aquatic vegetation and macrophytes and the groundwater-dominated flow regimes of the rivers are far less flashy than those in more impermeable areas. Furthermore, trampling of channel margins by livestock is less common due to the higher frequency of arable land use. However, river bank poaching can be found in areas where livestock drink from the stream channel (Plate 4.2). These fingerprinting results underpin the need for the River Itchen Countryside Stewardship Scheme (Environment Agency, 2000e) to promote land management strategies which target the reduction of sediment delivery from hill slopes. Such policies should be given priority over those aimed at controlling river bank erosion.

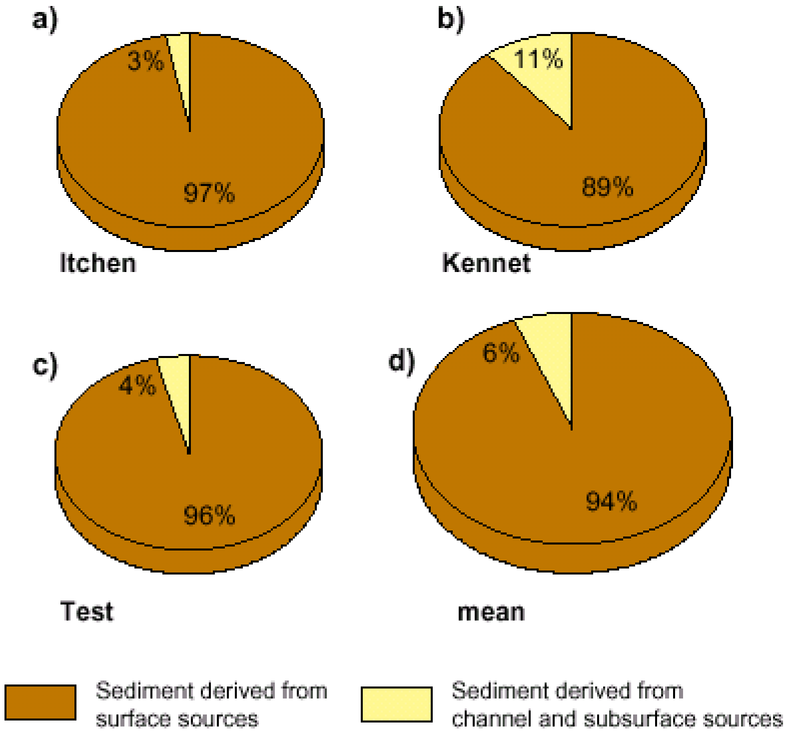

Figure 4.2: The typical provenance of interstitial sediment samples collected from the study catchments in southern England

Plate 4.2: Severely poached river bank near Easton in the Itchen study catchment

River Kennet

The results of the sediment fingerprinting survey undertaken in the Kennet study catchment are presented in Figure 4.2b. Eroding surface soils are again the most important source (89%) of interstitial sediment. There are a number of reasons why this source is dominant. These include an increase in the area of land supporting the production of autumn-sown arable crops throughout the Kennet tributary which has enhanced topsoil loss, and an increase in stocking levels, which has resulted in severe poaching of pasture surfaces. Riparian cultivation is commonplace and this enhances the connectivity between potential surface sediment sources and stream channels (Environment Agency, 2000f). Channel bank erosion is, nevertheless, also an important source of interstitial sediment, contributing 11%. In accordance with many of the other study catchments, poaching and degradation of channel banks by livestock is identified as a primary cause of such erosion (Environment Agency, 2000f). However, increasing implementation of land drainage measures has accentuated the flashiness of the flow regime, causing accelerated erosion of channel margins in some areas.

With respect to channel management, these results suggest that the Agency in partnership with the National Farmers' Union (NFU) and FWAG is correctly encouraging the adoption of the Code of Good Agricultural Practice (COGAP). Directing erosion control policies towards the management of surface sediment sources and their connections to the stream network will act as a useful means of reducing sediment delivery from agricultural land and of ameliorating the siltation of spawning gravels within the Kennet study area. Some resources should, nevertheless, also be directed to controlling channel/subsurface erosion at specific locations.

4.2.3 River Test

Figure 4.2c presents the results provided by the mixing model for the typical relative contributions from surface (96%) and subsurface (4%) sources of interstitial sediment within the Test study catchment. These data are highly consistent with the corresponding values for the neighbouring river Itchen and, assuming that spawning gravel siltation is a major priority, indicate that the local Salmon Action Plan should focus on control measures targeting the reduction of soil loss and sediment delivery to the stream network and the adoption of improved land husbandry. Consequently, the control of soil erosion and attenuation of sediment delivery from agricultural land should represent an integral component of the Test Valley (Environmentally Sensitive Areas) Scheme and local Landcare Projects currently being promoted by the Agency and CEFAS. The importance of surface, as opposed to channel/subsurface sediment sources, must clearly be taken into account in any attempt to address the problem of spawning gravel siltation in this study catchment.

4.2.4 Summary

Figure 4.2d shows that the mean relative contributions from eroding surface and channel/subsurface sources to the samples of interstitial sediment collected from the study catchments in southern England are 94% and 6% respectively. This information demonstrates the importance of including soil erosion control measures in local Salmon Action Plans. Without policies to target the protection of topsoil, salmonid spawning gravel siltation is likely to remain a serious environmental problem in this region.

4.3 Study Rivers in Northern England

4.3.1 River Esk

The mean relative contributions from the erosion of surface (89%) and subsurface (11%) sediment sources within the Esk study catchment are presented in Figure 4.3a. Sediment production on catchment slopes is associated with an efficient delivery system promoted by the steep topography characterising the North York Moors and surrounding areas. Grazing pressure promotes the poaching of surface soils beneath pasture (e.g. near Egton Manor, NGR NZ803050) and moorland (e.g. near Goathland, NGR NZ853027), whilst the cultivation of maize, wheat and barley exposes bare surface soil to rainsplash and rilling (e.g. near Hawthorndale Farm, NGR NZ867098). Sediment mobilised from hill slopes is frequently routed towards the channel system via roads and numerous footpaths. Extensive bank erosion can be readily observed at Castleton (NGR NZ685085), Houlsyke (NGR NZ735075) and Lealholm (NGR NZ764076) and is associated with undercutting and slumping during floods and uncontrolled livestock access to the stream channel. The removal of trees from the riparian zone has accentuated such problems (Environment Agency, 1999a).

These findings indicate that the River Esk Regeneration Programme (Environment Agency, 1999a), involving the Agency and the North York Moors National Park Authority, should consider erosion control measures for both surface and subsurface sediment sources. Failure to incorporate both of these aspects into local catchment management strategies is likely to result in the continuation of the spawning gravel siltation problem.

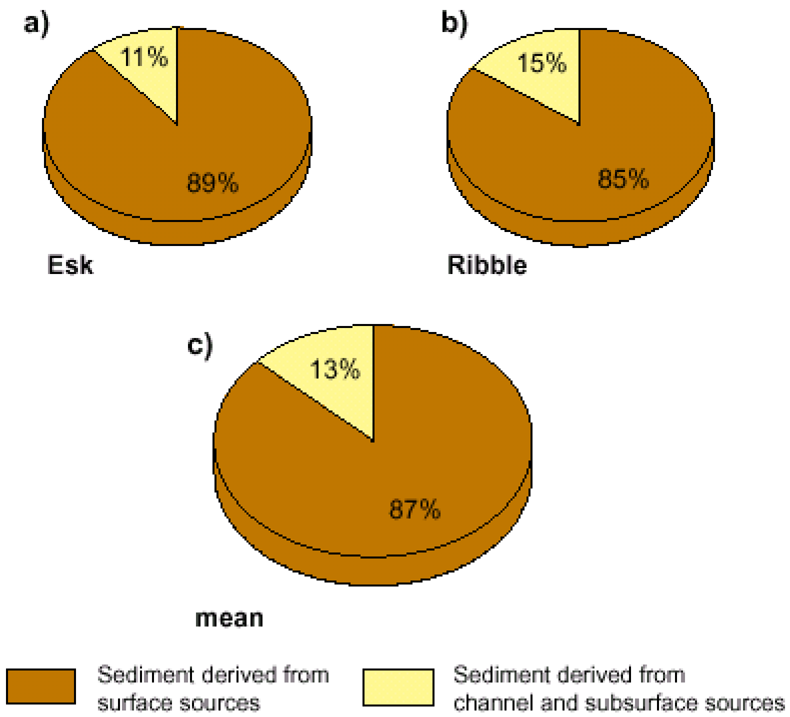

Figure 4.3: The typical provenance of interstitial sediment samples collected from the study catchments in northern England

4.3.2 River Ribble

The mean results of the sediment fingerprinting investigation undertaken for the Ribble study area are shown in Figure 4.3b. Eroding surface soils represent the dominant source of interstitial sediment, contributing 85%. Agricultural intensification over the past 50 years is responsible for increasing grazing pressures on local moorland and pasture and for an expansion in the cultivation of autumn sown cereals, which render bare soils susceptible to water erosion during the winter (Environment Agency, 1999b). Steep slopes and high rainfall intensities increase surface soil erosion and sediment delivery in the upper Ribble. Bank erosion, is, nevertheless, a significant source of the interstitial sediment responsible for the degradation of salmonid spawning habitats, contributing 15%. Widespread bank collapse is associated with the removal of river bank vegetation, the invasion of non-native plant species such as Japanese knotweed which fail to stabilise channel margins and localised poaching (Environment Agency, 1999b). Examples of river bank erosion are found in the upland areas of the upper Ribble (e.g. at NGR SD766793) and further downstream at Little Stainforth (NGR SD818673) and Halton Bridge (NGR SD853552). Although the Sustainable Rivers Management Project launched by the Agency is currently piloting the control of river bank erosion using willow raddling, riparian tree planting and stream bank fencing, the fingerprinting data indicate that attention should also be given to reducing sediment delivery from agricultural land in the Ribble valley.

4.3.3 Summary

Figure 4.3c presents the typical relative contributions of eroding surface (87%) and channel/subsurface sources (13%) to interstitial sediment sediment collected from the study rivers in northern England. Assuming these findings are representative for neighbouring rivers in the north of England, local attempts to reduce the siltation of salmonid spawning gravels should consider targeting more resources towards the control of sediment delivery from catchment surfaces. The reduction of channel bank erosion should, however, also be given priority in some localised areas.

4.4 Study Rivers in South/Mid Wales

4.4.1 River Taff

Figure 4.4a shows the mean relative contributions from surface and channel/subsurface sources to interstitial sediment collected in the Taff study catchment. Pressures on surface soils resulting from extensive sheep grazing and tourism activities throughout the upper Taff in the Brecon Beacons, combined with the high-energy fluvial environment created by locally severe rainfall intensities and steep topography, mean that the erosion of surface sources accounts for 45% of the interstitial sediment collected from this study area. Sediment production from surface sediment sources is also promoted by commercial forestry in the headwaters, whilst sediment delivery to the river channel from surface sources is greatly enhanced by the numerous footpaths and tracks leading down local hill slopes. Sediment generation from eroding channel banks is promoted by the widespread channel incision in the dynamic upland environment of the upper Taff, and the poaching and degradation of channel margins by livestock and anthropogenic activities. Consequently, channel banks contribute55% of the interstitial fine sediment collected from the spawning gravels within the

Taff study area. Due to the severity of bank erosion along the river Taff, channel margins in the middle and lower reaches of the study area are heavily protected by artificial means.

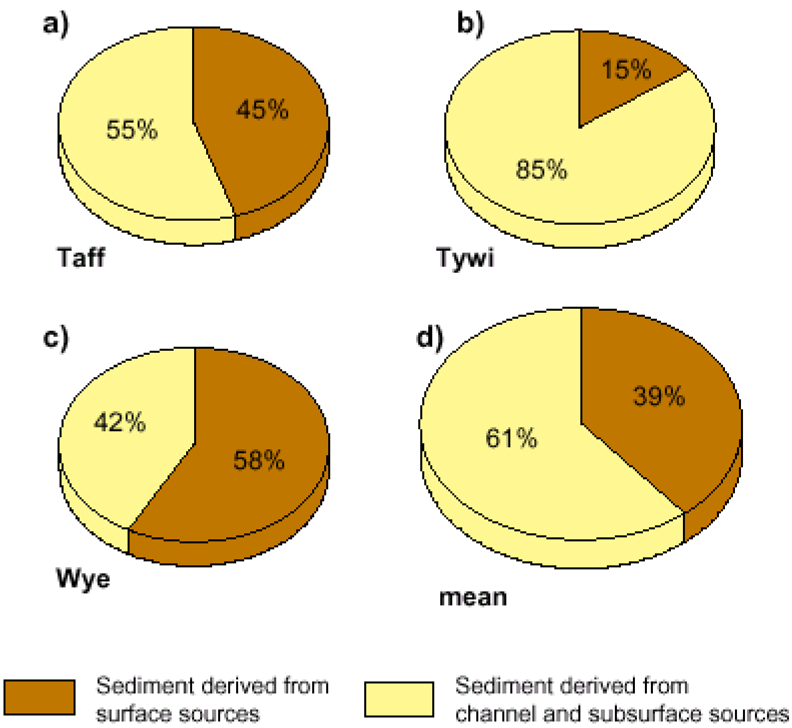

Figure 4.4: The typical provenance of interstitial sediment samples collected from the study catchments in south/mid Wales

4.4.2 River Tywi

Figure 4.4b illustrates the mean results of the sediment fingerprinting investigation for the Tywi study catchment. Conntributions are highest (85%) from eroding channel banks and lowest (15%) from eroding surface soils. Widespread bank erosion results from poaching, channel maintenance works and tree clearance in the riparian zone (Environment Agency, 1999c) and can, for example, be observed near the source of the Cennen (NGR SN653190) and further downstram near Parc Owen (NGR SN687197) and Trap (NGR SN653190, Plate 4.3). Sediment production from surface sources occurs as a result of the disturbance of topsoil by poaching (e.g. near Trap, NGR SN664196) and mobilised material is subsequently easily routed towards the stream channel via the steep topography and the roads or tracks characterising the Cennen valley. On the basis of these results, the remedial action currently being instigated by the Agency, Carmarthenshire Fishermen's Federation (CFF) and Carmarthenshire County Council, should focus primarily upon the reduction of channel bank erosion in the Tywi study area. In this context, the plans of the Agency to implement a collaborative programme of riparian tree management between landowners and the Countryside Council for wales (CCW) are likely to prove beneficial in enhancing the quality of local salmonid spawning gravels by reducing rates of bank erosion. The implementation of sediment management strategies aimed at controlling channel margin degradation should also be included as a local priority under the auspices of the All Wales Agri-Environment Scheme.

Plate 4.3: Channel bank erosion near Trap in the Tywi study catchment

4.4.3 River Wye

Typical contributions from the erosion of surface (58%) and subsurface (42%) sources of interstitial sediment within the Wye study catchment are presented in Figure 4.4c. Local high precipitation and steep topography (Plate 4.4) promote the natural erosion of topsoil beneath both forest and pasture. Surface erosion in the areas of managed forest occupying the upper Marteg is increased by the use of tracks and picnic sites associated with recreational activities. Evidence for such erosion exists at Pistyll (NGR SO009771) and Bwlch-y-Sarnau (NGR SO023750). Topsoil erosion in pasture areas is enhanced by surface trampling, e.g. near Waun (NGR SO013768) and Moelfre (NGR SO995745). Sediment delivery to the river channel from both pasture and forest areas occurs along local roads and tracks. Bank erosion is associated with the destabilisation of channel margins during high magnitude flow events, widespread poaching and degradation by livestock and mechanical operation associated with the management of local forests, including the construction of drains and access roads (cf. Newson, 1980). Overall, these estimates indicate that policies designed to ameliorate the siltation of salmonid spawning gravels in the Wye study catchment should incorporate strategies to control both surface and channel/subsurface erosion. The installation of gabions is already proving successful with respect to the latter, e.g. at St. Harmon (NGR SO988729).

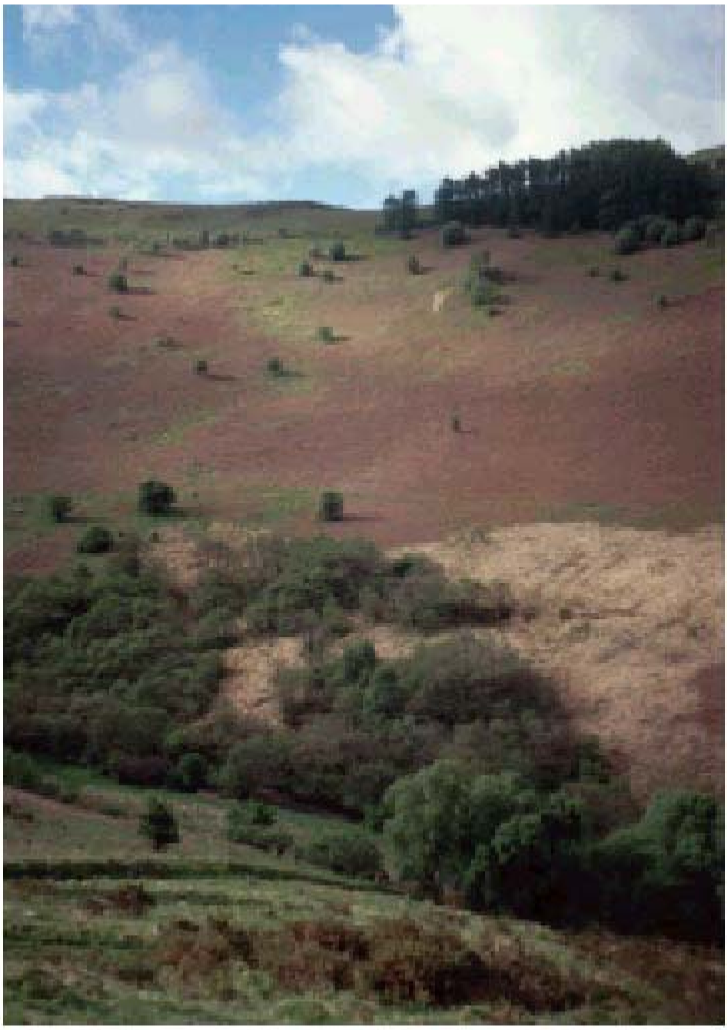

Plate 4.4: The steep topography of the Marteg valley in the Wye study catchment

4.4.4 Summary

Figure 4.4d presents the mean relative contributions from the erosion of surface and channel/subsurface sources to the samples of interstitial fine sediment collected from the study catchments in south/mid Wales. Whilst bank erosion (61%) is more important than surface soil erosion (39%), these findings emphasise that sediment production from both sediment source categories should be targeted by any management programme which seeks to reduce the siltation of salmonid spawning gravels in this region.

4.5 Study Rivers in North Wales

4.5.1 River Dee

In the case of the Dee study catchment, eroding surface soils were found to contribute 98% of the interstitial sediment retrieved from local spawning gravels (see Figure 4.5a). The significance of surface sediment sources reflects the severe poaching of pasture surfaces in pastoral areas of the catchment such as the Ceiriog (e.g. near Llanarmon, NGR SJ153331) and Llafar (e.g. upstream of Parc Bridge, NGR SH866344) tributaries, as well as the mobilisation of cultivated top soils characterising the areas of wheat and barley cultivation in the Alyn sub-catchment (e.g. at NGR SJ184526). Bank erosion contributes only 2% of the interstitial sediment collected from local spawning habitats (see Figure 4.5a) and this is likely to be primarily associated with the poaching resulting from uncontrolled stock grazing along channel margins. Examples of bank erosion can be found in the Llafar sub-catchment near Parc Bridge (NGR SH876339) and along the middle reaches of the Ceiriog tributary (NGR SJ164330). Excessive river bed weed growth in the middle and upper Dee provides an efficient trap for sediment originating from both surface and channel/subsurface sediment sources (Environment Agency, 1999d).

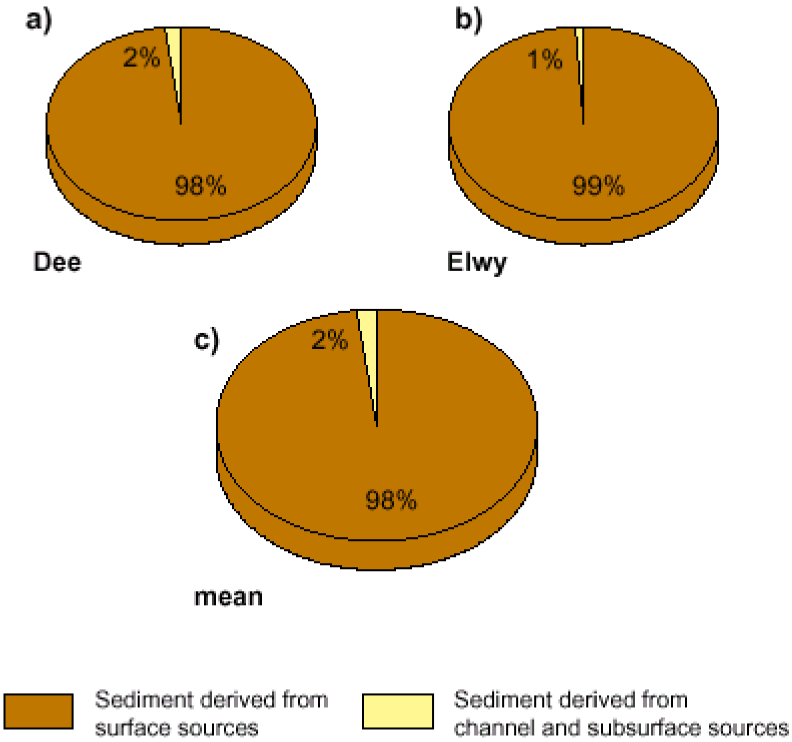

Figure 4.5: The typical provenance of interstitial sediment samples collected from the study catchments in north Wales

These results show that local catchment management strategies should target the reduction of sediment delivery from agricultural land (i.e. pasture and cultivated areas) in order to help restore spawning habitat quality. In this respect, the fingerprinting survey strongly supports the recent initiative of the Agency in association with the CCW and the North Wales Wildlife Trust (NWWT) to re-establish wetland buffer zones along the riparian corridor. Wetlands should provide an effective means of reducing sediment delivery from slope to river channel. At the same time, the sediment fingerprinting data suggest that less of the resources currently available for addressing the spawning gravel siltation problem should be directed towards current Agency plans to undertake a collaborative riparian tree management programme as a means of reducing bank erosion in the Dee catchment.

4.5.2 River Elwy

Similarly, in the Elwy study catchment, eroding topsoils were found to contribute 99% and channel banks 1% of the interstitial sediment sampled from local spawning habitats (see Figure 4.5b). Grazing pressures are primarily responsible for contributing to the erosion of the locally widespread pasture areas and examples are found near Cefn y Castel (NGR SH878642) and Plas Matw (NGR SH888649). Bank erosion is less common and is caused by the undercutting and destabilisation of channel margins during higher discharges and the trampling effects of livestock (e.g. at Pont y Newydd, NGR SH890646). On the basis of these findings, the Agency should pursue its plans (Environment Agency, 1999e) to target the control of surface soil erosion in collaboration with landowners, the CCW and the National Assembly of Wales Agricultural Department.

4.5.3 Summary

The above mixing model estimates yield mean relative contributions of 98% from surface and 2% from channel/subsurface sediment sources for the study areas in north Wales (see Figure 4.5c). On the basis of this information, it can be suggested that local management strategies targeting the regeneration of salmonid spawning habitats in these and neighbouring rivers should focus upon the control of sediment delivery from agricultural land, rather than channel banks.

4.6 The National Scene

Taking the mean of all the fingerprinting results, surface and channel/subsurface sediment sources account for equal proportions (50%) of the interstitial fine sediment collected from the 18 study rivers (see Figure 4.6). These data emphasise that nationally, both topsoil and channel bank erosion are significant causes of the spawning gravel siltation problem and underscore the value of designing and implementing combined erosion control measures for slopes and channel margins as integral components of the National Salmon Management Strategy.

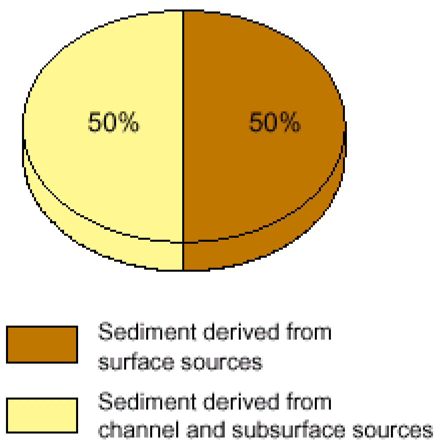

Figure 4.6: The overall typical provenance of interstitial sediment samples collected from the study catchments

It is, however, important to recognise that the national means conceal appreciable regional contrasts in the relative importance of surface and subsurface sediment sources (see Figure 4.7), which should be taken into account when devising local Salmon Action Plans. Spatial variability in the complex interaction of a number of factors controlling catchment sediment dynamics, including land use, topography and hillslope-channel coupling, are responsible for these regional differences. Figure 4.7 suggests that channel bank sources are dominant in south-west England and south/mid Wales, but that surface sources are dominant elsewhere. Channel bank erosion typically represents the most important contributor to spawning gravel siltation in south-west England due to the incised nature of many river channels and widespread trampling and degradation of channel margins and banks associated with the high livestock densities in this region.

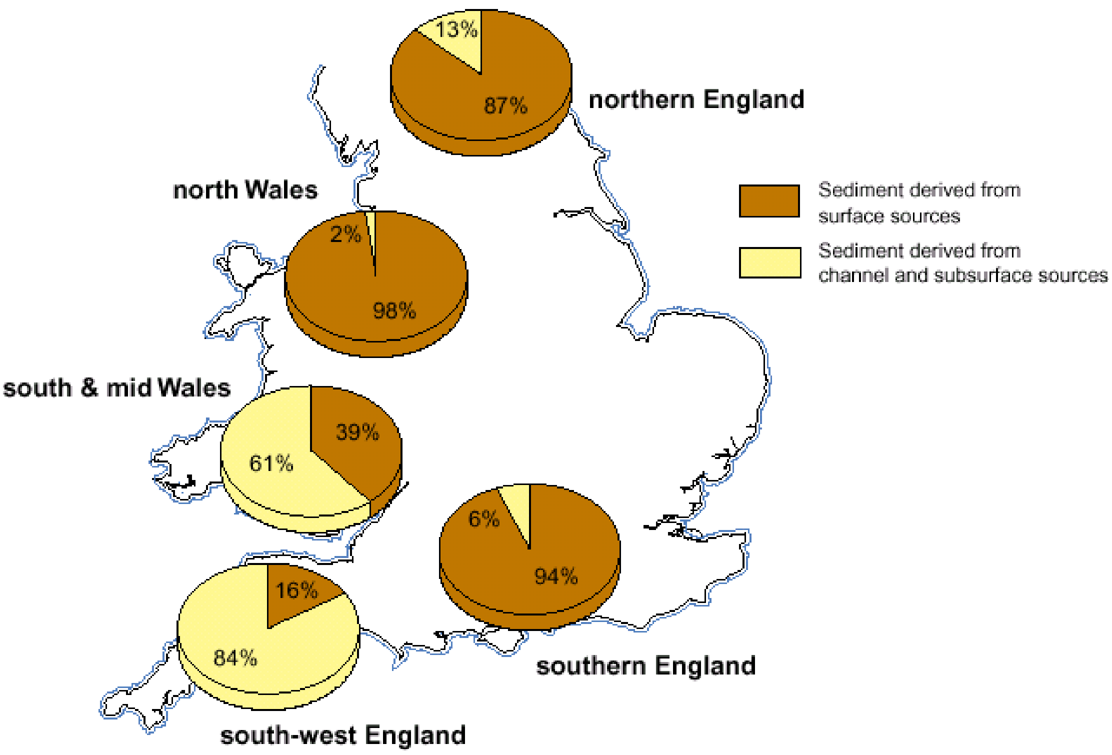

Figure 4.7: Regional variations in the typical provenance of interstitial sediment samples

In contrast, because of the greater importance of arable farming in southern England and the frequent evidence of erosion in cultivated areas used for autumn-sown cereals as well as the greater stability of the river channels, surface soils represent the most significant source of the interstitial fine sediment collected from local salmonid spawning gravels. Elsewhere, in northern parts of England and Wales, erosion from cultivated areas and probably more importantly from areas of upland and moorland pastures under increased grazing pressure results in the dominance of surface sediment sources. A combination of soil erosion associated with intensive pastoral farming and recreational activities, and upland channel incision and degradation by livestock results in both surface and subsurface sediment sources contributing significantly to the siltation of spawning gravels in the rivers of south/mid Wales. The relative importance or density of field boundaries within the landscape may also be an important control, since the upland areas of north Wales and northern England and parts of south/mid Wales are characterised by open landscape with few field boundaries.

Such areas are, in turn, likely to be characterised by increased slope-channel connectivity enhancing the delivery of sediment from surface sources. Similar arguments could be advanced for the chalklands of southern England which are now characterised by large fields and thus a reduced density of field boundaries.

Failure to consider these regional patterns is likely to compromise the effectiveness of local management plans targeting the rehabilitation of salmonid spawning gravels. In some parts of England and Wales, available resources should be directed primarily towards the control of soil mobilisation and subsequent sediment delivery to stream channels, whilst in others, greater emphasis should be aimed at reducing channel bank erosion. There are, however, some areas where the successful regeneration of salmonid spawning habitats will require remedial measures targeting the erosion of both surface and channel/subsurface sources of interstitial fine sediment. Furthermore, although the regional contrasts in interstitial sediment sources evident in Figure 4.7 can be used as a general guideline for devising appropriate local sediment management strategies, it is important to note that the regional patterns will inevitably encompass considerable catchment-specific variability in the precise relative contributions from individual sediment source types.

4.7 Limitations

The results presented above must, however, be qualified to take account of a number of potential limitations and problems associated with the investigation reported:

1. Because the source fingerprinting investigation was conducted at a reconnaissance level, the findings are necessarily based upon a limited number of samples of interstitial fines and catchment source materials. Although the results of this study are consistent and meaningful, any survey of catchment sediment sources based on sediment fingerprinting technique should endeavour to collect a representative range of source material and sediment samples, in order to maximise the reliability of the resulting estimates of sediment provenance. The results presented here must therefore be viewed as preliminary.

2. The representativeness of the provenance data is likely to have been influenced by the timing of interstitial sediment sampling. Seasonal Patterns in farming practices and river basin hydrological response may produce corresponding temporal variations in the provenance of interstitial fine sediment. Sediment sources may differ between spawning and non-spawning periods and the results obtained from source fingerprinting studies may vary according to the timing of the collection of samples of interstitial fines. Samples should be collected at different times of the year in order to provide a complete picture of the source of fine sediment infiltrating spawning gravels. However, because salmonids typically only spawn between November and January, the collection of interstitial fines during this project targeted those months in order to examine the origin of interstitial fine sediment during the period which is of greatest interest from the fisheries perspective.

3. The estimates of interstitial sediment provenance presented in this report have not been linked to corresponding information on the amounts of sediment infiltrating and accumulating in the spawning gravels in the study catchments. Sediment samples collected using retrievable basket samplers can, however, be employed to assemble both sets of information. The Agency is currently integrating the two data sets in

order to relate variations in siltation rates to the sediment sources involved and therefore to provide an improved understanding of the bed gravel sedimentation problem. A separate report will discuss the findings.

4. The findings on the source of interstitial fine sediment reported in this study have not been compared with equivalent information on the source of suspended sediment transported by the rivers in the study catchments. Such comparisons would, nevertheless, be advantageous for providing further information on the complexity of catchment sediment dynamics. Recent research at the University of Exeter has, for example, suggested that in some catchments, the sources of interstitial fines and suspended sediment may differ, suggesting that interstitial fines may not accumulate during the main periods of suspended sediment flux (i.e. higher flows) but rather during periods with lower flows.

5 CONCLUSION

5.1 Synthesis

The siltation of salmonid spawning gravels represents a serious environmental issue in many rivers supporting such fisheries throughout England and Wales. In seeking remedial measures, much emphasis, to date, has focused upon testing the effectiveness of various direct actions including gravel cleaning and egg box installation. However, given the costs of such actions and conflicting reports regarding their success, it is now increasingly recognised that a programme of prevention, as opposed to cure, offer a more appropriate and sustainable long-term strategy for addressing the spawning habitat siltation problem.

The need to prevent spawning gravel siltation has highlighted the importance of understanding sediment dynamics at the catchment scale. Knowledge of sediment mobilisation and transfer patterns and in particular, of sediment provenance, is now increasingly recognised as representing an essential prerequisite for the design and implementation of effective sediment control strategies aimed at reducing the siltation of spawning areas. Without accurate information on sediment origin, the resources available to catchment managers cannot be targeted to address the primary source of the problem. Obtaining reliable information on catchment sediment sources is, however, a difficult task. A variety of operational constraints, coupled with prohibitive financial costs and sampling problems preclude the routine use of most direct methods for investigating sediment origin. Because of these shortcomings, the fingerprinting approach has been increasingly recognised as an alternative indirect means of assembling such information. However, the potential utility of the fingerprinting approach for assessing the source of interstitial fines rather than suspended or floodplain sediment has only recently been demonstrated (Nicholls, 2000).

Recognising the need to devise sediment control policies specifically targeting the protection of spawning habitats, this study utilised a reconnaissance source fingerprinting approach to assemble information on the provenance of interstitial sediment collected from spawning gravels within 18 rivers throughout England and Wales. The principal conclusions of the investigation are:

1. The fingerprinting approach affords a viable means of assembling urgently required information on the provenance of interstitial sediment in salmonid spawning habitats in contrasting river basins. This study confirms the potential of the approach as a tool for undertaking surveys of catchment sediment sources.

2. Given the number of study areas and available resources, the fingerprinting investigation reported was necessarily undertaken at a reconnaissance level. Consequently the results are based on a limited number of samples of interstitial fines and catchment source materials, the former being collected over a short period. The findings are, nevertheless, judged to provide meaningful and representative information on the source of the interstitial sediment collected within the 18 study catchments. These results provide valuable information to inform the targeting of sediment control measures designed to safeguard salmonid spawning habitats.

3. The information on the relative importance of different sources of interstitial fine sediment provided by this study must be seen as representing a significant advance in our understanding of the fine-grained (<125μm) sediment dynamics of salmonid

spawning areas. In this respect, the study is believed to represent the first attampt at undertaking an extensive survey of the source of interstitial fine sediment within the spawning habitats of rivers in England and Wales.

4. Although the absolute contributions from surface and subsurface sources to interstitial sediment are inevitably catchment-specific, the results of this investigation provide some evidence of regional patterns. In south-west England, where the river channels are often incised, pastoral farming generally predominates and livestock numbers are frequently high, channel bank erosion is typically the most significant source of interstitial sediment, due to widespread poaching of channel margins. In southern England, where arable farming is more commonplace and channels are typically more stable, surface sediment sources are more significant due to the exposure of bare top soil to erosion risks during the cultivation of autumn sown cereals. Equally, surface soil erosion is generally more important as a sediment source in upland catchments where the lack of field boundaries in many areas of upland grazing and moorland promotes the efficient delivery of sediment particles from slope to channel, e.g. study catchments in Wales and northern England. In some instances, however, a combination of land use and physiographic characteristics results in both surface and channel/subsurface sediment sources being important. These patterns suggest that the selection of "type catchments" for different regions could offer an efficient framework for estimating the likely provenence of interstitial sediment within those regions.

5.2 Recommendations for Future Work

The results of the interstitial sediment fingerprinting survey provide a basis for the following recommendations for future work:

1. Further work is clearly required to exploit the potential of the fingerprinting approach for assembling information on the provenance of interstitial fine sediment. Such work should include the use of additional fingerprint properties in order to provide more powerful composite fingerprints which afford a basis for distinguishing sediment production from more discrete sediment sources such as areas under different land use. Furthermore, in some catchments, use of more powerful composite fingerprints could provide the basis for establishing the relative importance of different sub-catchments or parts of a basin as a sediment source. The provision of such detailed information can only assist the design of more comprehensive sediment control strategies.

2. Although this study focuses upon the <125µm fraction, future work should compare the provenance of different size fractions of interstitial sediment such as <63µm and <125µm particles. Adoption of this approach would permit investigation of potential contrast in the provenance of different size material and ultimately increase the scope for providing more specific erosion control measures. In catchments where interstitial sediment is characterised by coarser material, the significance of surface sediment sources is likely to be reduced due to the selectivity of drainage basin sediment delivery processes.

3. In this study, the basket traps have been used as a means of providing fine sediment for source fingerprinting. Such traps can also be used to provide information on the rate and amount of sediment accumulation in the post redd construction period.

Information on the rate of sediment ingress and accumulation would provide a valuable measure of the magnitude of the siltation problem, which could be linked to information on the source of that sediment. Contrasts in sediment provenenace could, for example, be linked to variations in the rate or total mass of sediment accumulation.

4. Interstitial sediment fingerprinting investigations should be undertaken over longer timescales as a means of improving the temporal representativeness of the resulting sediment provenance data. Sampling of interstitial fines at different times of the year would provide a basis for examining seasonal changes in sediment provenance and the impact of seasonal variability in land management practices. Longer-term studies could assist interpretation of the findings in terms of both land use change and intensification. The latter are frequently cited as major factors responsible for accelerated sediment delivery to river channels and increased siltation of salmonid spawning areas. It is, nevertheless, important to recognise that this study targeted the salmonid spawning period when the detrimental impacts of fine sediment infiltration are greatest.

5. Related to 4 above, there is a need to link information on the sources of interstitial fine sediment to information on land use change and intensification in order to establish why gravel siltation problems appear to have increased in recent years and to allow the identification of the land use change responsible for these problems.

6. Future investigations should also compare the provenance of interstitial sediment and the suspended load of the rivers draining particular catchments (cf. Nicholls, 2000). Such an approach offers a means of elucidating the complexity of catchment sediment dynamics and the interaction of sediment mobilisation, transfer, deposition and storage. These processes have important implications for the residence time of fine-grained interstitial sediment and hence for the longer-term implications of spawning gravel siltation.

5.3 Recommendations for Catchment Management

Some basic recommendations for catchment management plans addressing the protection of salmonid spawning grounds include:

1. All catchment management plans designed to reduce the siltation of salmonid spawning habitats should be based upon reliable information on the provenance of interstitial fines. Such information can be readily assembled using the fingerprinting approach and ensures that the resources available to catchment managers and planners are targeted in a cost-effective manner.

2. In catchments where interstitial fines predominantly originate from channel or subsurface sources, erosion control policies might include river bank fencing schemes, riparian tree planting programmes, the deployment of protective measures such as gabions and willow raddling, or a combination of such approaches.

3. In catchments where interstitial fines are primarily derived from surface sources, sediment management policies should promote appropriate land use and farming practices (cf. DEFRA, 1998, 1999). More specifically, these policies might emphasise the benefits of reducing autumn-sown cereal production, adopting minimum tillage

methods, sowing cover crops and controlling grazing pressures as a means of reducing sediment mobilisation, as well as the benefits of installing runoff barriers to attenuate sediment delivery from slopes to river channels.

4. Where possible, sediment control policies should adopt a holistic approach, encompassing the need to integrate management of the entire catchment sediment delivery system, as opposed to directing attention towards the exclusive control of individual components. Integration of sediment provenance information for different components of catchment sediment delivery, e.g. suspended, floodplain and interstitial sediment, would help to optimise the use of the limited resources available for managing the different sediment-related environmental problems currently being reported in river catchments in England and Wales.

6 REFERENCES

Acornley, R.M. & Sear, D.A. (1999). Sediment transport and siltation of brown trout *(Salmo trutta* L.) spawning gravels in chalk streams. *Hydrol. Process*. **13**: 447-458.

Beschta, R.L. & Jackson, W.L. (1979). The intrusion of fine sediment into a stable gravel bed. *J. Fish Res. Board Canada* **36**: 204-210.

Bottrill, L.J., Walling, D.E. & Leeks, G.J.L. (2000). Using recent overbank deposits to investigate contemporary sediment sources in larger river basins. In: I.D.L. Foster (Ed.) *Tracers in Geomorphology* (pp 369-387). Wiley, Chichester.

Carling, P.A. (1985). Oxygen flux through salmonid gravels. *Freshwater Biological Association Project* **73**.

Carling, P.A. & McCahon, C.P. (1987). Natural siltation of brown trout (*Salmo trutta* L.) spawning gravels during low-flow conditions. In: J.F. Craig & B.J. Kemper (Eds.) *Regulated Streams: Advances in Ecology* (pp 229-243). Plenum Press, New York.

Collins, A.L. (1995). *The Use of Composite Fingerprints for Tracing the Source of Susended Sediment in River Basins*. Unpublished Ph.D. thesis, University of Exeter, 548 pp.

Collins, A.L., Walling, D.E. & Leeks, G.J.L. (1996). Composite fingerprinting of the spatial source of fluvial suspended sediment: a case study of the Exe and Severn river basins, United Kingdom. *Geomorphologie: Relief, Processus, Environnement* **2**: 41-54.

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

Collins, A.L., Walling, D.E. & Leeks, G.J.L. (1997b). Fingerprinting suspended sediment sources in larger river basins: combining assessment of spatial provenance and source type. *Geogr. Ann*. **79A**: 239-254.

Collins, A.L., Walling, D.E. & Leeks, G.J.L. (1997c). Sediment sources in the upper Severn catchment: a fingerprinting approach. *Hydrology and Earth System Sciences* **1**: 509-521.

Collins, A.L., Walling, D.E. & Leeks, G.J.L. (1997d). Use of the geochemical record preserved in floodplain deposits to reconstruct recent changes in river basin sediment sources. *Geomorphology* **19**: 151-167.

Collins, A.L., Walling, D.E. & Leeks, G.J.L. (1998). Use of composite fingerprints to determine the provenance of the contemporary suspended sediment load transported by rivers. *Earth Surf. Process. Landforms* **23**: 31-52.

Collins, A.L., Walling, D.E. Sichingabula, H.M. & Leeks, G.J.L. (2001). Suspended sediment source fingerprinting in a small tropical catchment and some management implications. *Applied Geogr*. **21**: 387-412.

Crisp, D.T. (1993). The ability of UK salmon alevins to emerge through a sand layer. *J. Fish. Biol*. **43**: 656-658.

Crisp, D.T. & Carling, P.A. (1989). Observations on siting, dimensions and structure of salmonid redds. *J. Fish. Biol*. **34**: 118-134.

DEFRA (1998). *Code of Good Agricultural Practice for the Protection of Soil (1998 Revision).* DEFRA Publications, London, 66pp.

DEFRA (1999). *Controlling Soil Erosion. A Manual for the Assessment and Management of Agricultural Land at Risk of Water Erosion in Lowland England.* DEFRA Publications, London, 44pp.

Diplas, P. & Parker, G. (1992). Deposition and removal of fines in gravel-bed streams. In: P. Billi, R.D.Hey, C.R.Thorne & P. Tacconi (Eds.) *Dynamics of Gravel-bed Rivers* (pp 313-329). Wiley, Chichester.

Droppo, I.G. & Stone, M. (1994). In-channel surficial fine-grained laminae. Part 1: physical characteristics and formational processes. *Hydrol. Process*. **8**: 101-111.

Environment Agency (1999a). *Esk and Coast (Hartlepool to Filey Bay) LEAP Action Plan*. Environment Agency North East Region, 31pp.

Environment Agency (1999b). *Ribble LEAP Consultation Draft*. Environment Agency North West Region, 105pp.

Environment Agency (1999c). *Carmarthen Area LEAP Consultation Report*. Environment Agency Wales 181pp.

Environment Agency (1999d). *Dee LEAP Consultation Report*. Environment Agency Wales (CD-ROM version).

Environment Agency (1999e). *Conwy/Clwyd LEAP Consultation Report*. Environment Agency Wales, 106pp.

Environment Agency (2000a). *North Cornwall LEAP First Annual Review*. Environment Agency South West Region, 51pp.

Environment Agency (2000b). *Fal and St. Austell Streams LEAP Second Annual Review*. Environment Agency South West Region, 72pp.

Environment Agency (2000c). *Bodmin Moor to the Coasts LEAP: Review 2000*. Environment Agency South West Region, 92pp.

Environment Agency (2000d). *Tamar LEAP Annual Review 2000*. Environment Agency South West Region, 100pp.

Environment Agency (2000e). *Test and Itchen LEAP*. Environment Agency Southern Region, 64pp.

Environment Agency (2000f). *Kennet Valley LEAP*. Environment Agency Thames Region, 64pp.

Foster, I.D.L. & Walling, D.E. (1994). Using reservoir deposits to reconstruct changing sediment yields and sources in the catchment of the Old Mill Reservoir, South Devon, over the past 50 years. *Hydrol. Sci. J.* **39**: 347-368.

Frostrick, L.E., Lucas, P.M. & Reid, I. (1984). The infiltration of fine matrices into coarse-grained alluvial sediments and its implications for stratigraphical interpretation. *J. Geol. Soc.* **141**: 955-965.

Hausle, D.A., & Coble, D.W. (1976). Influence of sand in redds on survival and emergence of brook trout (*Salvelinus fontinalis*). *Trans. Am. Fish. Soc.* **1**: 57-63.

He, Q. & Owens, P.N. (1995). Determination of suspended sediment provenance using Caesium-137, unsupported lead-210 and radium-226: a numerical mixing model approach. In: I.D.L. Foster, A.M. Gurnell & B.W. Webb (Eds.) *Sediment and Water Quality in River Catchments* (pp207-227). Wiley, Chichester.

Heaney, S.I., Foy, R.H., Kennedy, G.J.A.,Crozier, W.W. & O'Connor, W.C.K. (2001). Impacts of agriculture on aquatic systems: lessons learnt and new unknowns in Northern Ireland. *Mar. Freshwater Res.* **52:** 151-163.

Horowitz, A.J. (1991). *A Primer on Sediment-trace Element Chemistry.* Lewis, Michigan, 134pp.

Iwamoto, R.N., Salo, E.O., Madej, M.A., McComas, R.L. & Rulifson, R.L. (1978). Sediment and Water Quality: A Review of the Literature Including a Suggested Approach for Water Quality Criteria With Summary of Workshop and Conclusions and Recommendations. *U.S. Environmental Protection Agency* **910/9-78-048**, 151pp.

Joshi, S.R. (1987). Nondestructive determination of lead-210 and radium-226 in sediments by direct photon analysis. *J. Radioanal. Nucl. Chem.* **116**: 169-182.

Kondolf, G.M., Sale, M.J., & Wolman, M.G. (1993). Modification of fluvial gravel size by spawning salmonids. *Water Resour. Res.* **29**: 2265-2274.

Lisle, T.E. (1989). Sediment transport and resulting deposition in spawning gravels, north coastal California. *Water Resour. Res.* **25**: 247-260.

Loughran, R.J., & Campbell, R.L. (1995). The identification of catchment sediment sources. In: I.D.L. Foster, A.M. Gurnell & B.W. Webb (Eds.) *Sediment and Water Quality in River Catchments* (pp189-205). Wiley, Chichester.

McManus, J. (1988). Grain size determination and interpretation. In: M.Tucker (Ed.) *Techniques in Sedimentology* (pp63-85). Blackwell, Oxford.

Middleton, G.V. (1970). Experimental studies related to problems of flysch sedimentation. In: J. Jajoie (Ed.) *Flysch Sedimentation in North America* (pp 253-272). Geological Association of Canada Special Paper **7**.

Newson, M. (1980). The erosion of drainage ditches and its effects on bedload yields in mid-Wales. *Earth Surf. Process.* **5**: 275-290.

Nicholls, D.J. (2000). *The Source and Behaviour of Fine Sediment Deposits in the River Torridge, Devon and their Implications for Salmon Spawning.* Unpublished Ph.D. thesis, University of Exeter, 324pp.

O'Connor, W.C.K. (1998). *An Investigation of Atlantic Salmon (Salmo salar L.) Spawning Habitat in Northern Ireland Rivers.* Unpublished D. Phil. Thesis, University of Ulster, 336pp.

Olsson, T.I., & Persson, B. (1988). Effects of deposited sand on ova survival and alevin emergence in brown trout (*Salmo trutta* L.). *Arch Hydrobiol.* **113**: 621-627.

Peart, M.R. (1993). Using sediment properties as natural tracers for sediment source: two case studies from Hong Kong. In: N.E. Peters, E. Hoehn, Ch. Leibundgut, N. Tase & D.E.Walling (Eds.) *Tracers in Hydrology* (pp313-318). IAHS Publ. No. **215**. IAHS Press, Wallingford.

Peart, M.R. (1995). Fingerprinting supended sediment sources: an example from Hong Kong. In: I.D.L. Foster, A.M. Gurnell & B.W. Webb (Eds.) *Sediment and Water Quality in River Catchments* (pp179-186). Wiley, Chichester.

Peart, M.R. & Walling, D.E. (1988). Techniques for establishing suspended sediment sources in two drainage basins in Devon, UK: a comparative assessment. In: M.P. Bordas & D.E. Walling (Eds.) *Sediment Budgets* (pp 269-279). IAHS Publ. No. **174**. IAHS Press, Wallingford.

Phillips, R.W., Lantz, R.L., Claire, L.L. & Moring, W.E. (1975). Some effects of gravel mixtures on emergence of coho salmon and steelhead trout fry. *Trans. Am. Fish. Soc.* **104**: 461-465.

Platts, W.S. Torquemado, R.J., McHenry, M.L. & Graham, C.K. (1989). Changes in salmon spawning and rearing habitat from increased delivery of fine sediment to the South Fork Salmon River, Idaho. *Trans. Am. Fish. Soc.* **118**: 274-283.

Reeves, G.H., Hall, J.D., Roelofs, T.D., Hickman, T.L. & Baker, C.O. (1991). Rehabilitating and modifying stream habitats. In: W.R. Meehan (Ed.) Influence of Forest and Rangeland Management on Salmonid Fishes and their Habitats. *Am. Fish. Soc. Spec. Publ.* **19**: 519-557.

Rosato, A., Prinz, F., Standburg, K.J. & Swendish, R. (1986). Monte Carlo simulation of particulate matter segregation. *Powder Technol.* **49**: 59-69.

Russell, M.A., Walling, D.E. & Hodgkinson, R.A. (2001). Suspended sediment sources in two small lowland agricultural catchments in the UK. *J. Hydrol.* **252**: 1-24.

Scrivener, J.C. & Brownlea, M.J. (1989). Effects of forest harvesting on spawning gravel and incubation survival of chum (*Oncorhynchus keta*) and coho salmon (*O. kisutch*) in Carnation Creek, British Columbia. *Can. J. Fish. Aquat. Sci.* **46**: 681-696.

Scullion, J. (1983). Effects of impoundments on downstream bed materials of two upland rivers in mid-Wales and some ecological implications of such effects. *Arch. Hydrobiol.* **96**: 329-344.

Sear, D.A. (1993). Fine sediment infiltration into gravel spawning beds within a regulate d river experiencing floods: ecological implications for salmonids. *Regul. Rivers: Res. Man.* **8**: 373-390.

Shackle, V.J., Hughes, S. & Lewis, V.T. (1999). The influence of three methods of gravel cleaning on brown trout (*Salmo trutta*) egg survival. *Hydrol. Process.* **13**. 477-486.

Slattery, M.C. & Burt, T.P. (1997). Particle size characteristics of suspended sediment in hillslope runoff and streamflow. *Earth Surf. Process. Landforms* **22**: 705-719.

Turnpenny, A.W.H. & Williams, R. (1980). Effects of sedimentation on the gravels of an industrialised river system. *J. Fish Biol.* **17**: 681-693.

Walling, D.E. & Collins, A.L. (2000). *Integrated Assessment of Catchment Sediment Budgets: A Technical Manual.* University of Exeter, 168pp.

Walling, D.E. & Kane, P. (1984). Suspended sediment properties and their geomorphological significance. In: T.P. Burt & D.E. Walling (Eds.) *Catchment Experiments in Fluvial Geomorphology* (pp 311-334). GoeBooks, Norwich.

Walling, D.E. & Moorehead, P.W. (1989). The particle size characteristics of fluvial suspended sediment: an overview. *Hydrobiol.* **176/177**: 125-149.

Walling, D.E. & Quine, T.A. (1993). *Use of Caesium-137 as a Tracer of Erosion and Sedimentation: Handbook for the Application of the Caesium-137 Technique.* University of Exeter, 196pp.

Walling, D.E. & Woodward, J.C. (1992). Use of radiometric fingerprints to derive information on suspended sediment sources. In: J. Bogen, D.E. Walling & T. Day (Eds.) *Erosion and Sediment Transport Monitoring Programmes in River Basins* (pp 153-164). IAHS Publ. No. **210**. IAHS Press, Wallingford.

Walling, D.E. & Woodward, J.C. (1995). Tracing sources of suspended sediment in river basins: a case study of the River Culm, Devon, UK. *Mar. Freshwater Res.* **46**: 327-336.

Walling, D.E., Owens, P.N. & Leeks, G.J.L. (1999). Fingerprinting suspended sediment sources in the catchment of the River Ouse, Yorkshire, UK. *Hydrol. Process.* **13**: 955-975.

Walling, D.E., Owens, P.N., Waterfall, B.D., Leeks, G.J.L. & Wass, P.D. (2000). The particle size characteristics of fluvial suspended sediment in the Humber and Tweed catchments, UK. *Sci. Total Environ.* **251/252**: 205-222.

Walling, D.E., Woodward, J.C. & Nicholas, A.P. (1993). A multi-parameter approach to fingerprinting suspended sediment sources. In: N.E. Peters, E. Hoehn, Ch. Leibundgut, N. Tase & D.E. Walling (Eds.) *Tracers in Hydrology* (pp 329-337). IAHS Publ. No. **215**. IAHS Press, Wallingford.

Yu, L. & Oldfield, F. (1989). A multivariate mixing model for identifying sediment source from magnetic measurements. *Quat. Res.* **32**: 168-181.