Natural England Research Report NERR007

Investigations into the use of critical sediment yields for assessing and managing fine sediment inputs into freshwater ecosystems

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Investigations into the use of critical sediment yields for assessing and managing fine sediment inputs into freshwater ecosystems

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Summary

The impacts of anthropogenically-enhanced fine sediment loads on freshwater habitats and biota are increasingly seen as a major environmental concern. Fine sediment is both a pollutant and a pollutant vector and has the potential to affect aquatic ecology both whilst in suspension and following deposition on the channel bed. However, the precise magnitude of many of the impacts of sediment on individual species is currently unquantified. Climate change is predicted to increase the intensity of rainfall events and thereby enhance fine sediment delivery even further. Combined with predicted higher water temperatures and associated thermal stress on freshwater communities, the outlook is one of increasing concern.

Natural England defines ‘conservation objectives’ for sites designated for wildlife in order to inform management and report on site status. This involves the specification of ‘favourable condition’, in which targets are defined for a range of biological and environmental attributes in different habitat types, including rivers, lakes, ditch systems and coastal waters. Suspended solids and siltation levels are explicitly included in the list of attributes for rivers, and also need to be managed to secure favourable condition in other habitat types. Similarly, the Environment Agency is interested in defining critical values for sediment in river catchments in order to support the achievement of Good Ecological Status (GES) and Good Ecological Potential (GEP) under the Water Framework Directive (WFD).

To date, integrated work aimed at linking the magnitude of fine sediment concentrations and loads to potential impacts on aquatic ecology at the catchment scale is limited. However, a need exists to establish sediment targets using best available information, in order to assist in the development of strategic sediment management regimes. Catchment sediment yields offer a potential basis for specifying such targets.

Against this background, in 2004 Professor Des Walling, Professor Bruce Webb and Dr Jo Shanahan of the Sediment Research Group, University of Exeter, were commissioned by the then English Nature in partnership with the Environment Agency, to investigate the utility and feasibility of setting and applying critical sediment yields for assessing and managing sediment inputs to aquatic systems.

A review of the availability, nature and quality of existing UK sediment yield data is presented, as a first step towards the development of targets for sediment control. A total of 146 yield estimates are classified according to a simple typology based on relief, catchment size and land use. Of these, 107 sites were considered to provide data of high or medium quality. Sediment yield values for these sites range from a minimum of 1 t km^{-2} $year^{-1}$ to a maximum of 311 t km^{-2} $year^{-1}$. The average sediment yield value reported is 44 t km^{-2} $year^{-1}$, which is close to the ‘typical’ value of 50 t km^{-2} $year^{-1}$ for UK rivers identified by Walling and Webb (1987).

Constraints and limitations associated with existing sediment yield data are highlighted. These relate to a range of factors that include data quality; the inherent spatial and temporal variability of sediment delivery systems; and the ‘lumped’ nature of sediment yield data. The associated need to consider complementary indicators of sediment yield, such as sediment rating curves and sediment sources is therefore outlined.

Approaches to target-setting in other countries have been reviewed. The following are considered in detail: Europe, Canada, Australia, New Zealand; and the USA. Of these, the USA is the only country to date that has implemented a statutory programme of target setting for sediment loads. These targets take the form of Total Maximum Daily Loads (TMDLs) and approaches range in complexity from quantitative, data-intensive modelling to qualitative, ‘narrative’ targets based on best professional judgement.

A brief review of the current understanding of the potential impacts of fine sediment on aquatic habitats is presented as a means of improving the ecological relevance of sediment targets. The report highlights the limited quantitative understanding of the relationships between levels of fine sediment delivery and

aquatic community responses. Negative ecological impacts associated with both suspended sediment and in-channel deposition of fine sediment are recognised.

This review highlights the fact that sediment yields alone are a poor metric for defining environmental status in respect of the impacts of fine sediment. However, they can be very useful in monitoring the effects of remediation measures and for compliance with specific objectives.

Two possible operational contexts for setting and applying sediment targets are outlined. The first is based on a ‘bottom-up’ approach , founded on an understanding of local conditions derived from a ‘toolkit’ of information sources, including analysis of historical suspended sediment data, biological impact data, fluvial geomorphological survey, sediment fingerprinting and budgeting, and catchment run-off, soil erosion and soil compaction surveys. This can generate a range of possible sediment-related targets from yield values through to biological end-points. The second is based on a ‘top down’ approach, providing an overall structure for national prioritisation of management need based on ‘hard’ generic sediment yield-based targets.

Whichever type of operational approach is adopted, a framework is proposed for generic targets related to sediment yield. These can potentially be used to either guide the development of local targets or set targets in a more rigid and nationally consistent way. The proposed framework would contain targets with two components: 1) a value of critical sediment yield applicable at the catchment or sub-catchment scale; and 2) complementary rating curve parameters to describe the relationship between suspended sediment concentration and river flow. This two-tier target allows consideration of the relationship between sediment and aquatic ecology at a more meaningful spatial and temporal resolution than that afforded by a value of sediment yield alone.

The proposed rationale employs a matrix methodology and look-up tables in order to set targets according to a two-step process. Under step 1, general targets can be set at the catchment or sub-catchment scale for different catchment types, taking account of geomorphological and hydrological conditions. Under step 2, these targets can be refined for specific broad habitats, communities or individual species based on their sensitivity to sediment-related impacts.

Guidelines for populating the target framework with generic values using the currently available data and ‘best professional judgement’ are presented. A preliminary, subjective, attempt to populate selected aspects of the framework with values for sediment yield is provided. Potential problems associated with defining critical sediment yields on the basis of existing information are highlighted, and required further work is outlined.

Recommendations for more fundamental work to improve the knowledge base for setting and applying sediment targets are presented. These relate to the following five areas:

- generating sediment yield data;
- linking sediment and ecology;
- modelling tools eg PSYCHIC;
- land use practices and sediment yields; and
- geomorphological techniques and their application.

The work was informed and enhanced by a major contribution from a group of fluvial geomorphologists (Malcolm Newson, Newcastle University, David Sear, Southampton University, and Harriet Orr, Lancaster University), who provided a different perspective on fine sediment problems and their management. This work is reported in full in Appendix 1 – in particular, Appendix 1 supplements Section 4 of the main report by expanding on the behaviour and complexities of fine sediment impacts and suggesting fluvial geomorphological contributions to their management. These suggestions have been incorporated as far as possible into the decision-making processes proposed in the main report.

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1 Introduction

Overview

1.1 The effects of anthropogenically-enhanced fine sediment loads on aquatic habitats and biota are a major environmental concern. Sediment is both a pollutant and a pollutant vector (ie pollutants can be attached to the surface of sediment and be transported as the sediment travels through a drainage basin) and has the potential to affect aquatic ecology both whilst in suspension and following deposition on the channel bed. The precise magnitude of many of the impacts of sediment on individual species are, however, as yet unquantified.

1.2 Natural England defines ‘conservation objectives’ for sites designated for wildlife in order to inform management and report on site status. This involves the specification of ‘favourable condition’, in which targets are defined for a range of biological and environmental attributes in different habitat types, including rivers, lakes, ditch systems, transitional and coastal waters. Suspended solids and siltation levels are explicitly included in the list of attributes for rivers, and also need to be managed to secure favourable condition in other habitat types. Similarly, the Environment Agency is interested in defining critical values for sediment in river catchments in order to support the achievement of Good Ecological Status (GES) and Good Ecological Potential (GEP) under the Water Framework Directive (WFD).

1.3 To date, work to define critical thresholds in relation to sediment input has focused on trying to specify the most ecologically relevant end-points, such as the level of fine sediment in salmonid spawning gravels, or suspended solids levels. Whilst thresholds of this type are vital, they are notoriously difficult to define and the exact specification of relevant end-point varies from species to species and habitat to habitat.

1.4 Ecological requirements relating to sediment load need to be defined using a common denominator that has practical relevance to catchment management. Critical sediment yield seems to have the potential to fulfil this role, linking into catchment management models such as PSYCHIC that can provide the basis for determining appropriate management action. To date, integrated work aimed at linking the magnitude of fine sediment concentrations and loads to potential impacts on aquatic ecology at the catchment scale is limited. However, a need exists to establish sediment targets using best available information, in order to assist in the development of sediment management regimes. Catchment sediment yields offer a potential basis for development of such targets.

1.5 Against this background, this project was commissioned by English Nature (as was) in partnership with the Environment Agency, to investigate the utility and feasibility of setting and applying critical sediment yields for assessing and managing sediment inputs to aquatic systems.

Project objectives

1.6 The project had the following five objectives:

- To review the available information on sediment yields in catchments of relevance to the UK (see section 2);
- to review management approaches to target-setting for sediment control adopted in other countries (see section 3);
- to provide a rationale for the use of sediment yields in the definition of environmental status consistent with Favourable Condition and Good Ecological Status of aquatic habitats (see section 5);

- where possible, provide best estimates of critical sediment yields for different catchment types (see section 6); and
- to recommend further work aimed at developing a refined procedure for determining critical sediment yields (see section 7).

Project organisation

1.7 This report has been produced by Professor Des Walling, Professor Bruce Webb and Dr Jo Shanahan of the Sediment Research Group within the Geography Department of the University of Exeter. A contribution to the report was received from Professor Malcolm Newson, Dr David Sear and Dr Harriet Orr of Newcastle, Southampton and Lancaster Universities respectively – this has been included as Appendix 1, with some of the material on impacts under Section 4. As much as possible of the thinking has also been incorporated into the development of the rationale for target-setting presented in Section 5.

2 The suspended sediment yield of UK catchments

Overview

2.1 The term 'sediment yield' refers to the total mass of sediment delivered to the outlet of a catchment during a specific time period. Sediment yields are usually reported in tonnes per year. To facilitate comparisons between catchments, sediment yields are frequently expressed as specific sediment yields, or the sediment yield per unit area (t km^{-2} $year^{-1}$).

2.2 The overall aim of this project is to investigate the potential for using catchment sediment yield data to develop targets for management of fine sediment and its associated ecological impacts in UK catchments. In order to achieve this, the first step must be to identify the availability and quality of the existing data on suspended sediment yields that might be used as a basis for target setting.

2.3 The focus of objective 1 is therefore a review of the available information on catchment suspended sediment yields, with particular reference to the UK. In order to address this objective, the following are presented:

- a brief overview of global and European suspended sediment yields, to put UK suspended sediment yields into context (see paragraph 2.5);
- a synthesis of available information on suspended sediment yields in the UK (see paragraphs 2.6 – 2.8);
- a preliminary attempt to categorise sediment yield values according to a simple catchment typology as a step towards establishment of critical sediment yields (see paragraphs 2.9 – 2.22);
- an overview of reliability and related issues associated with suspended sediment yield data (see paragraphs 2.23 – 2.24);
- a consideration of the potential use of sediment rating curves as a complement to sediment yield information when establishing targets (see paragraph 2.25 – 2.28); and
- a brief discussion of the need for information on sediment characteristics including sources (see paragraph 2.29 – 2.44).

2.4 Further discussion of the sediment yield data gathered under this objective is provided with respect to defining a rationale for development of critical yields in section 5 and further consideration of target-setting in section 6. Approaches to setting targets for sediment control in other countries are considered in section 3.

UK suspended sediment yields in the global context

2.5 At the global scale, specific suspended sediment yields are reported to range between <1.0 t km^{-2} $year^{-1}$ and in excess of 10 000 t km^{-2} $year^{-1}$ (Walling and Webb 1983). Available information indicates that the suspended sediment yields of UK catchments lie towards the lower bound of this range (ie < 100 t km^{-2} $year^{-1}$). Although the range of suspended sediment yields reported for Europe is significantly less than the global range, there are many areas in Europe where yields are well in excess of those found in the UK, particularly in Southern Europe. A similar situation exists in the USA. It is therefore difficult to transfer information on the magnitude of suspended sediment yields and the influence of land use and other anthropogenic impacts, relating to Europe or the USA, to the UK. The relatively low rainfall intensities, the lack of extended periods with high soil moisture deficits and the well-developed vegetation cover, combine with other terrain characteristics to produce relatively low specific suspended sediment yields across the UK and it is likely to be subtle, anthropogenically induced variations in the magnitude of these low sediment yields that impact adversely on aquatic ecology. Any attempt to understand the spatial variability of specific suspended sediment yields within the UK and the key controls on this variability, must therefore be based on data from UK catchments.

UK suspended sediment yields

2.6 As indicated above, annual suspended sediment yields in the UK are low by world standards. Available data indicate that values range from <1t km^{-2} $year^{-1}$ to in excess of 500t km^{-2} $year^{-1}$, but 'typical' yields are in the region of 50t km^{-2} $year^{-1}$ (Walling and Webb 1987). Existing understanding of the suspended sediment dynamics of British rivers indicates the following key characteristics:

- suspended sediment loads are almost exclusively non-capacity loads, ie the rivers could carry more suspended sediment than is actually transported. Sediment supply or availability therefore exerts a greater influence on suspended sediment transport than the hydraulic conditions or transport energy.
- Most rivers are characterised by seasonal and storm-period hysteresis in the suspended sediment concentration / discharge relationship, with concentrations for a given flow being higher on the rising stage than on the falling stage, and higher in summer than in winter.
- Significant suspended sediment transport is commonly highly episodic, being restricted to storm runoff events, particularly major runoff events. Typically, about 80% of the total suspended sediment yield is transported in about 2% of the time, or the equivalent of a total of only about 5-10 days per year.

2.7 Limited reliable suspended sediment load data are available with which to produce a meaningful assessment of the countrywide pattern of specific suspended sediment yields. To date, Walling and Webb (1987) have provided the only substantive synthesis of available data on the suspended sediment yields of UK catchments that considers the influence of both natural controls and land use activities on the magnitude of specific suspended sediment yields and the associated spatial patterns. The patterns identified by Walling and Webb (1987) are summarised in Table 1.

2.8 In addition:

- Walling and Webb (1987) and Newson and Leeks (1985) estimated long-term sediment yields in upland areas to be 30 t km^{-2} $year^{-1}$ and 50 t km^{-2} $year^{-1}$ respectively. In many instances, these values are impacted by land use and other human activities.
- White and others (1996) undertook a regional survey of sediment yields using reservoir sediment core data in 77 catchments in the south Pennines. The mean specific sediment yield was found to be 124.5 t km^{-2} $year^{-1}$, with a range from a minimum of 6.5 t km^{-2} $year^{-1}$ to a maximum of 1111.5 t km^{-2} $year^{-1}$. This range was tentatively linked to a number of catchment and reservoir variables that included altitude, gradient, topography, land use, and catchment development.

Table 1 Suspended sediment yields in the UK: national generalisations (after Walling and Webb 1987)

Suspended sediment yield	Catchment characteristics
High >100 t km^{-2} $year^{-1}$	Upland Average annual precipitation >1000mm Small/intermediate in size High catchment sediment delivery ratio
Low <25 t km^{-2} $year^{-1}$	Lowland Average annual precipitation - low Large in size Low sediment delivery ratio
Very low <5 t km^{-2} $year^{-1}$ eg Mendip Hills, central Wales	Upland Small Limited anthropogenic impact Resistant bedrock

Note: The sediment delivery ratio is the ratio between the sediment load delivered to the river network and the load reaching the catchment outlet.

A synthesis of available UK suspended sediment yield data

2.9 Sections 2.5 and 2.6 provide a context for the analysis undertaken in this project, which aims to explore the potential for defining critical sediment yields for specific catchment types. In order to achieve this aim it was necessary first to assemble and screen existing sediment yield data for UK catchments and, second, to classify or categorise these data according to catchment type.

Collation of data

2.10 Data were obtained from the following sources:

- existing syntheses;
- review of the relevant literature; and
- output from specific projects such as LOIS.

2.11 The assembled sediment yield data were derived using a range of sampling and monitoring procedures and are therefore of highly variable quality. Thus, for example, in some studies the measurement programme involved continuous recording of turbidity and the conversion of these data to a continuous record of suspended sediment concentration, which was combined with the continuous discharge record to derive the sediment load for the period of record. Such load values are likely to be quite reliable. In other studies, however, only a few spot samples were collected, in order to measure the suspended sediment concentration in the river at the time of sampling, and these concentration values were used to derive a sediment rating curve which was combined with the discharge record, in order to estimate the sediment load for the period of record. Such estimates are frequently of dubious reliability, due to the many uncertainties associated with the use of rating curves (cf. Walling 1977; Walling and Webb 1981). Equally, other estimates of sediment yield available in the literature are based on reservoir surveys. These have the advantage that they frequently encompass a much longer period and are arguably more representative of the longer-term mean, but the reservoir survey procedures and the methods used to estimate the volume of sediment accumulated can introduce significant uncertainties.

2.12 In order to assist in assessing the likely quality of the estimates of specific suspended sediment yield assembled within this study, the methodology employed for determining the sediment yield of each catchment was therefore also recorded (if available) and the associated quality of the data was assessed subjectively as high, medium or low. This categorisation or quality control was undertaken in order to provide a basis for assessing the likely reliability of the data in any attempt to use it to establish critical sediment yields. The criteria employed for this assessment of data quality are summarised in Table 2.

Table 2 A summary of the methodologies used for documenting suspended sediment yields and an associated assessment of likely data quality

Method
High quality
Continuous turbidity monitoring ≥2 years
Automatic sampling: daily plus during storm events ≥ 2 years
Lake/reservoir sediment cores (quality related to specific study)
Medium quality
Continuous turbidity monitoring <2years
Automatic sampling: daily plus during storm events < 2 years
Automatic sampling: daily
Rating curve developed from automatic sampling: weekly plus during storm events
Lake/reservoir sediment cores (quality related to specific study)
Low quality
Continuous turbidity monitoring <1 year
Rating curve developed from regular sampling: weekly (or less frequent) eg Harmonised Monitoring Programme
Rating curve developed from manual sampling
Yield data available but technique not known

Selection of typology

2.13 Catchment typologies are useful in helping to describe the variation in observed sediment yields in a way that can can inform catchment management. A typology is required that is sensitive to natural variations in sediment yield, allowing differences in yield occurring within any one catchment type to be attributable to anthropogenic factors. This greatly simplifies the management task of discriminating between natural and artificial differences in yields, and makes the process of target-setting that much easier. In practice, achieving this discrimination through a typology is difficult to achieve.

2.14 A number of options for defining a catchment typology exist. The options fall into five broad categories, namely:

- channel pattern-based, ie derived from planform classification;
- statistically-based, ie derived from numerical map-based data;
- scale-based, ie hierarchical models linked to catchment size;
- hydraulic geometry or regime-based, ie derived from channel dimensions and flow statistics; and

- process-based, ie derived from an understanding of channel equilibrium and adjustment.

2.15 Examples of each category are summarised in Table 3.

Table 3 Selected examples of catchment typologies

Basis	Example	Comment
Channel pattern	Brice (1975)	System based on planform sinuosity, braiding and branching.
Statistics	Raven and others (1998)	System using numerical map-based data such as altitude, geology and height of source eg the Environment Agency's River Habitat Survey.
Scale	Frissell and others (1986) Brierley and Fryirs (2000)	System that links channel type to catchment size.
Hydraulic geometry	Rosgen (1994)	System that divides streams into seven major types on the basis of hydraulic geometry and bed/bank materials.
Process	Brice (1981) Brookes (1988) Downs (1995)	Classification based on adjustment processes and trends of channel change such as bed degradation, widening, bank erosion and bar development.

2.16 It is important to note, however, that limitations associated with the application of all catchment typologies exist. These include:

- provenance and quality of data: for example, the data used to derive typologies may be limited and not representative of the nature of the catchments to which they are subsequently applied;
- UK rivers are heavily modified and this may not necessarily be accounted for;
- a high level of geomorphological understanding may be required to interpret and apply existing typologies;
- fluvial systems adjust at different rates and present morphology may not reflect present influences;
- UK fluvial systems are supply-limited, so consideration of local sources in addition to overall type is essential;
- catchment typologies are not explicitly linked to the mobilisation and transport of fine sediment or the consequent impact on ecology; and
- catchment geomorphology is highly variable and typologies may not necessarily reflect this.

2.17 Against this background, a catchment typology for the purposes of this project was designed according to the following criteria:

- to provide a clear link to sediment yield data and associated siltation impacts;
- to be simple to apply;
- to be flexible and open to further development; and

- to be consistent with the wider water management framework eg WFD and River Habitat Survey (RHS).

2.18 The data assembled under paragraphs 2.21 - 2.22 were therefore grouped according to three categories, namely:

- upland / lowland;
- size; and
- land use.

2.19 These categories were selected on the basis that they reflect key controls on sediment yield, such as annual rainfall and the sediment delivery ratio. Furthermore, the information required to use these criteria to classify individual catchments is generally readily available. The categories of upland and lowland reflect land above and below 200m respectively and are consistent with the typology used by the EA's RHS (cf. Raven and others 1998). The categories for catchment size were selected to be consistent with the high (reporting) level typology used for the WFD, in order to maximise future compatibility. These categories are as follows:

- <10km^2 ;
- 10-100 km^2 ;
- 100-1000 km^2 ;
- 1000-10 000 km^2 ; and
- >10 000 km^2.

2.20 The land use categories were selected to reflect a much-simplified overview of the nature and extent of anthropogenic impact. The typology provides a separation between those catchments that exhibit limited anthropogenic impact and those catchments where anthropogenic impact is likely to have an impact on the catchment sediment system. In the latter case, the distinction has been made between catchments where either rural land use (ie accommodating the full range of agricultural practices) or urbanisation predominates. Whilst it is recognised that this typology is limited, for example in terms of consideration of specific agricultural practices, those catchments where land use has the potential to accelerate soil erosion and sediment transport are distinguished from those that are likely to be 'semi-natural.

Data synthesis

2.21 The results of the sediment yield data compilation and subsequent classification are presented in Tables 4 and 5 and in Figures 1, 2 and 3. Table 4 presents the basic data classified according to the selected typology and the three data quality categories and Table 5 provides a summary of these data. Figure 1 provides a map showing the spatial distribution of all sites listed, whilst Figures 2 and 3 present maps showing the sediment yield values for all sites (Figure 2) and for those sites where the data were considered to be of either high or of medium quality, respectively (Figure 3). Data considered to be of low quality were excluded from further analysis at this point. Key points relating to the results presented in Tables 4 and 5 and in Figures 2 and 3 are summarised below.

- A total of 146 sediment yield estimates have been collated. Of these, 107 were classified as being of either high or medium quality and therefore suitable for further consideration for the purposes of target setting.
- Most of the data relate explicitly to suspended sediment yields, but it is important to recognise that the data obtained from reservoir surveys relate to **total** sediment load, since the reservoir deposits will incorporate both the suspended sediment load and the bed load transported into the reservoir. As such, the estimates of sediment load based on reservoir surveys give higher values than yields calculated for the same catchment using suspended solids data from rivers. In the absence of good information on the likely magnitude of bed load yields from these reservoir catchments, it is not possible to estimate the suspended load component.

However, a value of 10% is frequently cited for the relative magnitude of the bed load component in UK catchments, and if this value is accepted, the values of sediment yield based on reservoir surveys are unlikely to greatly overestimate the suspended sediment yield of the catchment. Total load as reported by the surveys was used to calculate the averages presented in Table 5.

- The values of specific suspended sediment yield presented in Table 4 range from a minimum of 1 t km^{-2} $year^{-1}$ to a maximum of 311 t km^{-2} $year^{-1}$. Particularly low yields (ie <5 t km^{-2} year $^{-}$1) are associated either with upland areas underlain by resistant rocks, or with chalk streams such as the Hampshire Avon and its tributaries.
- The average sediment yield value is 44 t km^{-2} $year^{-1}$, which is close to the 'typical' value of 50 t km^{-2} $year^{-1}$ for UK rivers identified by Walling and Webb (1987).
- The majority of the data (76%) relate to agricultural catchments, with data being evenly spread between catchment size classes. Data for 'pristine' and urbanised catchments are limited.
- The spatial distribution of the data reflects, in part, the focus of specific research projects or the on-going research interests of particular Universities. For example, high quality and spatially concentrated data are available for the Exe, Hampshire Avon, Wye and Humber catchments and for the South Pennines and Midlands. Limited data are available for eastern England (eg Sussex, Kent, Essex and Norfolk) and for Wales.
- The spatial distribution of the available data does not link readily with the distribution of areas deemed to be at high risk of failure to achieve the Water Framework Directive objective of Good Ecological Status, as identified by the national map of sediment delivery risk presented in Figure 4. For example, whilst some sediment yield data are available for areas of high sediment delivery risk identified in the south Devon, the Hampshire Avon and the Welsh Borders, no data are available for high-risk areas in Cumbria and East Anglia.

2.22 This data compilation represents a first step in any attempt to develop estimates of critical sediment yields and its potential application will be considered further in section 6. Against this background, it is important to recognise a range of issues associated with the potential use of these data. These are considered below.

Table 4 Selected UK sediment yield data according to a preliminary catchment typology

Catchment	Size Km^2	Data quality and technique	Sediment yield ($t\ km^{-2}\ year^{-1}$)	Author
		Upland: limited anthropogenic impact		
		<10km²		
1. Ebyr N.	0.07	Low: rating curve – 1971	1.1	Oxley (1974) in Walling and Webb (1981)
2. Ebyr S.	0.09	Low: rating curve –1971	0.8	Oxley (1974) in Walling and Webb (1981)
3. East Twin	0.18	Low: rating curve 1972-3	2.0	Finlayson (1977) in Walling and Webb (1981)
4. Mixenden	0.77	High: reservoir sedimentation study	11.00	Butcher and others (1993)
5. Snailsden	0.84	High: reservoir sedimentation study	289.46	Butcher and others (1993)
6. Gullet Syke	1.0	Low: long term estimate	194	Wilkinson (1971) in Walling and Webb (1981)
7. West Grain	1.51	Low: long term estimate	256	Wilkinson (1971) in Walling and Webb (1981)
8. Deanhead	2.00	High: reservoir sedimentation study	37.90	Butcher and others (1993)
9. Blackball stream at Lyshwell, Devon (unenclosed moorland)	2.1	High: continuous turbidity monitoring for 17-year study period	4	Walling and Webb (1987)
10. Holme Styles	2.20	High: reservoir sedimentation study	2.90	Butcher and others (1993)
11. Gorpley	2.80	High: reservoir sedimentation study	143.34	Butcher and others (1993)
12. Reva	2.91	High: reservoir sedimentation study	286.14	Butcher and others (1993)
13. Chew	2.92	High: reservoir sedimentation study	212.69	Butcher and others (1993)
14. Embsay	2.95	High: reservoir sedimentation study	165.39	Butcher and others (1993)

Table continued…

Catchment	Size Km^2	Data quality and technique	Sediment yield (t km^{-2} year^{-1})	Author
15. Green Withens	3.40	High: reservoir sedimentation study	21.73	Butcher and others (1993)
16. Gorple Upper	3.80	High: reservoir sedimentation study	64.24	Butcher and others (1993)
17. Graincliffe	5.00	High: reservoir sedimentation study	69.40	Butcher and others (1993)
18. Thornton Moor	5.12	High: reservoir sedimentation study	35.11	Butcher and others (1993)
19. Barden Upper	6.34	High: reservoir sedimentation study	125.05	Butcher and others (1993)
20. Cod Beck	7.12	High: reservoir sedimentation study	74.36	Butcher and others (1993)
21. Ingbirchworth	7.72	High: reservoir sedimentation study	88.25	Butcher and others (1993)
22. Silsden	7.85	High: reservoir sedimentation study	221.61	Butcher and others (1993)
23. Blackmoor-foot	8.20	High: reservoir sedimentation study	89.81	Butcher and others (1993)
24. Widdop	8.90	High: reservoir sedimentation study	101.30	Butcher and others (1993)
25. Kinder	8.95	High: reservoir sedimentation study	135.14	Butcher and others (1993)
10-100km^2				
26. Strines	11.10	High: reservoir sedimentation study	113.40	Wilkinson (1971) in Walling and Webb (1981)
27. Langden Brook	15.3	Low: long term estimate	232	Butcher and others (1993)
28. Langsett	21.06	High: reservoir sedimentation study	169.30	Butcher and others (1993)
29. Broomhead	21.96	High: reservoir sedimentation study	51.00	Butcher and others (1993)
Upland: agriculture				
<10km2				

Table continued…

Catchment	Size Km^2	Data quality and technique	Sediment yield (t km^{-2} year^{-1})	Author
30. N. Tyne	5.0	Medium: reservoir sedimentation study	25.0	Ledger and others (1974) in Walling and Webb (1981)
31. N. Esk	7.0	Medium: reservoir sedimentation study	26.0	Ledger and others (1974) in Walling and Webb (1981)
32. Loxley	7.4	Medium: reservoir sedimentation study	49.7	Young (1958) in Walling and Webb (1981)
33. Churnet	9.8	Medium: reservoir sedimentation study	6.7	Rodda and others (1976) in Walling and Webb (1981)
		10-100km2		
34. Bradgate	17.8	Medium: reservoir sedimentation study	45.6	Cummins and Potter (1972) in Walling and Webb (1981)
35. Rede	40.0	Medium: reservoir sedimentation study	43.1	Hall (1967)
36. Wyre	47.3	Medium: reservoir sedimentation study	34.8	Rodda and others (1976) in Walling and Webb (1981)
		100-1000km2		
37. Swale at Grinton	220	Low: rating curve 1955-7	111	Marshall (1957) in Walling and Webb (1981)
		Lowland: limited anthropogenic impact		
38. Merevale Lake, North Warwickshire (Oak woodland/commercial timber)	2.01	High: lake sediment cores	4-9	Foster and others (1990)

Table continued…

Catchment	Size Km^2	Data quality and technique	Sediment yield (t km^{-2} year^{-1})	Author
		Lowland: agriculture		
		<10km2		
39. East Devon catchment 1	0.11	Medium: automatic sampling 1967-8	9.5	Walling (1971) in Walling and Webb (1981)
40. Fulking	0.18	Low: rating curve 1968-70	12	Collins (1973) in Walling and Webb (1981)
41. Jubilee (Rosemaund catchment), Herefordshire (extensive tile drain system)	0.31	High: continuous turbidity monitoring plus automatic sampling 1997-99	131.0	Walling and others (2002)
42. East Devon catchment 2	0.47	Medium: automatic sampling 1967-8	37	Walling (1971) in Walling and Webb (1981)
43. Seeswood Pool, North Warwickshire	0.65	High: 2-hourly turbidity meter records	8.7	Foster (1995)
44. East Devon catchment 3	0.78	Medium: automatic sampling 1967-8	50	Walling (1971)
45. Nutley	0.18	Low: rating curve 1968-70	5.8	Collins (1973) in Walling and Webb (1981)
46. Slapton Wood, Slapton, Devon	0.93	Medium: 1987-88	72.86	O'Sullivan and others (1989)
47. Slapton Wood, Slapton, Devon	0.94	Medium: automatic sampling 1971-2	8.4	Troake and Walling (1973)

Table continued…

Catchment	Size Km^2	Data quality and technique	Sediment yield (t km^{-2} year^{-1})	Author
48. New Cliftonthorpe (Smisby catchment), Derbyshire (extensive tile drain system)	0.96	High: continuous turbidity monitoring plus automatic sampling 1997-99	64.0	Walling and others (2002)
49. Belmont (Rosemaund catchment), Herefordshire (extensive tile drain system)	1.50	High: continuous turbidity monitoring plus automatic sampling 1997-99	81.9	Walling and others (2002)
50. Stokely Barton, Slapton, Devon	1.53	Medium: 1987-88	31.26	O'Sullivan and others (1989)
51. Stokely Barton, Slapton, Devon	1.53	Medium: 1980-81	11.6	Park (pers.comm.) in Foster and others (1996)
52. Old Mill, Dartmouth Devon	1.58	High: reservoir sediment cores 1942-1991	54 (range from 20 to 90)	Foster and Walling (1994)
53. Yendacott catchment, Devon	1.60	Medium: continuous turbidity monitoring 1995 to 1996	88.10	Shanahan (1998)
54. Seeswood Pool, North Warwickshire	1.61	High: 2-hourly turbidity meter records	68.9	Foster (1995)
55. Seeswood Pool, North Warwickshire	2.4	High: reservoir sediment cores 1954-1995	8-36	Foster (1995)

Table continued…

Catchment	Size Km²	Data quality and technique	Sediment yield (t km^{-2} year^{-1})	Author
56. Lower Smisby (Smisby catchment), Derbyshire (extensive tile drain system)	2.6	High: continuous turbidity monitoring plus automatic sampling 1997-99	80.3	Walling and others (2002)
57. Balcombe	3.1	Low: rating curve 1968-70	44	Collins (1973) in Walling and Webb (1981)
58. East Devon catchment 4	4.97	Medium: automatic sampling 1967-8	46	Walling (1971) in Walling and Webb (1981)
59. Clayhill 2	5.18	Low: rating curve 1968-70	14	Collins (1973) in Walling and Webb (1981)
60. East Devon catchment 5		Medium: automatic sampling 1967-8	56	Walling (1971) in Walling and Webb (1981)
61. Chew Choke Stream	6.47	Low: rating curve 1971-2	70	Brookes (1974)
62. Billingshurst	7.6	Low: rating curve 1968-70	148	Collins (1973) in Walling and Webb (1981)
63. Clayhill 1	8.6	Low: rating curve 1968-70	13	Collins (1973) in Walling and Webb (1981)
64. Jackmoor Brook at Pynes Cottage, Devon	9.8	High: continuous turbidity monitoring for 17-year study period	30	Walling and Webb (1987)
		10 –100 km2		
65. Start, Slapton, Devon	10.79	Medium: 1987-88	9.67	O'Sullivan and others (1989)

Table continued…

Catchment	Size Km^2	Data quality and technique	Sediment yield (t km^{-2} year^{-1})	Author
66. Catchwater Drain	15.0	Low: rating curve 1966-8	8.9	Imeson (1970)
67. Chitterne (Avon basin)	16	High: continuous turbidity measurements plus automatic samplers	2.4	PSYCHIC (pers. comm.)
68. Winterbourne	17.6	Low: rating curve 1968-70	1.8	Collins (1973) in Walling and Webb (1981)
69. Hodge Beck	18.9	Low: rating curve 1966-8	488	Imeson (1970)
70. Sem (Avon basin)	21	High: continuous turbidity measurements plus automatic samplers	9.2	PSYCHIC (pers. comm.)
71. Coombe Pool, Warwickshire	22.25	High: reservoir sediment cores 1946-1995	36	Foster (1995)
72. Gara, Slapton, Devon	23.62	Medium: 1987-88	9.25	O'Sullivan and others (1989)
73. Gauze Brook	24	Low: rating curve 1971-2	28	Brookes (1974)
74. Sid	39.3	Medium: automatic sampling 1967-8	47	Walling (1971) in Walling and Webb (1981)
75. River Dart	46	Medium: continuous turbidity monitoring 1975	91	Walling (1978) in Walling and Webb (1981)
76. River Dart at Bickleigh, Devon	46.0	High: continuous turbidity monitoring for 17-year study period	58	Walling and Webb (1987)
77. River Lowman at Tiverton, Devon	53.7	High: continuous turbidity monitoring for 17-year study period	52	Walling and Webb (1987)
78. Stretford Brook (Wye basin)	55	High: continuous turbidity measurements plus automatic samplers	13.2	PSYCHIC (pers. comm.)
79. River Piddle	63.5	High: continuous turbidity monitoring	11.0	Walling and Amos (1999)

Table continued…

Catchment	Size Km^2	Data quality and technique	Sediment yield (t km^{-2} year^{-1})	Author
80. River Batherm at Bampton, Devon	64.5	High: continuous turbidity monitoring for 17-year study period	35	Walling and Webb (1987)
81. Worm Brook (Wye basin)	69	High: continuous turbidity measurements plus automatic samplers	27.7	PSYCHIC (pers. comm.)
82. Wellow Brook	70	Low: rating curve 1971-2	48	Brookes (1974)
83. Frome (Wye basin)	77	High: continuous turbidity measurements plus automatic samplers	40.5	PSYCHIC (pers. comm.)
84. West Avon (Avon basin)	81	High: continuous turbidity measurements plus automatic samplers	4.7	PSYCHIC (pers. comm.)
85. East Avon (Avon basin)	89	High: continuous turbidity measurements plus automatic samplers	4.95	PSYCHIC (pers. comm.)
86. Garron Brook (Wye basin)	93	High: continuous turbidity measurements plus automatic samplers	20.1	PSYCHIC (pers. comm.)
87. Marden	96	Low: rating curve 1971-2	52	Brookes (1974)
88. River Clyst at Clyst Honiton, Devon	98.2	High: continuous turbidity monitoring for 17-year study period	26	Walling and Webb (1987)
		100-1000 km2		
89. W. Adur	108	Low: rating curve 1968-70	41	Collins (1973) in Walling and Webb (1981)
90. Ebble (Avon basin)	109	High: continuous turbidity measurements plus automatic samplers	4.4	PSYCHIC (pers. comm.)
91. Nadder (Avon basin)	109	High: continuous turbidity measurements plus automatic samplers	9.9	PSYCHIC (pers. comm.)

Table continued…

Catchment	Size Km^2	Data quality and technique	Sediment yield (t km^{-2} year^{-1})	Author
92. River Barle at Brushford, Devon	128.0	High: continuous turbidity monitoring for 17-year study period	16	Walling and Webb (1987)
93. Chew	133	Low: rating curve 1971-2	26	Brookes (1974)
94. Cuckmere	133	Low: rating curve 1968-70	9.2	Collins (1973) in Walling and Webb (1981)
95. Midford Brook	147	Low: rating curve 1971-2	37	Brookes (1974)
96. Semington Brook	152	Low: rating curve 1971-2	15	Brookes (1974)
97. Rother	154	Low: 1972	14	Wood (1976) in Walling and Webb (1981)
98. Upper Exe at Pixton, Devon	160.0	High: continuous turbidity monitoring for 17-year study period	19	Walling and Webb (1987)
99 Ystwyth	170	Low: rating curve 1973-5	164	University of Wales (1977)
100. Almond	176	Low: rating curve 1972-4	59	Al-Ansari and others (1977) in Walling and Webb (1981)
101. Ouse	179	Low: rating curve 1967-8	33	Collins (1973) in Walling and Webb (1981)
102. River Nadder at Wilton	220.6	Medium: continuous turbidity monitoring February 1999 to August 2000	12.5	Heywood (2000)
103. River Culm at Woodmill, Devon	226.0	High: continuous turbidity monitoring for 17-year study period	32	Walling and Webb (1987)
104. White Cart	235	High: continuous turbidity measurement 1964-7	122	Fleming (1970) in Walling and Webb (1981)
105. Frome	256	Low: rating curve 1971-2	35	Brookes (1974)

Table continued…

Catchment	Size Km^2	Data quality and technique	Sediment yield (t km^{-2} year^{-1})	Author
106. River Torridge, Devon	258	High: continuous turbidity monitoring	89.0	Nicholls (2000)
107. River Creedy	262	High: continuous turbidity monitoring 1972-4	53	Walling (1978) in Walling and Webb (1981)
108. River Creedy at Cowley, Devon	262.0	High: continuous turbidity monitoring for 17-year study period	39	Walling and Webb (1987)
109. Avon	266	High: continuous turbidity measurement 1964-7	174	Fleming (1970)
110. River Culm at Rewe, Devon	273.0	High: continuous turbidity monitoring for 17-year study period	20	Walling and Webb (1987)
111. River Esk	310	Low: rating curve 1956-7	25	Marshall (1957) in Walling and Webb (1981)
112. River Avon at Amesbury	323.7	Medium: continuous turbidity monitoring February 1999 to August 2000	4.5	Heywood (2002)
113. Kelvin	335	Medium: continuous turbidity measurement 1967-8	33	Fleming (1970) in Walling and Webb (1981)
114. River Exe at Stoodleigh, Devon	422.0	High: continuous turbidity monitoring for 17-year study period	20	Walling and Webb (1987)
115. River Wylye at South Newton	445.4	Medium: continuous turbidity monitoring February 1999 to August 2000	1.4	Heywood (2002)
116. River Tweed	490	High: continuous turbidity monitoring	310.8	Bronsdon and Naden (2000)
117. River Nidd at Cowthorpe	484.3	High: continuous turbidity monitoring for November 1994 to October 1997 plus automatic and manual sampling	17.1	Wass and Leeks (1999)

Table continued…

Catchment	Size Km^2	Data quality and technique	Sediment yield (t km^{-2} year^{-1})	Author
118. River Swale at Catterick Bridge	499	High: continuous turbidity monitoring for November 1994 to October 1997 plus automatic and manual sampling	58.4	Wass and Leeks (1999)
119. Welland	531	Low: rating curve 1968-70	14	Collins (1973) in Walling and Webb (1981)
120. River Exe	601	Medium: continuous turbidity monitoring 1974-5	24	Walling (1978) in Walling and Webb (1981)
121. River Exe at Thorverton, Devon	601.0	High: continuous turbidity monitoring for 17-year study period	28	Walling and Webb (1987)
122. River Exe at Thorverton, Devon	601.0	Medium: continuous turbidity monitoring for January to December 1983	40.37	Lambert and Walling (1987)
123. Avon	666	Low: rating curve 1971-2	27	Brookes (1974)
124. Leven	784	Medium: continuous turbidity measurement 1966-7	36	Fleming (1970) in Walling and Webb (1981)
125. River Wharfe at Tadcaster	814	High: continuous turbidity monitoring for November 1994 to October 1997 plus automatic and manual sampling	15.3	Wass and Leeks (1999)
126. River Wharfe, Northeast England	818	Medium: 15 minute discharge and suspended sediment concentration records for January 1995 to December 1996	13	Walling and others (1997)
127. River Calder at Methley Bridge	899	High: continuous turbidity monitoring for November 1994 to October 1997 plus automatic and manual sampling	25.9	Wass and Leeks (1999)
128. River Usk	912	Low: rating curve 1957-72	46	Brookes (1974)

Table continued…

Catchment	Size Km^2	Data quality and technique	Sediment yield (t km^{-2} year^{-1})	Author
129. River Ure at Westwick Lock	914	High: continuous turbidity monitoring for November 1994 to October 1997 plus automatic and manual sampling	35.4	Wass and Leeks (1999)
		1000-10 000km2		
130. River Teviot	1110	High: continuous turbidity monitoring	59.2	Bronsdon and Naden (2000)
131. River Don at Doncaster	1256	High: continuous turbidity monitoring for November 1994 to October 1997 plus automatic and manual sampling	12.6	Wass and Leeks (1999)
132. River Swale at Leckby Grange	1350	High: continuous turbidity monitoring for November 1994 to October 1997 plus automatic and manual sampling	33.5	Wass and Leeks (1999)
133. River Swale at Leckby	1383	Low: rating curve 1956	25	Marshall (1957) in Walling and Webb (1981)
134. River Avon at East Mills	1477	Medium: continuous turbidity monitoring February 1999 to August 2000	4.2	Heywood (2002)
135. Nene	1530	Low: rating curve 1968-70	11	Collins (1973) in Walling and Webb (1981)
136. Clyde at Blairston	1700	Medium: continuous turbidity measurement 1967-8	62	Fleming (1970) in Walling and Webb (1981)
137. Clyde at Daldowie	1900	High: continuous turbidity measurement 1964-7	60	Fleming (1970) in Walling and Webb (1981)
138. River Aire at Beale Weir	1932	High: continuous turbidity monitoring for November 1994 to October 1997 plus automatic and manual sampling	21.6	Wass and Leeks (1999)

Table continued…

Catchment	Size Km^2	Data quality and technique	Sediment yield (t km^{-2} year^{-1})	Author
139. Tyne	2159	Low: manual sampling 1959-61	61	Hall (1967)
140. River Ouse, Northeast England	3315	Medium: 15 minute discharge and suspended sediment concentration records for January 1995 to December 1996	23	Walling and others (1997)
141. River Ouse at Skelton	3315	High: continuous turbidity monitoring for November 1994 to October 1997 plus automatic and manual sampling	23.9	Wass and Leeks (1999)
142. River Wye	4040	Low: rating curve 1949-72	51	Brookes (1974)
143. River Severn	6850	Low: rating curve 1937-72	65	Brookes (1974)
144. River Trent at North Muskham	8231	High: continuous turbidity monitoring for November 1994 to October 1997 plus automatic and manual sampling	10.2	Wass and Leeks (1999)
		Lowland: urban		
		<10km		
145. Wyken Slough, Warwickshire	4.5	High: reservoir sediment cores 1954-95	10	Foster (1995)
		10 –100 km2		
146. Holmer Lake (Urban/mining)	18.37	High: reservoir sediment cores 1954-95	20.1	Walling and Webb (1987)

Table 5 Summary of high and medium quality sediment yield data findings

Catchment type	Size	Number	Sediment yield range t km^{-2} $year^{-1}$	Sediment yield average t km^{-2} $year^{-1}$
Upland: Rough pasture	<10km^2	20	3– 286	109
	10-100 km^2	3	51 – 169	111
Upland: Agriculture	<10km^2	4	6.7 – 49.7	27
	10-100 km^2	3	35 – 46	41
Lowland: limited anthropogenic impact	<10km^2	1	4 - 9	7
Lowland: Agriculture	<10km^2	19	8 – 131	51
	10-100 km^2	18	2 - 58	28
	100-1000 km^2	27	1 – 311	46
	1000-10 000 km^2	10	4 - 59	31
Lowland: Urban	<10km^2	1	10	10
	10-100 km^2	1	20	20

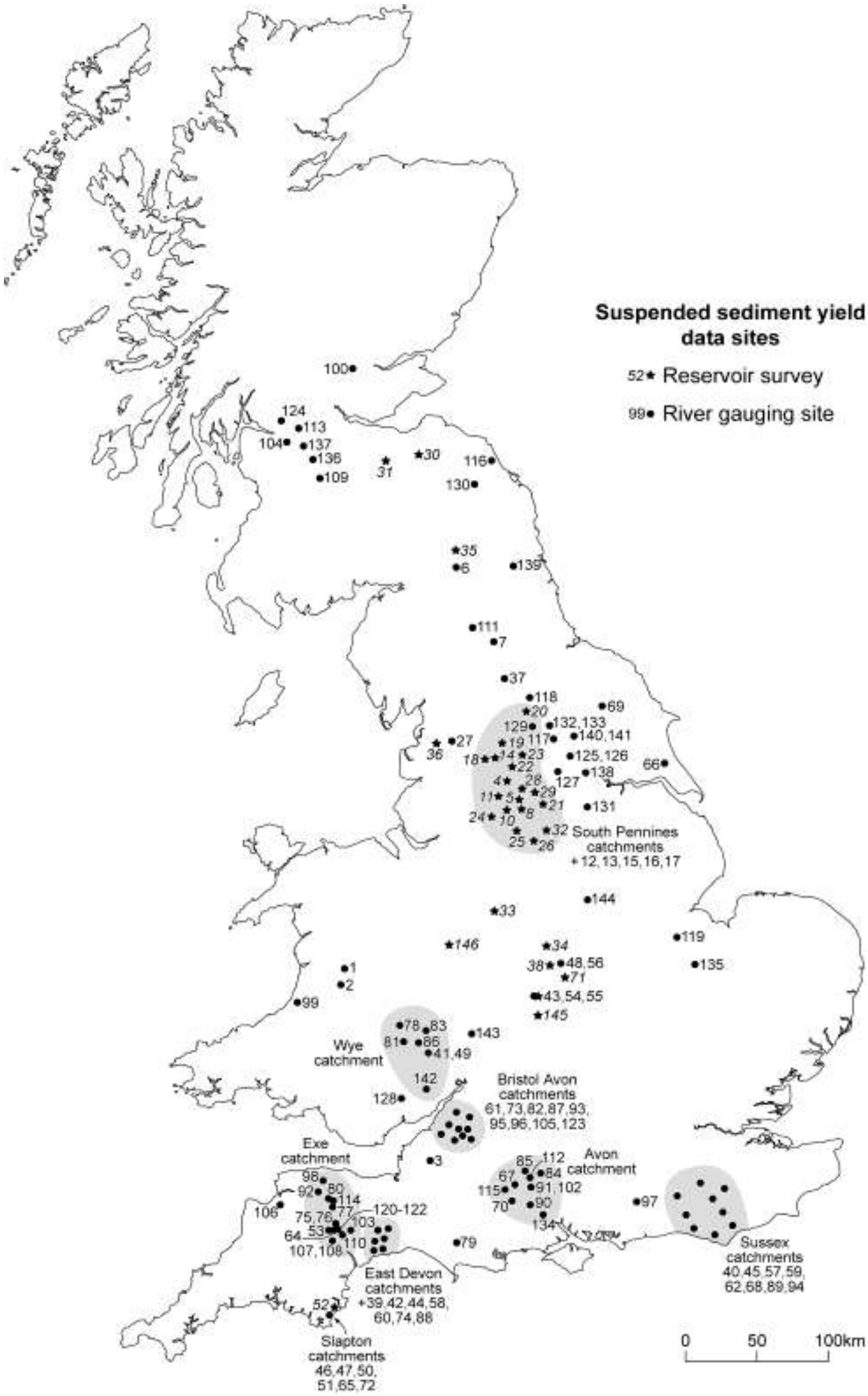

Figure 1 Distribution of sediment yield data sources (see Table 4 for index of catchment names)

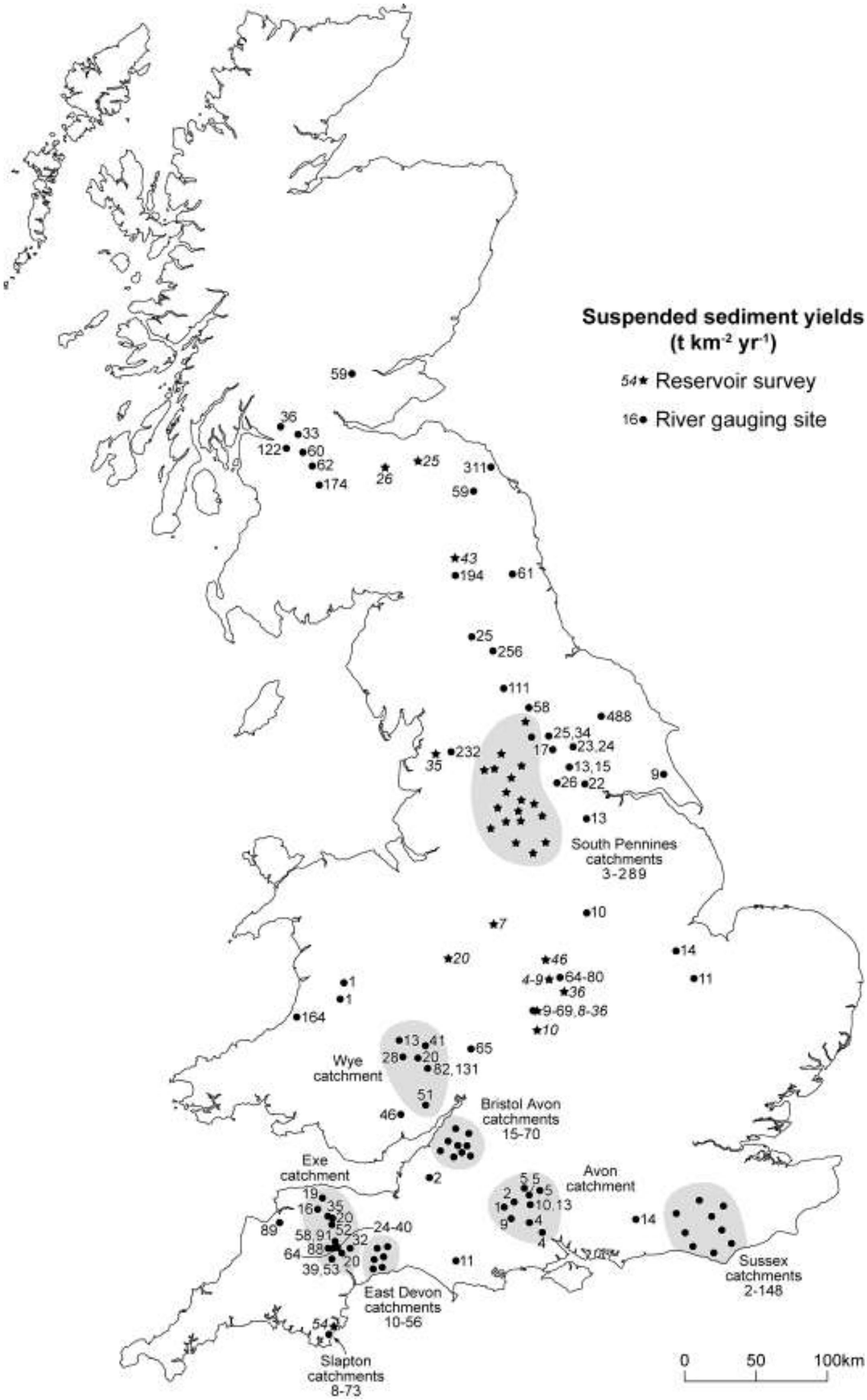

Figure 2 Countrywide variation of suspended sediment yields in the UK: high, medium and low quality data

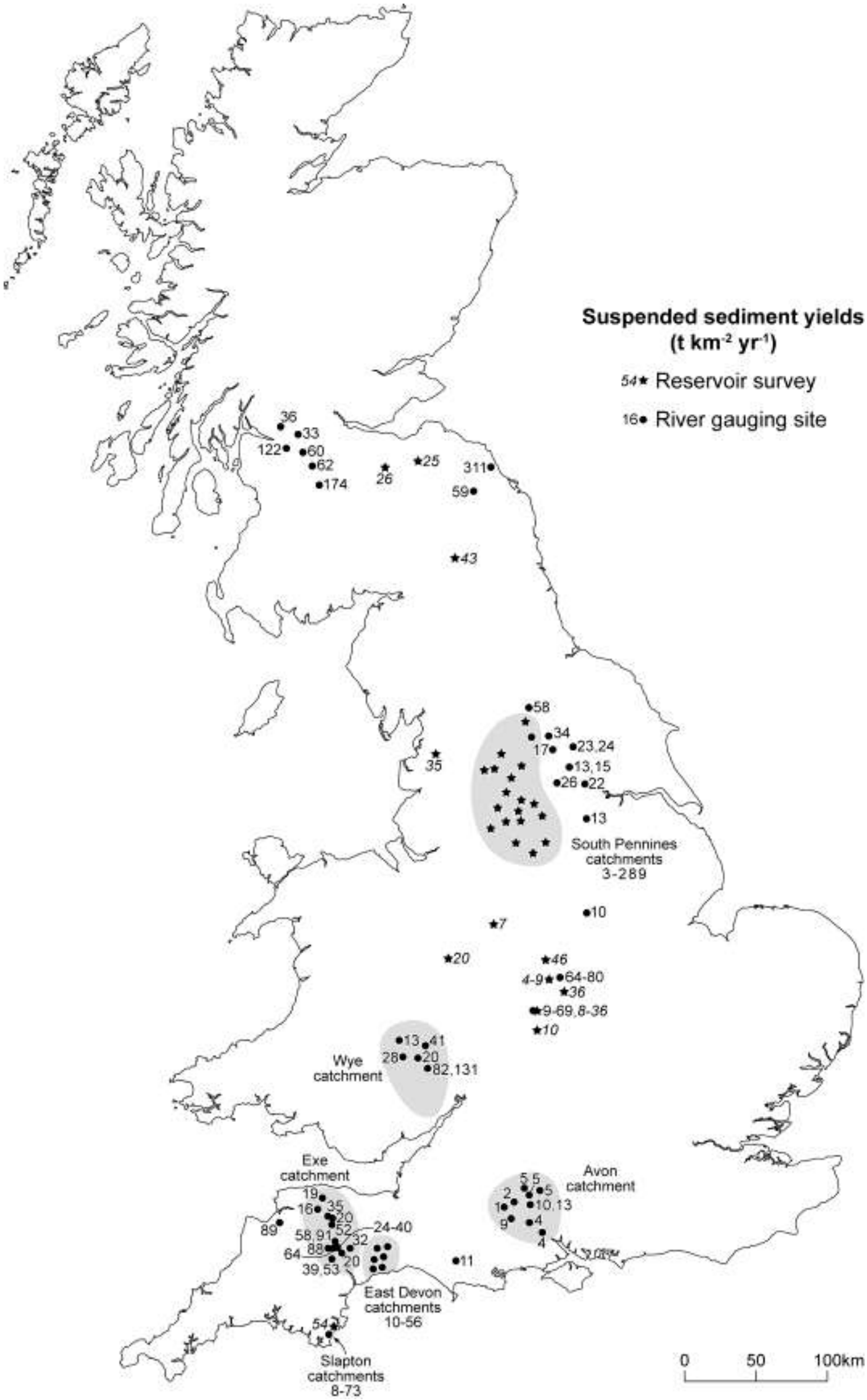

Figure 3 Countrywide variation of suspended sediment yields in the UK: high and medium quality data

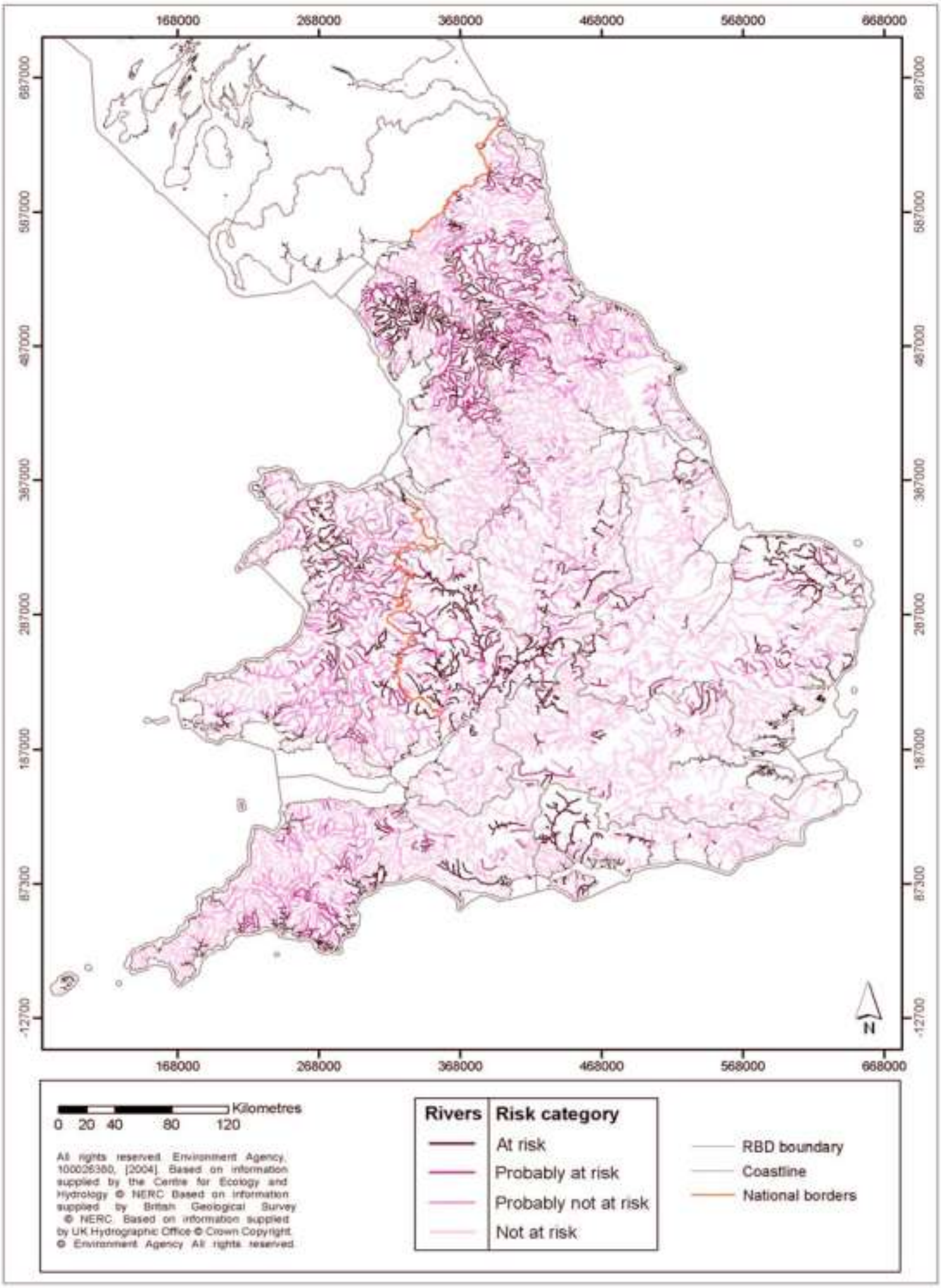

Figure 4 River water bodies at risk of not achieving Water Framework Directive objectives due to sediment delivery pressures as identified by the Environment Agency (2004)

Sediment yield data constraints and limitations

2.23 Objective 4 of this project addresses the use of the data compilation presented above in order to develop preliminary estimates of critical sediment yields for different catchment types. In this context, it is important to highlight a number of constraints or limitations relating to both sediment yield data in general and to the data specific to this study. These include the following:

- In the absence of a national suspended sediment monitoring network, existing suspended sediment yield data are derived primarily from local research projects and catchment investigations. Data are therefore inherently limited in three key ways viz:

  a) erratic and unrepresentative spatial coverage;
  b) limited long-term data sets; and
  c) wide variation in the techniques and procedures used for data collection, potentially compromising data consistency.

  In addition, the inherent temporal variability of sediment delivery systems has been widely documented. As a result, the representativeness of short-term data sets will frequently be open to question and the potential for making meaningful comparisons between catchments and different data sets, in order to categorise sediment yields according to different catchment types, could again be compromised.
  An extreme example of the potential lack of consistency between data derived from different studies is provided by the estimates of the suspended sediment yield of the Hodge Beck catchment in the North York Moors reported by Imeson (1970) and Arnett (1979). These values were 488t km-2 year -1 and 2.1t km-2 year -1 respectively. The major discrepancy between the two estimates could reflect the different study periods and the different locations of the measuring points, but the main source of the contrast in the magnitude of the two estimates is likely to be the different sediment sampling strategies and load calculation procedures used by the two studies. In most cases this potential cause of inconsistency should be highlighted by the quality screening undertaken for the data assembled in this study and by the rejection of unreliable estimates of sediment yield.
- The suspended sediment yield of a catchment provides a valuable measure of the total volume of sediment delivered to the catchment outlet on an annual basis. However, annual catchment sediment yield data represent a spatially- and temporally-lumped measure of sediment flux that may not necessarily provide information at an appropriate spatial and temporal scale for relating to catchment ecology and defining targets. For example, a low annual sediment yield may mask the potential impact of a short period of high load and a significant associated ecological impact. In addition, sediment yield data may not readily reflect variable ecological impacts associated with different sediment supply, sediment transport and channel flow conditions. In view of this, the potential for employing additional or complementary indicators of sediment yield, and more particularly suspended sediment rating curves, is considered in paragraphs 2.25 - 2.28. The rationale for a sediment yield approach is discussed further in Section 5.
- Similarly, whilst suspended sediment yield data can provide a valuable summary of fine sediment fluxes at the catchment scale, the need to recognise the ‘sediment delivery problem’ (cf. Walling 1983) is well documented. Only a proportion, and possibly only a small proportion, of the sediment eroded from the surface of a catchment will be delivered to the sub-catchment or catchment outlet as the sediment yield and the associated delivery or conveyance processes are highly variable, both spatially and temporally. In view of this, additional information relating to the relative importance of different sediment sources and the ‘efficiency’ of sediment delivery from those sources may be required to complement sediment yield data and to inform catchment management. Suspended sediment sources are therefore considered further in paragraphs 2.29 - 2.44.
- The catchment typology used in this project represents a first attempt to apply a classification to the assembled data. The potential exists for further refinement to include consideration of factors such as the permeability of the underlying geology and specific land use types.

However, in view of the limited amount of data available and potential limitations in its reliability, any further subdivision of the data set should only be undertaken with caution, in order to minimise the problems of reducing the reliability and credibility of the resulting critical sediment yield estimates.

- The suspended sediment yield of a catchment represents only a proportion of the total sediment flux at the catchment outlet. Whilst this project is specifically concerned with ecological problems associated with fine sediment and thus suspended sediment fluxes and the deposition of associated fines, it may prove useful to incorporate consideration of bed load yields (most of which is coarse sediment) into future work, in order to provide an integrated assessment of sediment management requirements. The stream power calculations provided by GeoRHS may provide a useful framework for further work on estimating bed load fluxes.

2.24 It is important to recognise that sediment is both a pollutant in its own right and a pollutant vector. This project is concerned primarily with sediment and its physical impact on aquatic ecology, rather than sediment-associated contaminants. Any attempt to establish critical sediment yields based on the sediment yield data assembled presented will therefore necessarily be designed to reflect the potential thresholds of the impact of sediment per se and will not extend to consideration of secondary impacts introduced by sediment-associated contaminants, which are likely to respond to different controls. Where, for example, sediment-associated phosphorus inputs to a river or water body are of concern due to eutrophication, the critical sediment yield could be substantially lower than that based on potential physical impacts. Further work is undoubtedly required to explore this additional facet of fine sediment loadings and to incorporate it into future attempts to set integrated targets for suspended sediment yields.

Suspended sediment concentration/flow relationships and rating curves

2.25 The aim of this project is to investigate the potential for establishing sediment targets as a basis for reducing the deleterious impacts of fine sediment on aquatic habitats and aquatic ecology. Emphasis is being placed on the use of catchment sediment yields derived from suspended solids data as the basis for such targets. The focus of objective 1 is to assemble existing sediment yield data and to classify it as a first step towards target-setting. The findings of this exercise have been presented and important issues relating both to the quality and therefore reliability of existing sediment yield data and to the value of this spatially- and temporally-aggregated measure have been identified. In particular, the need to develop sediment-targets that can be applied at spatial and temporal scales that are meaningful in terms of aquatic ecology has been highlighted. In view of this, the potential for using sediment rating curves to complement the sediment yield-based approach will be further explored within Sections 5 and 6. It is therefore useful to consider the availability and characteristics of such data for UK catchments.

2.26 Suspended sediment rating curves, which represent plots of suspended sediment concentration or suspended sediment load versus discharge (river flow) for an individual measuring station, provide a useful means of characterizing the fine sediment dynamics of a catchment and potentially offer a useful complement to a yield-based approach for setting sediment targets. Whereas a value of sediment yield provides a lumped measure of the sediment output from a catchment, the sediment rating curve provides further information on the range of sediment concentrations or sediment discharges found in a stream and their variability at different levels of flow. A given value of sediment yield could, for example, result from either short-lived periods of high concentration associated with high flows or lower concentrations occurring over more extended periods.

2.27 Thus, the target could be defined primarily in terms of the magnitude of the suspended sediment yield, but this could be further qualified in terms of the characteristics of the sediment rating curve or flow/concentration relationship. An example of a suspended sediment concentration versus discharge relationship for the River Creedy in Devon is presented in Figure 5. Such rating curves are commonly plotted on logarithmic axes. The rating curve provides a means of summarizing the temporal variation of suspended sediment concentrations or loads in a catchment and, more particularly, their variability in response to discharge, rising and falling stage and season. Simple measures derived from the rating curve such as the slope, and the typical concentrations encountered during low flows and high flows, defined in terms of frequency of exceedence, could potentially be incorporated into any sediment yield target. Such target refinement could, for example, be designed to accommodate variation between seasons.

2.28 The data needed to establish and characterise rating curves could be obtained either from the literature or from the Environment Agency's Harmonised Monitoring Programme. The latter data are available for a substantial number of larger UK catchments and could afford an opportunity for documenting changes in the relationship between sediment concentration and flow, in response to human impact, for specific catchments. Further investigation would be required to identify the full potential of these data sources for establishing rating curves and defining key parameters that could be incorporated into sediment targets. It is important to note that data quality issues similar to those detailed for sediment yield data exist, particularly for high flows.

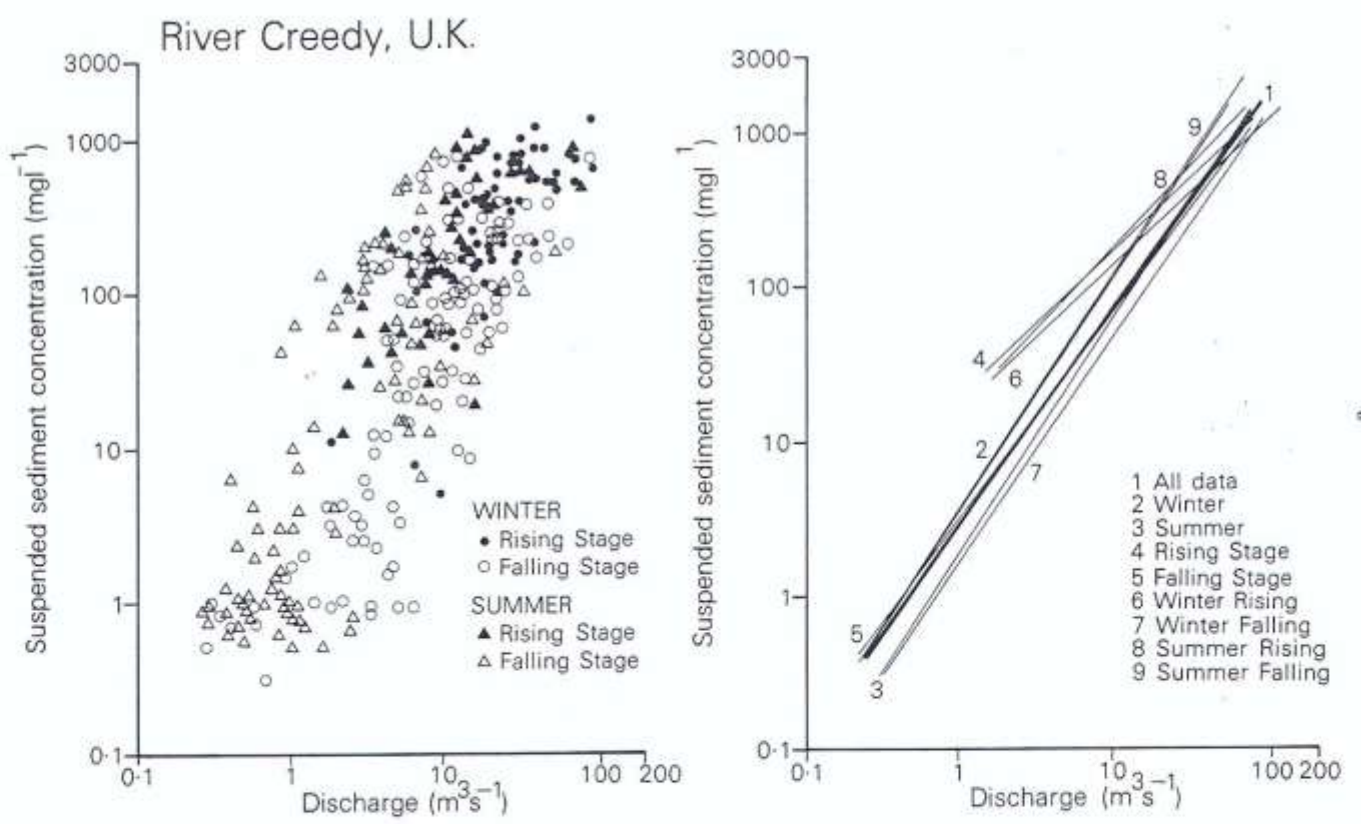

Figure 5 The suspended sediment concentration/discharge relationship for the River Creedy, Devon (Walling and Webb 1987)

Fine sediment characterisation

2.29 Traditionally, the suspended sediment response of a catchment has been characterised in terms of either the magnitude of the sediment flux or yield or the magnitude of the concentrations and this project places emphasis on these characteristics in attempting to define and establish targets. However, in addition to these basic magnitude considerations, scope exists to include other measures of the sediment response, and, more particularly, the physical and chemical properties of the sediment. These could include the grain size composition of the sediment, since this could have a significant influence on ecological impact. However, there are currently few data available on this parameter and existing understanding suggests that UK catchments are characterised by relatively limited variability in grain size composition. Similar, if not more substantive, constraints would face any attempt to consider selected geochemical properties.

2.30 Another measure of the sediment response, which will reflect sediment properties, is the source of the sediment. The focus of this project is sediment derived from erosion of the catchment surface and the channel network, since these will be the dominant sources in most catchments. However, it should be recognised that additional sources of suspended sediment exist. These include the suspended solids associated with the effluent from sewage treatment works, algae, phytoplankton and other primarily organic autochthonous material.

2.31 Catchment sediment sources can be classified in a variety of ways, but in this context the basic distinction between sediment originating from channel erosion and that mobilised from the catchment surface is likely to be most meaningful in terms of contrasting characteristics. Surface sources could be further categorised in terms of land use (eg areas under woodland, pasture and arable cultivation). Information on sediment source is also potentially important if an attempt is made to introduce sediment management or control measures, since any control measure must be targeted at the dominant source or sources.

2.32 Thus, for example, if the primary source of the suspended sediment output from a catchment is the channel system, with bank erosion representing a key contribution, control measures targeted at the catchment surface would have only a limited effect in reducing the sediment yield. Equally, if the cultivated areas of the catchment surface are the dominant source, control measures should be targeted at those areas rather than the channel system. Since, in many instances, the establishment of sediment targets is likely to be coupled with a requirement to implement control or management measures aimed at meeting those targets, information on sediment source is highly relevant.

2.33 The importance of information on sediment source relates primarily to catchment management activities aimed at meeting prescribed targets, rather than establishing or defining those targets in the first place. However, if sediment-associated nutrients and contaminants were to be considered when setting targets, the importance of sediment source in influencing sediment quality means that sediment source could assume greater importance in target-setting per se. A given sediment yield derived primarily from bank sources is likely to have a much lower nutrient and pesticide content than the same amount of sediment derived from surface sources. In some situations it may be appropriate and useful to include other sediment sources, as indicated above. Further consideration of the role of sediment sources in target setting is presented in section 5.

2.34 It is difficult to obtain information on sediment source using traditional approaches (such as erosion pins and plots), however a number of further opportunities exist. These can be considered under two main strands: first, sediment source fingerprinting techniques; and second, field-based fluvial geomorphological survey methods. Each is considered in turn below.

Sediment source fingerprinting

2.35 Recent advances in the application of source fingerprinting techniques (eg Walling and Woodward 1995, Collins and others 1997; Walling and others 1999), have provided a reliable basis for assembling such information. In brief, this approach involves the collection of suspended sediment samples from a river and comparisons of the geochemical properties or ‘fingerprint’ of this sediment with those of potential sources. Statistical procedures are commonly employed to select geochemical properties capable of discriminating between potential sources and to select an optimum composite fingerprint to use for source tracing. By using a multiparameter mixing model, it is possible to estimate the relative contribution of several sources to suspended sediment samples collected at the outlet of a catchment. If these samples are representative of the overall sediment yield, it is possible to establish the relative contributions the designated sources to the suspended sediment yield from a catchment.

2.36 The Sediment Research Group at the University of Exeter has undertaken a considerable number of sediment source tracing investigations in UK catchments and the results of this work now provides a useful indication of suspended sediment sources in British rivers (see Walling and Collins 2005). In these studies, a broad categorisation of sources into channel or bank /

subsurface erosion and the catchment surface under different types of land use, namely, woodland, permanent pasture, and arable cultivation, has been employed and this has made it possible to begin to assemble a national data base for suspended sediment sources. To date, data are available for 48 catchments and the locations of these are shown on Figure 6. The estimates of sediment source contributions to the sediment yields of these catchments are presented in Table 6 and these are further summarised in Figure 7, which presents frequency distributions for the contributions from the two main groups of sources, namely, surface sources and channel/subsurface sources.

2.37 Although not totally representative of the potential range of catchment types in the UK, this sample of 48 catchments provides a reasonable coverage of different areas of the UK, including both upland and lowland areas and catchments with contrasting geologies. As a result it is seen to provide a meaningful indication of the likely range of contributions of the main suspended sediment sources indicated to the suspended sediment yields of UK catchments. Figure 7 highlights the wide range of relative contributions of the catchment surface and channel/subsurface sources to the sediment yields of British rivers, with both sources accounting for up to 60% of the sediment yield in different catchments. There are a significant number of catchments where the channel/subsurface contribution exceeds 40% and also where the surface contribution exceeds 90%. If generalizations are required, Figure 7 indicates that contributions in the range 85-95% from the catchment surface and 5-15% from channel/subsurface sources are arguably typical of British catchments, but is important to recognize the wide range of contributions from both sources.

Field-based fluvial geomorphological survey methods

2.38 In addition to the possibility of quantifying sediment sources using the fingerprinting technique, a number of geomorphological approaches, based on field observation, exist for elucidation of sediment sources. The methods are detailed in the Guidebook of Applied Fluvial Geomorphology (Sear and others 2003) and include the following:

- RHS (cf. Raven and others 1998);
- GeoRHS, ie the refined geomorphological and floodplain component for the RHS (cf. Geodata Institute 2003);
- Catchment Baseline Survey (CBS) (cf. Sear and others 2003);
- Fluvial audit (cf. Sear and others 2003);
- Geomorphological dynamics assessment (cf. Sear and others 2003); and
- Stream reconnaissance survey (cf. Thorne 1998).

2.39 The methods provide varying degrees of detail at a range of scales. Selection of the appropriate method is dependent on a range of factors. Walker (and others, in press) describes these factors as falling into four categories, as follows:

- output intensity (eg subcatchment vs contiguous reach scale);
- assessment function (eg characterisation vs understanding of change);
- project cost and complexity; and
- economic and environmental risk (eg detailed assessment for sediment problems in a SSSI).

2.40 Further details of the use of geomorphological methods in sediment source and impact evaluation are provided in Appendix 1.

Table 6 Estimates of source type contributions for a selection of British catchments obtained using the source fingerprinting technique

			% Contribution[2]					
			Topsoil from areas under					
Catchment No[1]	River/catchment	Area (km²)	Woodland	Pasture/ moorland	Cultivated	Channel banks	Drains	Study
1	Ettrick Water	500	3	49	-	48	a	
2	Teviot	1110	15	21	24	39	a	
3	Tweed	4390	7	20	35	39	a	
4	Swale	1350	-	42	30	28	b	
5	Ure	914	0.7	45	17	37	b	
6	Nidd	484	6.9	75	2.8	15	b	
7	Ouse	3315	-	25	38	37	b	
8	Wharfe	814	4.4	70	3.6	23	b	
9	Aire	282	-	45	-	55		c
10	Aire	-	-	57	-	43		c
11	Aire[3]	1932	-	7	20	33		c
12	New Cliftonthorpe	0.96	-	30	33	6	31	d
13	Lower Smisby	2.6	-	26	37	6.2	31	d
14	Upper Hore	1.6	11	63	-	26		e
15	Hafren	-	78	28	-	4		e
16	Upper Severn	8.7	22	68	-	12		e
17	Upper Severn	580	48	29	-	23		e
18	Rhiw	140	2	89	2	7		e
19	Vyrnwy	778	2	83	4	11		e
20	Perry	181	2	71	22	5		e
21	Severn	4325	2	65	25	8		e
22	Tern	852	1	40	53	5		e
23	Jubilee	0.31	-	3.1	37	12	48	d
24	Belmont	1.5	-	3.9	30	11	55	d
25	Frome	77	-	14	38	48		f
26	Stretford Brook	55	-	9	48	43		f
27	Dore	42	-	2	56	42		f

Table continued…

Catchment No[1]	River/catchment	Area (km^2)	% Contribution[2] Topsoil from areas under: Woodland	Pasture/ moorland	Cultivated	Channel banks	Drains	Study
28	Worm	69	-	25	20	55		f
29	Garron Brook	93	-	14	46	40		f
30	E. Avon	89	-	19	64	17		f
31	W. Avon.	85	-	25	71	4		f
32	Till	55	1	46	33	20		f
33	Chittern	16	-	30	69	1		f
34	Sem	21	-	10	78	12		f
35	Ebble	109	-	37	52	11		f
36	Nadder	221	-	4	54	32		f
36	Nadder	221	1.3	16	69	14		g
37	Upper Avon	324	1.8	12	78	8.2		g
38	Wylye	446	1.7	14	73	11		g
39	Lower Avon	1477	1.4	16	64	19		g
40	Waldon	78	4	48	27	21		h
41	Upper Torridge	115	2	48	29	21		h
42	Torridge	258	2	47	28	23		h
43	Barle	128	6	85	1	8		e
44	Bathern	64	1	87	3	9		e
45	Lowman	54	2	54	40	4		e
46	Dart	46	3	82	11	5		e
47	Exe	601	3	72	20	5		e
48	Culm	276	-	30	60	10		i
49	Culm	276	-	35	53	12		j

[1] See Figure 6.

[2] In several cases contribution values were abstracted from histogram plots and represent approximate values.

[3] There were additional contributions from urban sources in this catchment, ie STW solids 18% and road dust 22%. a = Owens and others (2000); b = Walling and others (1999); c = Carter and others (2003); d = Russell and others (2001); e = Collins and others (1997a, b); f = Walling and others (unpublished); g = Heywood (2003); h = Nicholls (2001); i = Walling & Woodward (1995); j = He & Owens (1995).

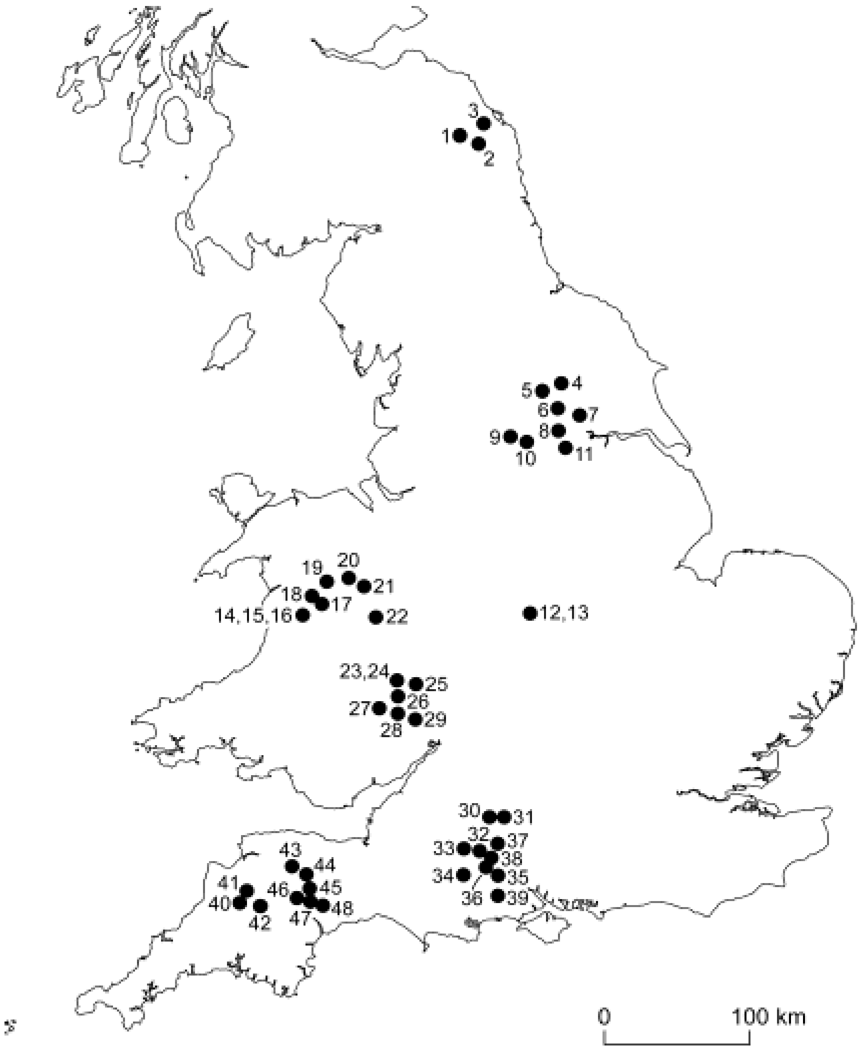

Figure 6 The location of the UK catchments for which information on suspended sediment source has been assembled (see Table 6)

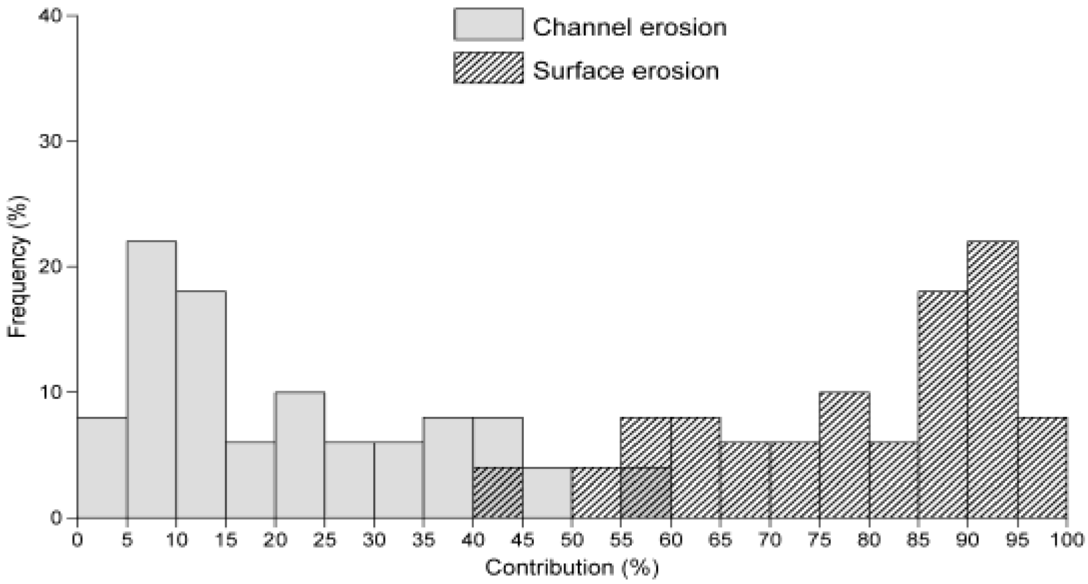

Figure 7 Frequency distributions of the percentage contributions from surface sources and channel / subsurface sources for the study catchments identified in Figure 6

2.41 Fluvial audit is the most comprehensive option available and includes full consideration of all desk-based resources, full field survey and consideration of the role of management and morphological adjustment. Fluvial audit represents the ‘leading geomorphological tool for application to data collection contiguously along all watercourses of interest at the catchment scale’ (Walker, and others, in press: 8). The approach offers a number of advantages for sediment source identification and management. For example, data relating to sediment sources, pathways and stores are collected according to a coherent, spatially referenced framework. This allows storage and analysis of data using a GIS and therefore provides the potential for comparison both between catchments and within an individual catchment over time. In addition, audits are performed by experienced fluvial geomorphologists and therefore allow interpretation of cause and effect as input to management.

2.42 It is, however, important to recognise a number of important contrasts between the two approaches to investigating sediment sources outlined above.. The source fingerprinting approach has been applied primarily to fine sediment and, if time integrated sampling is used, it can also provide a longer-term assessment of sediment source. In many instances, fine sediment will represent the dominant cause of ecological impacts linked to excess sediment delivery. Furthermore, as indicated in Figure 7, the fingerprinting approach is applicable to both channel and catchment surface sources and is able to provide information on their relative importance.

2.43 In contrast, field-based geomorphological surveys are primarily applicable to coarser, channel-derived sediment where sources are commonly clearly visible. Although it is possible to identify catchment surface sources as pathways, a single survey is likely to be inadequate for identifying all such sources, which may vary in significance throughout the year. Moreover, it should be recognised that some surface sources may be difficult to identify in the field, unless a site is visited during a storm event. In addition, such field-based surveys are unlikely to be able to provide a reliable assessment of the relative importance of surface and channel sources. Such information may be an important requirement when targeting control measures.

2.44 Clearly, fluvial geomorphological assessment is valuable for assessing other forms of anthropogenic impact, most notably morphological impacts caused by channel modifications and coarse sediment supply. Fluvial geomorphological assessment and sediment source fingerprinting are both critical tools for problem evaluation in catchments, and an understanding of local issues should ultimately guide the choice of method.

3 Approaches to target-setting for sediment control in other countries

Overview

3.1 The availability, nature and quality of existing sediment yield data for the UK were reviewed in Section 2, as a first step towards development of sediment targets. In order to inform target-setting for sediment control in the UK and to place this process into a broader context, the next step is to consider the experience of target-setting in other countries. A review of overseas approaches was undertaken using:

- an internet keyword search;
- a internet search of specific agencies and institutions in other countries; and
- direct contact with staff from specific agencies and institutions in other countries.

3.2 Drawing on the information provided by the above searches, the following areas have been considered in further detail:

- Europe (including Eire and Scotland);
- Canada;
- Australia;
- New Zealand; and
- USA.

3.3 All of the above recognise the need to set sediment targets and have a legislative framework for their development and application. Of these, both New Zealand and the USA have developed guidelines that relate to sediment and its impact on aquatic ecosystems. However, the USA appears to be the only country that has actually implemented a statutory programme of target setting for sediment loads. These targets take the form of Total Maximum Daily Loads (TMDLs) and are considered in greater detail below.

3.4 Against this background, the experience of TMDL establishment in the USA is able to provide a useful input to the development of sediment targets in the UK. In particular, the site-specific nature of target setting in the US enables a range of potential approaches to be considered. However, it is important to recognise the significant differences in both the sediment dynamics of the catchments and resource availability (especially data), when considering the relevance of US experience to UK catchments. The application of the findings to the UK is considered further in section 5.

Approaches in other countries

Europe

3.5 The experience of specific European countries was investigated, as well as the overall approach of the EU. Information from the Internet, published sources and direct contact with individuals and organisations was reviewed. It became evident that present progress towards target setting for sediment control in individual countries was limited overall and that future progress was likely to be in association with the WFD and as a result of individual projects such as this.

Sources

- European Environment Agency - URL://www.eea.eu.int
- EU - URL://www.europa.eu.int
- European Topic Centre on Water - URL://water.eionet.europa.eu
- UK Environment Agency - URL://www.environment-agency.gov.uk
- SedNet - URL://www.SedNet.org
- Brian Kronvang, DERI, Silkeborg, Denmark (DW)
- Peter Fox, UK Environment Agency
- Roy Richardson, SEPA

Key findings

- It appears that to date no European country has developed or implemented sediment targets.
- The WFD presents a legislative framework for development of targets for achieving Good Ecological Status (GES) for surface waters by 2015. Guidance on establishing reference conditions and ecological quality class boundaries is provided under the EU Common Implementation Strategy for the WFD. 'Suspended material' is identified as a main pollutant under Annex VIII of the WFD. The potential for future development of sediment targets therefore exists.
- This project represents a first step towards development of sediment targets as a contribution to the specification of environmental conditions consistent with GES in the UK.

Canada

3.6 A review of Internet sources and direct contact with individuals at the Canadian equivalent of the Environment Agency indicated that sediment is considered as a pollutant in Canadian waters and that guidelines for its management do exist. However, the applicability of these guidelines to the UK is limited by their focus on sediment-associated contaminants (ie sediment quality) and by their qualitative nature.

Sources

- Environment Canada - URL://www.ec.gc.ca
- Ian Droppo , Environment Canada, Ontario
- Barry Smith, Environment Canada, Ontario

Key findings

- No suspended sediment standards exist in Canada.
- Canadian Environmental Quality Guidelines (CEQGs) exist for water, sediment, soil and tissue. These are nationally approved, scientifically based indicators of environmental quality and are mandated Federally under the Canadian Environmental Protection Act (CEPA) 1999.
- A CEQG exists for total particulate matter and suspended sediment is identified as a component of this.
- The suspended sediment CEQG for freshwater with respect to aquatic life is identified as 'narrative', ie a qualitative statement.
- The focus of sediment management under the CEQGs appears to be on sediment-associated contaminants rather than sediment load per se.

Australia

3.7 A review of Internet sources was undertaken to determine the Australian perspective. Progress towards setting sediment targets appears to be at a similar stage to that in the UK. The legislative framework is in place and turbidity/suspended solids targets are being developed via projects within individual regions.

Sources

- CSIRO Heartlands initiative -URL://www.clw.csiro.au/heartlands
- Australian Research Centre for Water in Society - URL://www.clw.csiro.au/research/society/arcwis
- National Heritage Trust - URL://www.nht.gov.au
- Natural Resource Management - URL://www.environment.gov.au/nrm/index.html

Key findings

- The National Action Plan for Salinity and Water Quality (NAP) and Natural Heritage Trust (NHT) are major national programmes that aim to improve the management of Australia's natural resources. The programmes are management-led and implemented together via regional plans for each of 56 regions.
- The NAP requires that regional targets relating to resource condition are set for a range of parameters, including turbidity/suspended particulate matter in aquatic environments.
- To measure progress against the targets, a suite of related indicators has been developed under the National NRM Monitoring and Evaluation Framework. Turbidity/suspended solids are identified through a 'heading' as an indicator of resource condition.
- The legislation is relatively new (key documents revised in April 2003) and it appears that targets for individual regions have not yet been set.
- The Heartlands initiative is a programme to improve land use in the Murray-Darling Basin. One project within this initiative is concerned with 'managing sediment and nutrients to maintain water quality and aquatic ecosystems'. It involves setting targets for sediment and nutrient delivery and associated management responses.

New Zealand

3.8 A review of Internet and published sources was undertaken and this was complemented by direct contact with individuals at NIWA. Turbidity and optical water quality and their ecological impact represent the focus of sediment control in New Zealand and non-statutory guidelines for their protection have been developed. However, no statutory guidelines for suspended and deposited sediment exist.

Sources

- National Institute of Water and Atmospheric Research Ltd. - URL://www.niwa.cri.nz
- Professor Murray Hicks - NIWA
- Dr Rob Davies-Colley – NIWA
- Davies-Colley, R.J. and Smith, D.G. Turbidity, suspended sediment and water clarity review.
- Smith, D.G. and Davies-Colley, R.J. If visual water clarity is the issue, then why not measure it?

Key Findings

- NIWA highlights the need to consider the impact of fine sediment on aquatic ecology, both whilst sediment is in suspension and once it has settled. The ecological impact of sediment whilst in suspension was identified as being of greater concern.
- In view of the above, the research focus in New Zealand concerns the impact of suspended sediment on optical water quality and its link to aquatic ecology. To this end, New Zealand has developed non-statutory guidelines for protection of optical water quality from suspended sediment contamination. Guidelines include both absolute and relative thresholds for visual clarity that relate to water use and classification.
- It is important to note, however, that such guidelines relate to suspended sediment 'pollution'. The guidelines have not yet been consistently and effectively applied to diffuse sediment sources and do not consider the ecological impact of sediment once settled.

USA

3.9 The Internet was used to provide a large quantity of information relating to the US experience; the sources identified below provide a representative selection of this. As stated previously, the US is the only country that currently sets targets for sediment within a statutory framework. These TMDLs are applied to impaired waters on a state-by-state basis. Whilst an overarching framework for their development exists, there is no uniform methodology for target development and application. As a result, a wide variety of approaches have been employed. Their potential application to the UK is considered further in section 4.

Sources

3.10 Numerous Internet sources are available that relate to development of sediment targets for each state. Sources include:

- US Environmental Protection Agency - URL://www.epa.gov
- Protocol for developing Sediment TMDLs, First Edition (1999) US EPA, Office of Water, Washington DC.
- Copeland (1997) Clean Water Act and TMDLs. Environment and Natural Resources Policy Division.
- Hawkins (2003) Survey of Methods for Sediment TMDLs in Western Rivers and Streams of the United States. Report to US EPA Office of Water, Assessment and Watershed Protection Division, Washington DC.
- Sediment TMDL for Deer Creek: Yazoo River Basin (2003) Mississippi Department of Environmental Quality, Jackson MS.
- Lower Arkansas River Basin TMDL (2000)
- Guide to Selection of Sediment Targets for Use in Idaho TMDLs (2003) Idaho Department of Environmental Quality.
- TMDL Development for Sediment in the Stekoa Creek Watershed (2000) US EPA Region 4.
- Garcia River Sediment TMDL (1998) US EPA Region IX.
- Moore, M., Testa, S., Cooper, C.M., Smith, S., Knight, S.S. and Lizotte, R.E. (undated) Clear as Mud: the Challenge of Sediment Criteria and TMDLs. USDA-ARS National Sedimentation Laboratory.
- Kansas Department of Health and Environment - www.kdhe.state.ks.us
- Waite Osterkamp, Research Hydrologist, US Geological Survey WRD, Tucson AZ

Key findings

- Section 303 (d) of the Clean Water Act (1972) requires states, territories and authorised tribes to identify and list impaired waters every two years and to develop total maximum daily loads (TMDLs) for pollutants. These TMDLs establish allowable pollutant loadings and provide the basis for states to implement water quality based controls on a catchment-by-catchment basis. Sediment represents one of 3 key pollutants for which technical guidance is available (the others being pathogens and nutrients).
- A protocol for developing sediment TMDLs was published by the US EPA in October 1999. This provides a general over-arching approach to setting sediment targets according to the following stepwise progression from problem identification through to implementation of management via target setting:
  - problem identification;
  - development of numeric targets;
  - source assessment;
  - linkage of targets to sources;
  - load allocation (ie among sources);
  - monitoring and evaluation; and
  - implementation of sediment control measures.

- Within the over-arching framework, a variety of approaches to development of TMDLs have been undertaken. These appear to fall into 2 categories:
  - sediment yield based, ie load per unit time; and
  - indicator based, ie linked to indicators such as aquatic biology, channel condition (cf. Rosgen - organisation by stream types) and hillslope sediment dynamics (cf. Reid and Dunne 'Rapid Sediment Budgeting').
- Within these two categories, approach selection is catchment-specific and appears to be linked primarily to data availability. Approaches range from data-intensive modelling and monitoring in order to define quantitative yield targets; to qualitative, 'narrative' TMDLs based on avoiding a reduction in known ecological quality via sediment control at source. In addition, the role of 'sound judgement' is identified in the Protocol as critical.
- A survey of potential approaches to development of TMDLs based on sediment yield was undertaken for the US EPA by the Watershed Resources Program of the University of Arizona (Hawkins 2003). The report identified four general approaches, as follows:
  - Channel-based approaches eg direct calculation via flow and suspended sediment concentration data or rating curves; transport equations and models; turbidity surrogates.
  - Upland-based approaches (ie consideration of catchment sources) eg erosion models such as USLE, RUSLE, MUSLE.
  - Regional regression models (ie extrapolation from available data) eg regression models, area regressions, PSIAC method, proxy data.
  - Local methods (ie site-specific combinations of the above approaches) eg source identification, BOISED.
- In addition, it is important to note that the same report stressed that the wide variation and uncertainty inherent in yield estimates presents a significant limitation to successful target allocation.
- A further report by Moore and others (undated) considered the challenge of sediment criteria and TMDLs. The report highlighted the difficulty of applying threshold figures to highly variable sediment yield data. In view of this, elucidation of the link between fine sediment and a measurable ecosystem response was identified as a useful focus for improved catchment management.
- Inherent in the TMDL process is the linkage of the target to management action eg good agricultural practices. This is incorporated into the TMDL approach in two main ways:
  - as a separate management plan alongside numerical, yield-based TMDLs; and
  - integrated within indicator definition eg % reduction in eroding banks.
- TMDL development is summarised in Table 7. The examples include those selected to illustrate a range of appropriate approaches in the US EPA protocol document (cf. examples 1-6).

3.11 Further consideration of the relevance of US experience to development of sediment targets in the UK is provided in section 5.

Table 7 Summary table to show a range of approaches to TMDL development in the USA

Catchment	Approach to TMDL development	TMDL	Management
1. Sycamore Creek, Michagan	Rates of average sediment loading from nonpoint sources estimated via site specific monitoring data, load estimation equations and nonpoint source loading models Linkage of sediment oxygen demand to dissolved oxygen levels via modelling Assumption of proportional relationship between SOD and suspended solid loads	52% reduction in overall suspended solid loads Allocation of reduction between agricultural erosion (56%), streambank erosion (100%) and urban runoff (30%)	Cropland best management practices Bank stabilisation
2. South Fork Salmon River, Idaho	BOISED site-specific sediment loading model Local model developed to estimate sediment delivery from roads Suspended sediment monitoring data since 1960s Regional professional experience	25% reduction in sediment inputs from anthropogenic sources	Road improvement projects Slide restoration projects
3. Ninemile Creek, Montana	Sediment, flow and salmon redd counts monitoring data Best professional judgement of a multi agency team Reference site comparisons	80% reduction in annual sediment loads	Rangeland best management practices Streambank stabilisation

Table continued…

Catchment	Approach to TMDL development	TMDL	Management
4. Upper Birch Creek, Alaska	Sediment, flow and biological monitoring data (20 years) Regression analysis of turbidity and total suspended solids Analysis of critical flow and loading conditions Estimation of nonpoint source contributions via comparison with reference areas	Maximum total suspended solids per day	Not stated
5. Chris Creek (hypothetical)	Rapid sediment budget Measurement of erosion potential from roads	% erosion reduction by source type	Forestry best management practices Road improvements
6. Wendell Creek (hypothetical)	Sediment rating curves and sediment budget RUSLE Comparison to reference site sediment budget Best professional judgement	Average annual loads by tributary (5-year average)	Rangeland best management practices Bank and slide stabilisation Road improvements
7. Stekoa Creek, Georgia	Rainfall erosivity index Multi Resolution Land Cover land use data 30m digital elevation model Comparison to reference sites	% reduction in sediment load overall to meet target of 90t per square mile Reduction allocated by source type	Cropland best management practices Road improvements

Table continued…

Catchment	Approach to TMDL development	TMDL	Management
8. Little Arkansas River, Arkansas	Biological monitoring to provide annual indices: Macroinvertebrate Biotic Index (MBI) and % Ephemera, Plecoptera and Trichoptera (EPT) Taxa (count) – annual sampling plus 16-year record Qualitative link assumed between suspended sediment and biological indices	Narrative suspended sediment standard, ie '…shall not interfere with…the survival and propagation of aquatic…wildlife' % composition of EPT taxa of 40% or more between 2004-8	Targeted program of conservation farming, grass buffer strips, reduced riparian activity, minimisation of construction impacts.
9. Deer Creek, Mississippi	Historic flow and sediment transport data from reference sites Land use data - Mississippi Automated Resource Information System based on Landsat Thematic Mapper images Linked to channel evolution framework: Simon and Hupp (1986)	Sediment yield standard range of 2.4 E-03 to 7.3 E-03 in tonnes per acre per day at the 'effective discharge' ie channel forming flow identified as the 'critical condition' for the site	Best land management practices

4 Sediment targets in an ecological context

Introduction

4.1 This section provides a brief review of the current understanding of the links between fine sediment delivery and impacts on aquatic biota. Our current level of understanding of these links is critical to the rationale that is adopted for target-setting. This summary is largely drawn from two relatively recent literature reviews: Wood and Armitage (1997) and Reiser (1998).

4.2 The extensive database of long term fine (generally < 2mm) sediment yield derived from lakes demonstrates that fine sediment delivery has been accelerated by human modification of the land surface (Walling 1995, 1996). Soil erosion rates under natural and cultivated conditions are variable but always enhanced. Transport within the river network is also enhanced (Walling 1995).

4.3 The conclusion of these studies must be that in pre-disturbed landscapes, annual fine sediment yields in UK river systems were possibly between 3-10 times lower than present, although it is important to consider the specificity of catchment geomorphology and climatic fluctuations within these values (Walling 1996). The progressive influence of human modification to channel, corridor and floodplain environments must also have made for complicated ecosystem impacts, principal amongst which may have been the ‘closing off’ of floodplain deposition routes.

4.4 It can be inferred from the above that aquatic organisms in the UK are generally adapted to conditions with lower fine sediment loads, but with a tolerance to short term increases associated with runoff events. The influence of climate change on magnitude-frequency and flow-duration characteristics of these runoff events is likely to exacerbate any effects of fine sediments on aquatic biota.

Characterising mechanisms of impact

4.5 Wood and Armitage (1997) summarise the key linkages between sediment delivery and biological effects in rivers in Figure 8. Many of these impacts also apply to standing water habitats, particularly those waters that have naturally coarse and open substrates. Reiser provides a similar schematic in respect of effects on salmonids in Figure 9. This illustrates the importance of separating three major subcomponents of increased sediment loads from the catchment, which operate via six aspects of habitat quantity and quality to impact five life-stages of salmonid fish. Reiser stresses that, as well as changes in sediment loads, a major driving variable is flow (comprising the elements of volume, timing and local hydraulics).

4.6 Armitage and Wood provide a summary of the wider negative consequences of enhanced sediment delivery in Table 8, separating out the effects of increased suspended sediment concentrations from enhanced fine sediment deposition. In Table 9 (linked to Figure 9), Reiser differentiates between acute and chronic impacts on both invertebrates and fish; and emphasizes the component of recovery – human perception tends to be of irreversible ‘damage’.

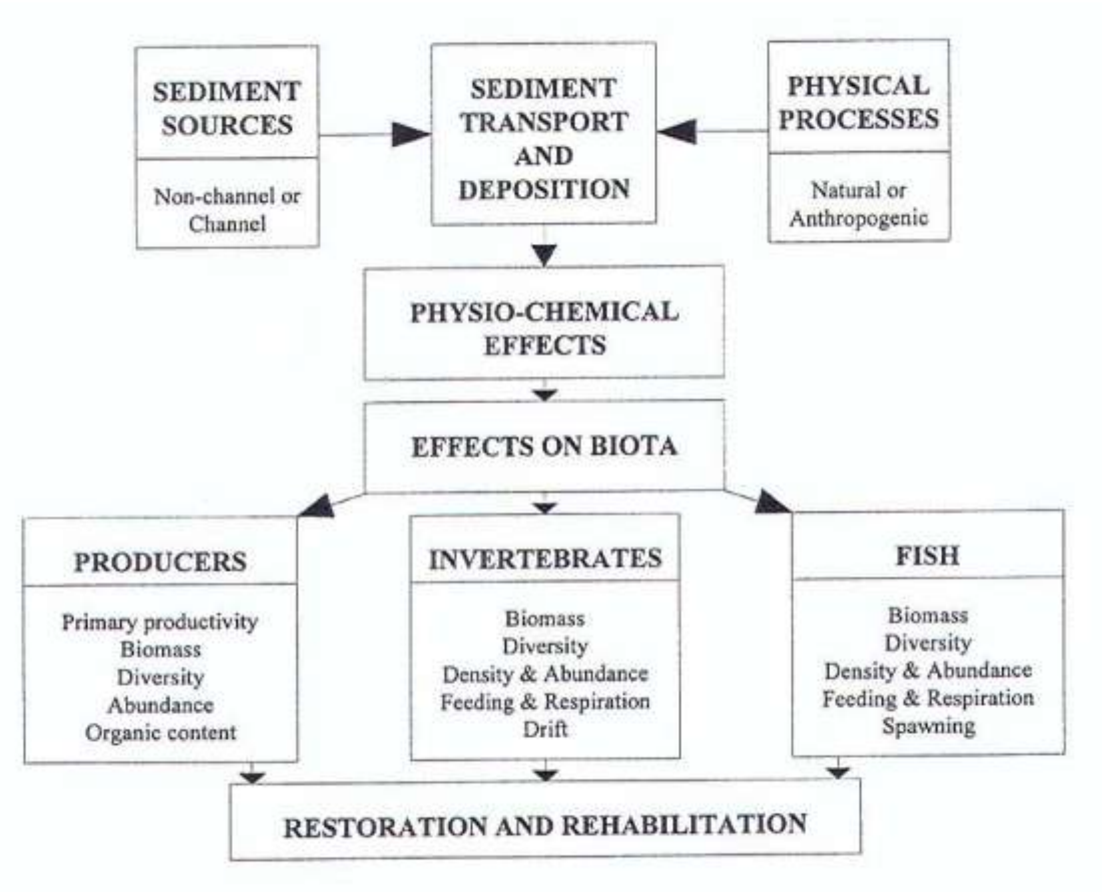

Figure 8 An overview of fine sediment in the lotic environment (Wood and Armitage 1997)

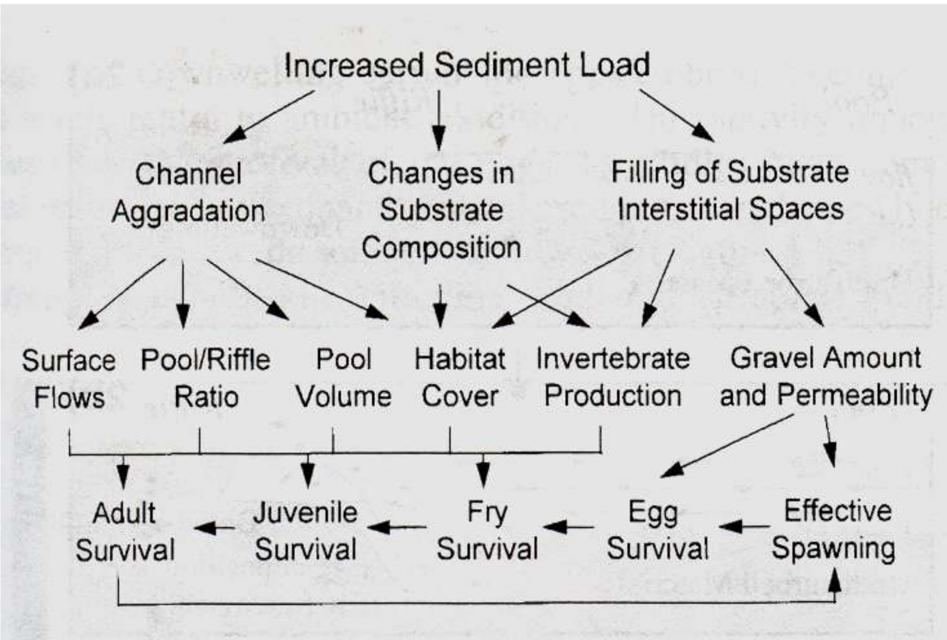

Figure 9 Process linkages between increased sediment yields and biotic impacts – the case of salmonids (from Reiser 1998)

Table 8 A summary of the negative impacts of increased suspended and deposited fine sediment on aquatic ecology (based partly on Wood and Armitage 1997)

Problem	Ecological impact
Suspended sediment	
Increased turbidity and reduced light penetration Reduced availability of food Pollutant vector	Reduced primary productivity Reduced species diversity Reduced abundance Increased invertebrate drift Change in community structure Damage to macrophyte leaves and stems via abrasion Reduced aquatic flora Reduced rate of fish growth Reduced tolerance to disease in fish Modification of fish migration patterns Reduced hunting efficacy in fish
Deposited sediment	
Alteration of channel morphology Alteration of substrate composition Reduced substrate permeability and dissolved oxygen content Reduced habitat availability Pollutant vector	Reduced primary productivity Reduced species diversity Reduced abundance Increased invertebrate drift Change in community structure Reduced aquatic flora Decline in quality of salmon spawning habitat and reduced salmonid embryo survival Deposition of silt on respiratory structures Impeded feeding of filter feeders

Table 9 Generalised effects of different types of sediment influxes to gravel-bed rivers on invertebrate and fish communities, and general recovery sequences (from Reiser 1998)

Sediment Influx Type	Effect	Impacts	Recovery Sequence
Short Duration/High Volume (SDHV)	Acute	Generally a point-source/event-induced influx; causes immediate loss of invertebrate communities, loss of incubating fish embryos within the gravel, loss of rearing habitat (space) within pools.	Recovery time dependent on when the influx occurred, stream gradient, channel morphology, and hydrologic regime (Approximate Recovery Time: 1-10 years)
Long Duration/High Volume (LDHV)	Acute/Chronic	Immediate and sustained loss of invertebrate communities; immediate loss of fish embryos and continued reduced production potential; reduction in rearing habitat (pool volume and loss of interstitial habitats); changes in species composition (invertebrates and fish) likely; channel morphology changes (aggradation/braiding)	Recovery time dependent on timing and degree of effectiveness of source control, channel morphology, hydrologic regime, and overall quantity and size of deposited sediments (Approximate Recovery Time: 10s of years)
Short Duration/Low Volume (SDLV)	Small Imperceptible	Subtle/undetectable changes; possibly some reduction in invertebrate biomass or density; impacts on fish egg incubation possible but unlikely (dependent on timing of release)	Recovery time generally quick (Approximate Recovery Time: within weeks or months depending on when sediment influx occurred)
Long Duration/Low Volume (LDLV)	Chronic – variable magnitude	Difficult to detect without long term monitoring program; generally a non-point source influx; can result in: 1) gradual change in invertebrate community density, diversity and taxa richness; 2) alteration in fish habitat (degradation of spawning and rearing habitats) leading to reduced production potential and possible shifts in species composition.	Recovery time variable depending on timing, magnitude and duration of the influx, effectiveness of the source control, and stream competency. In some cases, LDLV influx of sediments may have no appreciable effects on the aquatic ecosystem, provided amounts do not exceed transport capacity.

Quantitative data on fine sediment impacts

4.7 Table 10 provides a few quantitative observations of biological impacts from fine sediment, taken from a range of sources. Reiser (1998) also provides a set of graphs illustrating the relationship between embryo and egg survival for salmonids in relation to the constitutions of the bed sediments (including fines), copied here as Figure 10.

4.8 For suspended solids, some standards have been developed that are based on the prevention of chronic damage to fish gills – the guideline standard of 25 mgl-1 in the EU Freshwater Fish

Directive is an example of such a standard. Other direct and indirect impacts of suspended solids, such as damage to early life stages of fish, reduced light penetration, transient peaks of very high concentrations, and links to excessive sediment deposition, are not considered by such standards.

Table 10 Examples of quantified impacts of fine sediment on specific aquatic species

Species	Impact/channel conditions	Data/threshold	Author
Salmo trutta L.	Ebbw Fawr River in South Wales – post coal mining	98%-100% death of eyed salmonid eggs	Turnpenny and Williams (1980)
	Reduced DO and gravel permeability	Survival threshold of DO supply of 16μg cm^{-2} $hour^{-1}$	
Atlantic Salmon	River Avon, Hampshire Fine sediment accumulation in spawning redds	Embryo survival <50% when sediment of <1mm and <2mm made up more than 8% and 7% of redd substrate respectively	Heywood (2002)
Salmonids	Various US studies. DO supply to salmonid embryos in redds	Minimum concentration of 5mgl-1 DO in interstitial water	Chapman (1988)
Atlantic salmon	Effect of clay/silt deposition on salmon ova in redds	>30% reduction in load required to meet ova survival threshold	See Paragraphs 4.9 - 4.22
Fish	Effect of suspended solids on fish growth and emigration	Transient concentrations of 125-275mgl^{-1} suspended solids	Reiser 1998
Fish	Inability to support good freshwater (cyprinid) fisheries in European rivers	Suspended sediment concentrations >80mg l^{-1}	Alabaster and Lloyd (1980)
Aquatic moss *Eurhynchium riparioides*	Deleterious abrasion of plant leaves by suspended coal particles	3 weeks at concentration of 300 mg l^{-1}	Lewis (1973)
	No development of side shoots	>500mg l^{-1}	
	Reduced spore germination by 42%	>5000mg l^{-1}	

Table continued…

Species	Impact/channel conditions	Data/threshold	Author
Ranunculus penicillatus	Smothered and eliminated by fine sediment mobilised by channelisation in Wallop Brook, Hampshire	Maximum sediment deposition depth of 130cm in pools and 5cm in riffles	Brookes (1986)
Nasturtium officionale	Decline by 60%		

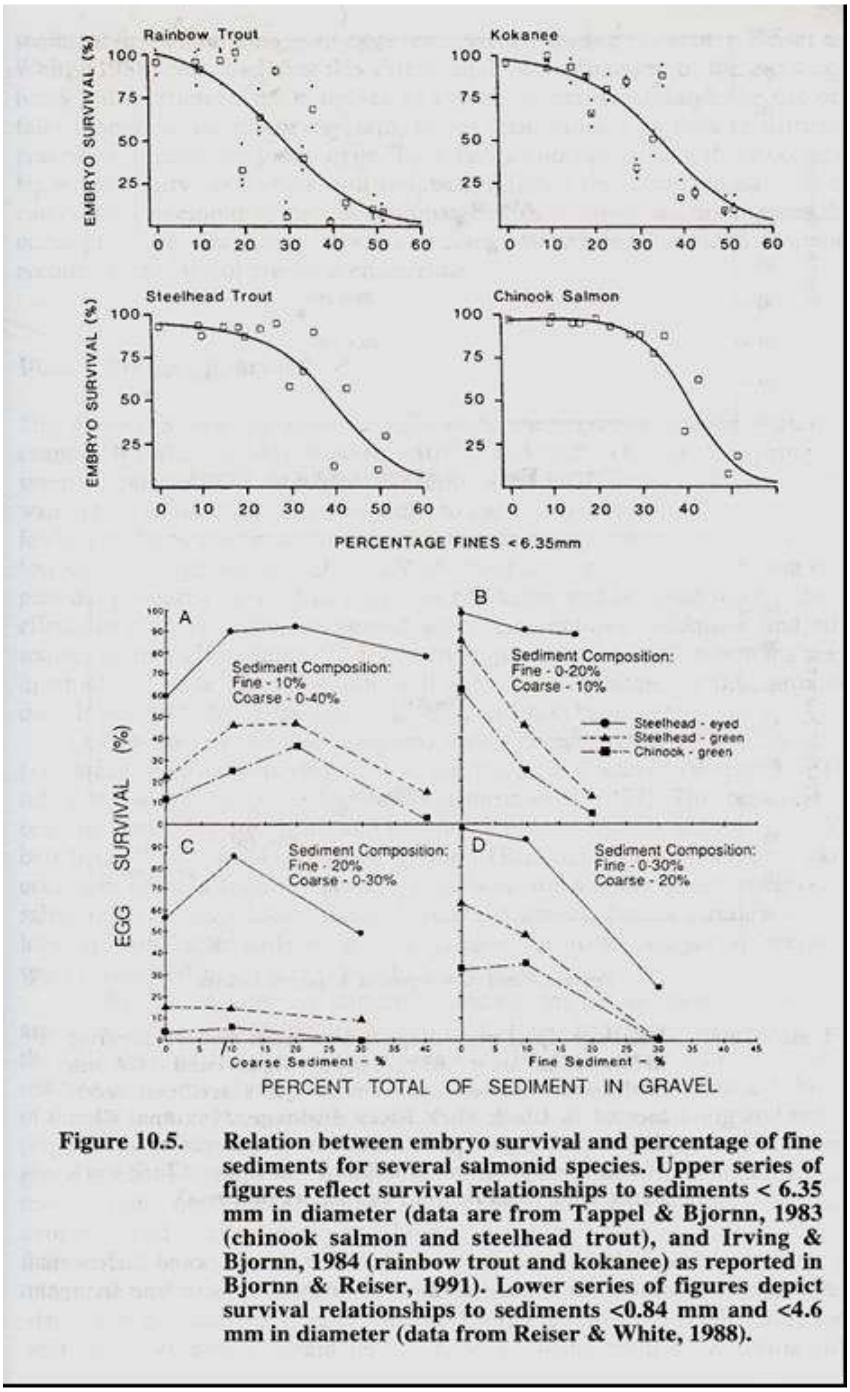

Figure 10 Relationship between salmonid embryo survival and fine sediments (from Reiser 1998)

Fine sediment accumulation in salmonid spawning gravels: an example of the problem of defining critical loads

4.9 Under natural processes small quantities of silt and clay are delivered to the river system. Aquatic communities are typically adapted to these conditions and are able to cope. Anthropogenic activities and in particular land management actions have been shown to increase the supply and delivery of fine sediment (sand, silt and clay) from the catchment surface to the river network (Theurer and others 1998, Walling and Amos 1999); though the influence of bank erosion sources may be locally as well as regionally significant (Walling and others 2001).

4.10 Causes of fine sediment runoff from catchment surfaces are associated with changes in agricultural practice, particularly towards larger areas of arable cultivation or more intensive livestock grazing. Also critical for salmonid survival have been changes in the timing of arable cultivation, which in Europe has moved from spring to autumn sown cereals; a time that coincides with the incubation of salmon eggs within the river gravel. Increases in stock density and mechanised farm practices that compact the soil under pasture result in increased runoff and soil erosion (McMellin and others 2002). Similarly, runoff from land under livestock farming can be associated with delivery of organic waste to the river network (Theurer and others 1998). The delivery of fine sediment from agricultural sources is also associated with enhanced levels of sediment-bound nutrients, pesticides and herbicides whose impact on salmon incubation remains largely unknown. The increasing recognition of catchment and in particular agricultural land use as a primary source of fine sediment delivery to the river network has initiated a move towards managing land use practice to reduce delivery of fines (Heaney and others 2001; McMellin and others 2002).

4.11 Salmon and other fish species lay their eggs in gravel nests called redds. The process of redd-cutting creates pockets of eggs overlain by loose gravels from which the fine sediments have either been removed by entrainment during the cutting process, or redeposited at the base of the redd by a process of 'kinematic sieving'. Successful incubation requires that the ambient oxygen concentration within the redd is sufficient to support the oxygen gradient required to drive diffuse oxygen exchange across the egg membrane at different water temperatures and stages of embryonic development (Silver and others 1963; Daykin 1968; Wickett 1975; Turnpenny & Williams 1980; Chevalier & Carson 1985).

4.12 The concentration gradient required to support diffuse oxygen exchange is maintained by the bulk movement of oxygen through the riverbed. Fine sediment intrusion into the incubation zone will restrict the passage of oxygenated water by blocking interstitial pore spaces and reducing interstitial flow velocities within the incubation zone (Chapman 1988, Alonso and others 1996; Bjorn and Resier 1997; Acornley and Sear 1997; Theurer and others 1998) and, if oxygen consuming materials are introduced into the riverbed, by lowering oxygen concentrations (Whitman and Clark 1982; Chevalier and Carson 1984; Štěrba and others 1992). These two processes are not discrete, and lowered interstitial flow velocities may exacerbate the impact of oxygen demands on oxygen concentration. It should also be noted that lowered interstitial flow velocities may also reduce natural flushing of harmful metabolic waste products that are excreted by embryos, potentially contributing to mortalities (Burkhalter and Kaya 1977). A conceptual model of the main factors leading to a reduction in oxygen to incubating embryos is shown in Figure 11.

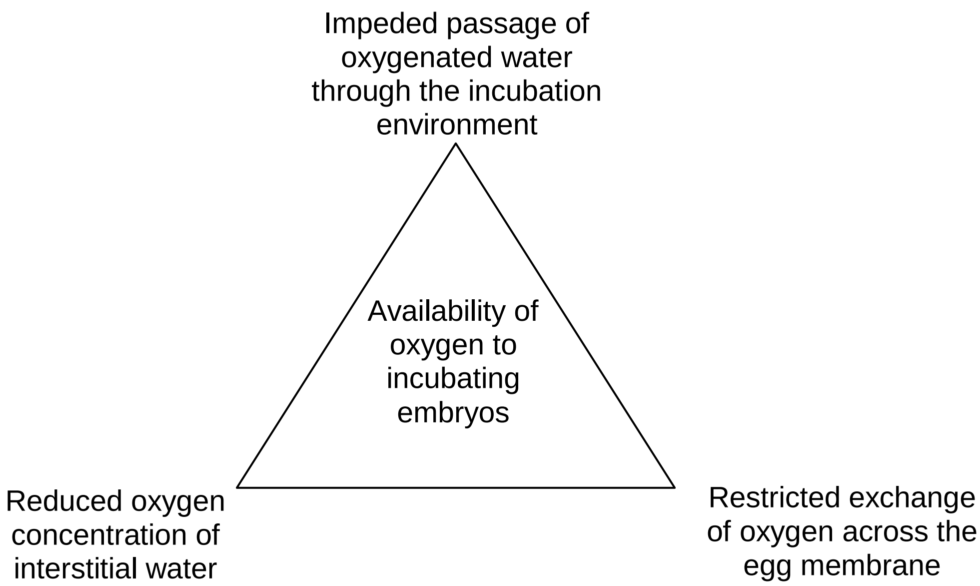

Figure 11 Conceptual model of the factors contributing to the availability of oxygen to incubating embryos within spawning gravels (after Sear and others, in press)

4.13 The factors influencing oxygen availability operate contemporaneously and over a variety of spatial and temporal scales. Therefore, awareness of environmental conditions that will result in oxygen deficiencies within spawning gravels requires identification of potentially harmful factors, and awareness of how these factors interact to influence oxygen availability. Limiting conditions will be determined by physical and biological characteristics of the river and its surrounding catchment. Consequently, the precise factors influencing oxygen availability may vary significantly between and within river systems.

4.14 For instance, in agricultural catchments, excessive sedimentation may be coupled with inputs of organic and nutrient rich material associated with over-grazing or poorly managed fertiliser and waste application. These materials may reduce interstitial flow velocities, exacerbating the impact of oxygen demands. Similarly, the infiltration of a small amount of clay post-redd creation may promote the development of a sedimentary seal around incubating embryos that restricts oxygen consumption. Finally, if the infiltration of inorganic and organic material results in interstitial flow velocities that are inadequate to supply oxygen at a rate sufficient to support respiratory requirements, mortalities may ensue.

4.15 These observations have important implications for management strategies that aim to restore the productivity of salmon spawning and incubation gravels through the reduction of fine sediment loads within the river network. Grainsize measures are frequently applied to assess the quality of salmon spawning gravels. Such measures typically include some estimate of the percent sediment below an empirically determined size fraction, or else some moment measure that reflects the influence of the finer sediment on the overall population of particles. However, although potentially providing a statistically significant relationship with pre-hatching success, bulk measures of fine sediment accumulation cannot be linked directly to embryonic survival. Rather it is the impact of the sediment on the supply of oxygen to the incubating embryos that influences survival. This distinction is important because considerable expenditure and reliance is placed by fisheries management agencies on the validity of these measures, and they inform condition assessments of riverine Sites of Special Scientific Interest.

4.16 Thus, it can be argued that whilst the former appear to provide a relatively simple measure of the quality of the incubation environment, in the light of the model of oxygen supply advanced above (Figure 11), the interpretation of these correlations remain problematic. Furthermore, although these grainsize measures can be obtained fairly easily in the field using freeze coring techniques, the redd-cutting action of the hen salmon substantially modifies the bed texture (Kondolf and others 1993) and hence the value of these measures of grainsize distributions and porosity are changed. Consequently, unless artificial or natural redds are assessed at times coincident with hatching or emergence, conceptually the measurements of the grain size of spawning beds alone are difficult to justify.

4.17 Sediment accumulation in gravels is strongly correlated with the availability of fine sediment in the water column (Carling 1984; Sear 1993). This relationship provides river managers with one method for controlling the accumulation of fine sediment in spawning gravels and, hence restoring the productivity of spawning gravels towards unimpacted levels. Thus, if through some form of river or land management (depending on the source of fine sediments), it is possible to reduce sediment loads, then the quantity of fine sediment stored within the redds will decrease and oxygen supply should increase. Current water management practices are reducing the delivery of fine sediment from the catchment via bank erosion control, riparian buffer practices and modified land use practices (Summers and others 1996; Crisp 2000; SEPA 2002).

4.18 More recently, recognition of the role that fine sediments play in delivering sediment-bound nutrients (phosphorus in particular) and pollutants to aquatic ecosystems has resulted in a new impetus to reduce fine sediment inputs from catchments (DEFRA 2002). However, in the presence of high organic matter loads even relatively small rates of accumulation can have disproportionate impacts on spawning habitats. Similarly, a small quantity of clay, can have a disproportionately large impact on the productivity of incubation gravels.

4.19 The SIDO (Sediment Intrusion and Dissolved-Oxygen) model (developed by United States Department of Agriculture, Alonso and others 1996) was designed to quantify the relationship between the survival of pre-emergent salmonids and the quality of the incubation environment. The model simulates the impact of fine sediment accumulation on the movement of water, sediment and dissolved-oxygen through the stream-redd system that comprises spawning and incubation habitat. The original model was refined and recalibrated for Atlantic salmon and UK hydrologic and sedimentary conditions (SIDO-UK) as part of a DEFRA-funded project (URL://gg-svr7.geog.soton.ac.uk/staff/das/profile/Documents/DEFRA_Final.pdf).

4.20 To test the ability of the model to accurately describe the intragravel environment of the study sites, the predicted decline in DO and intragravel flow velocity (IFV) was compared with the decline recorded in the field. In general, the model can be considered to predict the trends and magnitude of dissolved oxygen concentrations accurately. With respect to IFV, although the numerical accuracy of the North American model has been improved for SIDO-UK, it is not physically robust enough to predict accurate IFV.

4.21 Following calibration, the model was used to assess the effectiveness of contrasting river management schemes. An example for the River Ithon is presented in Table 11. The objective is to identify the effect of reducing the supply of clay and silt-size material by 10, 20, 30, 40, 50 and 75%. The intra-gravel parameters considered were: (i) number of days for the redd to reach 20% and 50% maximum filling, DO and IFV at point of hatching.

4.22 Previous studies have suggested that oxygen concentrations of 5mgl-1 are required to support incubating embryos (Chapman 1988). The model predicts that a reduction in fine sediment supply of at least 30% would be required to increase the DO above the required threshold.

Table 11 Modelled influence of reduction in fine sediment on intra-gravel dissolved oxygen (IDO) & intra-gravel flow velocity (IFV) in the River Ithon.

Reduction in clay and silt	Days to 50% max filling	Days to 20% filling	DO mg l^{-1}	Average IFV cm h^{-1}
0%	50	71	5.5	19.7
20%	54	78	5.5	20.2
30%	55	80	6.1	20.7
40%	57	83	7.3	21.1
75%	64	93	7.3	21.3

Key messages

4.23 Key points are highlighted below, whilst further information on the complexities of the sediment delivery system is provided in Appendix 1.

1) The links between fine sediment delivery and aquatic ecology are poorly understood and few quantitative data relating changes in sediment yield to ecological impacts are available. Furthermore, since sediment yield data are likely to be characterized by significant errors and uncertainties, any assessment of the impact of changing sediment yield on specific habitats requires careful interpretation.
2) Fine sediment has the potential to adversely affect aquatic ecology via two main mechanisms viz:

- Excessive suspended sediment loads or concentrations; and
- Excessive deposition within the river channel or other aquatic habitats (eg lakes).

a) It is important to take account of both mechanisms when establishing sediment targets, since they may require different types of target. The balance between transported and deposited sediment in a given reach is likely to be highly variable, both spatially and temporally, and there is constant interchange between transport and storage.
b) The ultimate impact of increased fine sediment deposition will reflect both the sediment dynamics of a catchment and the scale of investigation.
c) The impacts of increased fine sediment, both within the water column and on the channel bed, on aquatic ecology and its subsequent recovery, are linked to the tolerance or sensitivity of different biota to sediment and to the life cycle stage at which sediment inputs are experienced.
d) Quantitative data that link increased suspended sediment concentrations or amounts of deposited sediment with specific aquatic species for particular river types, which could provide as a basis for target-setting, are severely limited. Work on Atlantic salmon is most advanced and can provide an ecological basis for numerical targets in relation to salmon rivers. It is unclear how well such targets would protect freshwater communities in the round.

5 Developing a rationale for target-setting for sediment control in the UK

Introduction

5.1 Three strands of information that should contribute to the development of a rationale for setting for sediment –related targets have been reviewed in this report, viz:

1) Sediment yield data availability, nature and quality (Section 2): 107 sites with high and medium quality data have been identified;
2) The experience of sediment target setting in other countries (Section 3): the US has been identified as the only country that has implemented targets within a statutory framework; and
3) The ecological impact of excess sediment (Section 4): quantification of specific impacts is limited, but negative impacts are more widely reported.

5.2 An approach is required that is useable in the short-term for operational decision-making. It needs to take account of the uncertainties in the quantification of relationships between sediment delivery and ecological impact, whilst at the same time recognising the likelihood of damage to the biota of different habitats from anthropogenically enhanced loads of fine sediment. It also needs to take account of the individual nature of catchments and the difficulties of basing decisions on generalised statements about sediment delivery systems and their ecological risks and impacts. Lastly, it needs to consider that targets need to be relatable to both the management response and the ecological risks – with the current knowledge base this is difficult to achieve within one type of target.

Lessons from the US approach

5.3 As stated previously, the US provides the only current examples of the implementation of statutory targets for sediment control. TMDLs are set for impaired waters on a catchment-by-catchment basis via a wide range of approaches. However, whilst an overall framework for setting TMDLs exists, there is no uniform methodology for their development or evaluation. Approaches range from catchment-wide, yield-based targets to localised, pragmatic, management-led targets. These targets are established using methods that range from complex modelling to 'best professional judgement'. Despite the apparent availability of information relating to the US experience, direct transfer of US approaches and data to the UK is hampered for three key reasons.

1) The fine sediment dynamics of US catchments will frequently differ from those of UK catchments. Direct transfer of specific US targets to UK catchments is therefore not possible.
2) No uniform approach has been developed for the US. The specification for this project seeks to develop a 'standard' methodology that can be applied either to all catchments, or to clearly defined catchment types.
3) US approaches tend to be highly data intensive and rely on the availability of detailed data and a wide range of well-tested and generally accepted prediction and modelling procedures. Such data and resource requirements are difficult to meet in the UK at present.

5.4 Awareness of the US experience does, however, provide a valuable background when attempting to both develop a target-setting protocol for the UK and provide guidelines for its application.

Discussion of possible operational approaches for the UK

5.5 Two possible approaches are outlined below. The first is based on a 'bottom-up' approach. It provides a pragmatic tailored approach to the management of sediment problems, based on an understanding of local conditions derived from a 'toolkit' of information sources. This approach generates catchment-specific targets that may be descriptive or numeric. This is similar to the US approach, but includes the concept of a framework of guideline yield-related targets that are used to inform local target-setting. The second is based on a 'top down' approach. It provides an overall framework for national prioritisation of management need based on generic, numeric yield-related targets, which are then used to direct local management action. However, the implementation of this second approach is currently constrained by limitations associated with both the availability of appropriate data and our understanding of the link between sediment yield and ecology. At present, therefore, the ability to establish and apply such sediment yield targets is inherently restricted, particularly at the local scale.

5.6 It is suggested that Approach 1 is more suited to the current knowledge base, whilst Approach 2 may be suitable in the longer term following the experiences gained from application of Approach 1 in selected catchments and new knowledge acquired from strategic, process-based R&D on the relationships between sediment delivery and ecological impacts in the full range of catchment and habitat types. In this sense the two approaches are linked, with the guideline targets used in Approach 1 being refined and expanded for use in Approach 2.

Approach 1 - a bottom-up approach

5.7 This approach is summarised in Figure 12. The starting point for this approach is appraisal of catchment sediment dynamics at the local level. Such appraisal would employ a toolkit of methods, ranging from catchment modelling, to analysis of historical sediment data, to field-based fluvial geomorphological approaches. The outcome of this initial appraisal would subsequently be used to inform two strands of action, namely to specify environmental objectives and to implement management change.

5.8 For the first strand of action, sediment-related targets would be specified on the basis of available local data relating to sediment, flow and ecology and relevant generic, guideline targets. The resulting targets would reflect, in part, the nature and availability of local data. In view of this, such targets might be either descriptive or numeric. Descriptive targets, could, for example, specify % reductions in exposed channel banks, % increases in vegetated area of the catchment surface or delivery of a specified number of farm plans. Numeric targets could be based on rating curves, flow-weighted mean concentration of sediment, siltation rates, sediment quality and biological indicators as well as on sediment yield.

5.9 For the second strand of action, the outcome of the local catchment appraisal would be used to identify high-risk sediment 'hot spots' in order to target mitigating resources, such as farm visits and associated plans, to sediment source areas. Monitoring of the impact of management change on sediment delivery or associated local sediment-related problems can then be undertaken to inform development/refinement of sediment-related targets under the first strand of action as outlined above. In addition, if catchment modelling is used to inform management, the potential exists for changes in sediment delivery to be predicted and to provide an additional set of data for target development.

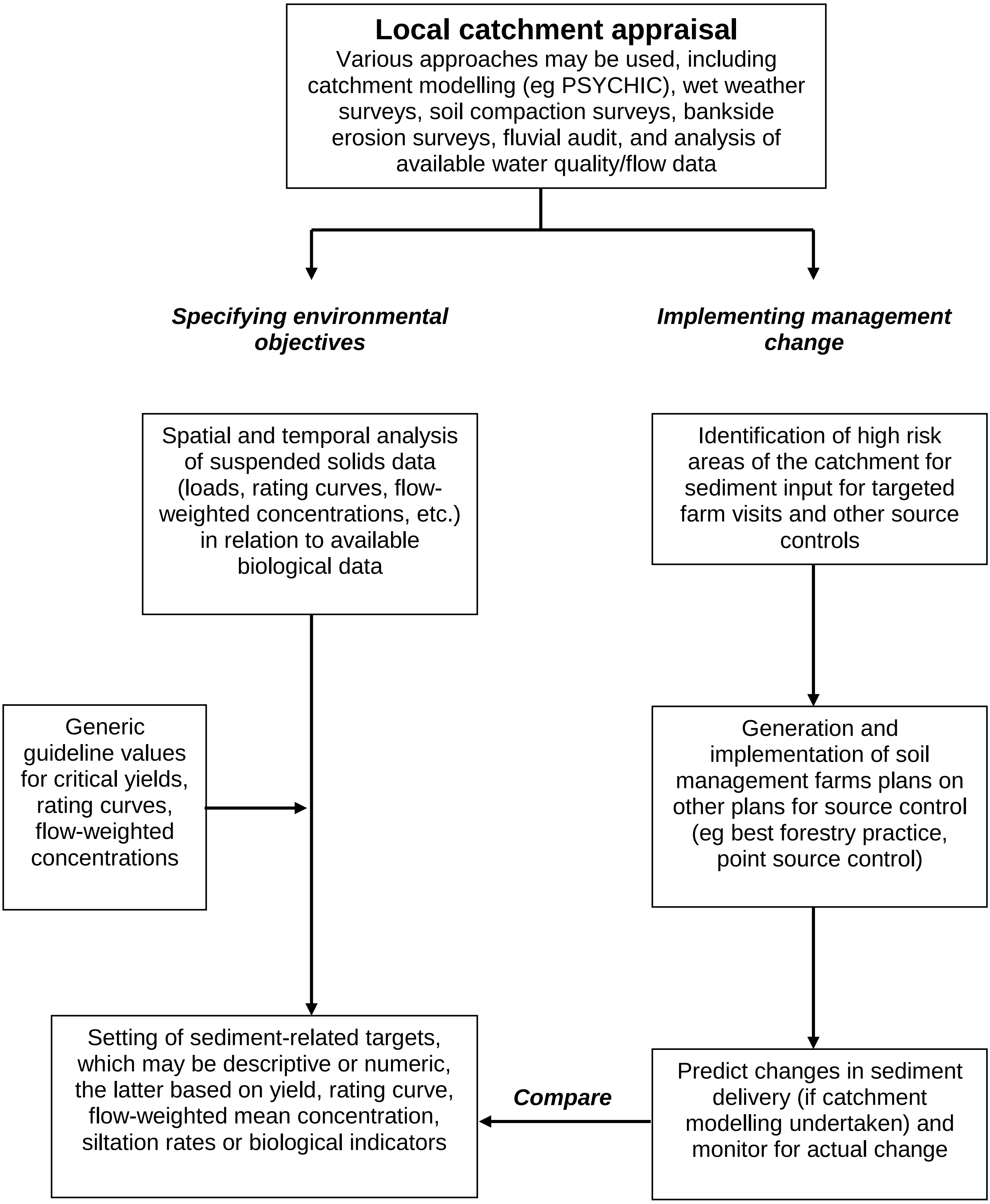

Figure 12 Options for an operational approach to setting and applying targets: Approach 1 - a bottom-up approach

5.10 A key strength of this approach is the ability to consider sediment-related issues at the local level within an understanding of sediment delivery at the catchment scale. The facility therefore exists for development of targets that are spatially and temporally integrated. For example, targets can accommodate linkage between downstream 'hot spots' and upstream delivery, and seasonality in the transfer of sediment from the catchment surface to the river channel.

5.11 Within this approach it is important that concerted efforts are made to include numeric sediment delivery-related targets in any suite of targets generated, so that links can be made with activities associated with sediment management, The more qualitative and ecologically orientated the target, the more difficult it is to relate the target to the managment response. Equally, the more sediment delivery-related the target, the more difficult it is to relate to ecological risk and impact. This argues for a suite of targets that covers both sediment delivery and ecological risk.

Approach 2 - a top-down approach

5.12 A stepwise, iterative approach is outlined below, within which sediment yield targets represent the first step; broad targets are then translated into management action and refined at the local level. The strategy is outlined below and summarised in Figure 13.

Step 1: Initial target- setting
Step 1 involves definition of a set of initial, broad catchment-scale sediment yield-related targets for a range of catchment types (the same as that used as guideline targets in Approach 1). These targets are applied across the country, in order to establish targets for particular catchments.

Step 2: Catchment prioritisation
Step 2 involves prioritising catchments according to a hierarchy of management need. The role of the sediment targets is to provide an overall indication of the scale of sediment delivery to receiving waters that is likely to be assimilable without adverse effects. In order to prioritise catchments, sediment target values can be compared with actual or predicted sediment loads in order to identify those catchments that fail to meet the target. The extent of failure can be used to determine the relative risk of ecological impact and therefore to prioritise the need for sediment control.

Step 3: Identification of management needs: catchment scale
Step 3 involves linkage of sediment yield targets and management at the catchment scale. Diffuse pollution modelling tools such as PSYCHIC are particularly useful in this context since they generate outputs that are based on sediment yield. A wider range of assessment tools, including field-based, fluvial geomorphological methods could be used to add detail to the understanding of the sediment delivery system. Such tools would highlight problem areas for strategic implementation of improved management or control measures. It is important to note that the tools are not mutually exclusive, rather, their use in combination would be advantageous.

Step 4: Identification of management needs: local scale
The role of step 4 is to provide detailed, site-specific information at the local scale in order to support and refine the broad, catchment scale management needs identified under steps 2 and 3. As for step 3, modelling tools such as PSYCHIC and field-based fluvial geomorphological methods are potential techniques that could contribute usefully to the identification of appropriate management action at the farm/field-scales.

Step 5: Implement management response
Step 5 of the proposed strategy involves design and implementation of a management response based on identification of need under steps 3 and 4. The response may be determined by scenario testing for specific land use/management changes using models such as PSYCHIC, by site-specific application of initiatives such as Best Farming Practices (EA 2001), or by a combination of the two. The advantage of a catchment modelling approach is that the effects of management action on achieving sediment-based targets can be simulated, as a means of validating the management response.

Step 6: Monitor for compliance
The role of step 6 is to monitor for compliance against sediment yield targets. In order to achieve this, overall monitoring at the catchment scale is required as a minimum. In addition, further monitoring of managed hot-spots at the subcatchment scale would provide detail relating to the efficacy of management and elucidate the overall role of the hot-spot within the catchment.

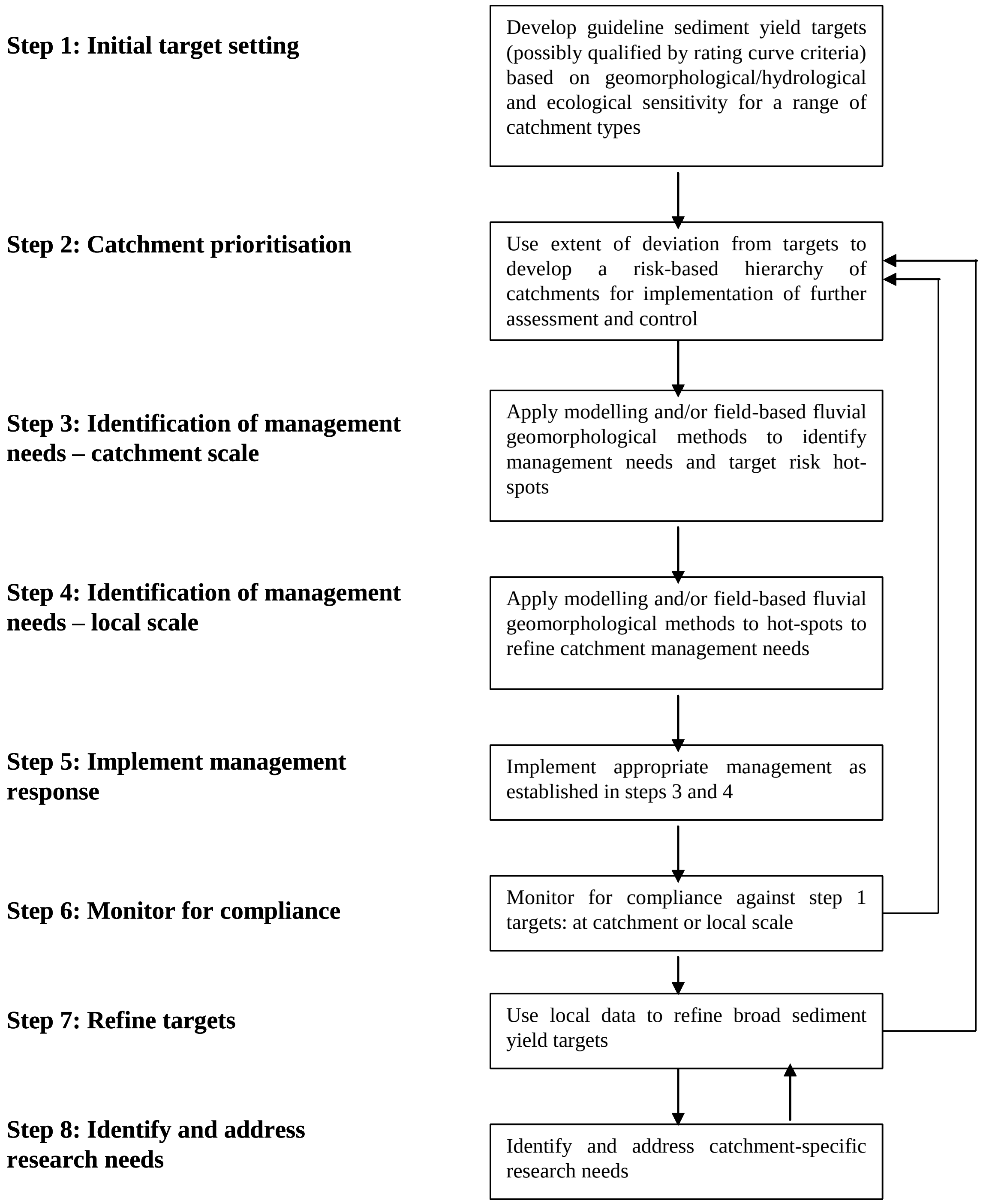

Figure 13 Options for an operational approach to setting and applying targets: Approach 2 - a top-down approach

Step 7: Refine targets
As mentioned above, step 7 of the proposed strategy involves using local, site-specific data to inform and refine broad sediment yield targets based on catchment type alone. Refined targets could then be used to feed back into the catchment prioritisation process under step 2.

Step 8: Identify and address research needs
The final step of the process is to identify and assess site-specific research needs based on the data obtained under steps 2 to 7. For example, research needs could range from the need for an improved understanding of the efficacy of a particular land management technique in a specific environment, to the need for further data relating to sediment delivery linkages at the catchment scale. Data derived from such research could be used to feed back up to step 7 to refine targets and therefore subsequently into the overall strategy via step 2.

Comparison of the approaches

5.13 Both approaches outlined conform to a broad pattern of target-setting, appraisal of management needs, and monitoring for change/compliance. The key difference lies in the extent of dependency on generic sediment yield-related targets – in Approach 1 generic targets are used to support the development of local targets, whereas in Approach 2 they are more central to directing the scale and nature of management action. In between the two approaches, various hybrid approaches might be identified that have value.

5.14 The tools that can be used for catchment-scale appraisal are the same in both cases. Key tools are catchment models and field-based geomorphological techniques: catchment models work from the gathering grounds to the receiving water network, whilst geomorphological techniques work from the river network out into the catchment. The strength of catchment models lies in the understanding of catchment and land management processes, whilst the strength of geomorphological techniques lies in the understanding of in-river processes. Synergies arise between the two types of tool in the characterisation of run-off pathways from the catchment to the receiving water network.

5.15 A key modelling tool is the PSYCHIC model, which was developed on behalf of DEFRA, the Environment Agency and English Nature (cf. www.psychic-project.org.uk). It represents a pragmatic modelling approach to establishing the catchment-scale effects of changes in land management on the loads of phosphorus and, more importantly in this context, fine sediment. The model has the key strategic advantage of having the potential to link sediment yield targets to catchment management initiatives, such as DEFRA’s Catchment-Sensitive Farming delivery project, for the purposes of the Water Framework Directive and bringing designated wildlife sites into favourable condition.

5.16 Application of the model enables management to be strategically directed within a catchment, with predictive assessment of the likely environmental benefits (in terms of reductions in sediment load). Moreover, linkage of sediment yield targets to PSYCHIC would enable the nature of the management required to bring designated wildlife sites into favourable condition, or catchments within GES, to be established. It is important to recognise that PSYCHIC cannot characterise run-off pathways, so ground-truthing (for example via catchment visits, wet weather surveys, soil compaction surveys and local farm knowledge) is required to provide a realistic appraisal.

5.17 PSYCHIC operates at two levels: Level 1 offers the opportunity for catchment scale screening of management need as outlined above. Level 2 operates within the framework of level 1 and provides additional detail at the farm scale in high-risk areas identified under level 1. The facility therefore exists within the model for priority catchments to be screened further to refine implementation of management locally. The requirement for ground-truthing and the associated potential for overlap with fluvial geomorphological methods exist as for level 1.

5.18 It is important to note that PSYCHIC offers one potential modelling tool for application within the approaches outlined and that additional opportunities for modelling exist. These include, for example, the Sediment Impact Assessment Methods (SIAM) currently being developed by the Flood Risk Management Research Consortium.

5.19 Field-based fluvial geomorphological methods should be seen as both a valuable qualitative alternative to the modelling approach typified by PSYCHIC, and an important complement to that approach. Such methods can be employed to develop an improved understanding of sediment sources, pathways and storage at the catchment scale in order to inform management. In addition, the potential exists for the findings of fluvial geomorphological assessments to be considered alongside PSYCHIC in order to supplement the ground-truthing element of the PSYCHIC modelling tool as identified above.

A proposed framework for developing sediment yield targets

5.20 This section considers, within the context of either of the approaches outlined in the previous section, how best to frame generic targets relating specifically to sediment yield. The difficulties of relating simple yield targets to ecological risk have been described in paragraphs 2.23 - 2.44. In particular, sediment yield may be considered to be too coarse and lumped a measure to link adequately to potential impacts on aquatic ecology. For example, a given sediment yield may be associated with relatively low suspended sediment concentrations in one catchment (eg an upland catchment with a relatively high annual runoff), but much higher concentrations in another (eg a lowland catchment with a relatively low annual runoff). Furthermore, a value of flow-weighted mean concentration, derived by dividing the annual load by the annual water discharge, is also likely to be unable to discriminate between varying levels of potential ecological impact, although may be useful in a suite of indicators. The key control on the impact is likely to be the degree to which concentrations vary around this mean value, and more particularly the magnitude of the higher concentrations occurring during storm events, and the timing of these events within the year. In some rivers, suspended sediment concentrations may vary relatively little about the mean value, whereas in others, maximum concentrations could be well in excess of an order of magnitude greater.

5.21 In view of this, it is proposed that generic targets might be based on two parameters or components. The first is a value of critical sediment yield applicable at the catchment or sub-catchment scale. Such targets would reflect a broad understanding of sediment mobilisation and delivery processes for a range of catchment types and their potential impact on aquatic ecology. These simple yield targets would be complemented by generalised information on the range and variability of ambient suspended sediment concentrations, as provided by a generalised concentration / discharge relationship or rating curve. The rating curve information would thus provide a second level or tier of detail to complement the sediment yield information. This second tier would enable general yield targets based on catchment type to be supported by further data specific to the geomorphological and hydrological characteristics of individual catchments as defined by the characteristics of the rating curve.

5.22 Use of rating curves as a complement to yield targets would allow consideration of the relationship between sediment and aquatic ecology at a more meaningful spatial and temporal resolution than that afforded by sediment yield alone. For example, rating curve targets could be set that relate to seasonal variation in sediment concentration and that therefore consider the temporal variability of the ecological sensitivity of different catchments. In addition, incorporation of both sediment yield and rating curve characteristics into a target regime permits impacts associated with both excessive suspended sediment concentrations in the water column and excessive sediment deposition within the channel to be explicitly considered.

5.23 The basis of the proposed framework for sediment yield targets is the table, or matrix, presented in Table 12. The key features of the matrix and its application are outlined below.

5.24 The starting point of the matrix is **catchment type**. Each category can be represented in the left hand column. This matrix considers upland and lowland catchments for a range of size categories as defined in paragraphs 2.9 - 2.22. For each catchment type, the facility for developing two sets of sediment targets exists, first via step 1 and subsequently via step 2. Step 1 provides a coarse target for **all habitats and species, annually** and at the **catchment scale**. Step 2 provides a more refined target that can be based on any combination of selected **broad habitats** (ie different receiving waters such as rivers, lakes, transitional waters and wetlands), **communities, and individual or indicator species and accommodate variation for winter and summer.** For each step, a two-parameter target can be established. The first component or parameter represents an overarching target based on sediment yield; and the second, a complementary target based on rating curve data. Methodologies for establishing the individual targets will be considered in section 6.

5.25 Step 1 considers the overall geomorphological/hydrological and ecological sensitivity according to three categories, ie high, medium and low. Geomorphological/ hydrological sensitivity can be seen as reflecting at least three groups of factors: firstly, catchment characteristics, including slope-channel connectivity, the natural buffering capacity of a catchment for attenuating sediment mobilisation during high magnitude events, and sediment sources; secondly, hydrological characteristics, relating primarily to the runoff regime and the associated ability of a catchment to either flush or deposit sediment; and finally, channel characteristics, which influence the likelihood for deposition at the reach scale. Thus for example, a chalk stream characterised by low gradient and low stream power would be considered to have a high sensitivity, whilst the sensitivity of an upland stream with a high channel gradient would be classified as 'low'.

5.26 Ecological sensitivity reflects the likely relative tolerance of aquatic ecology to sediment inputs. Here it is important to consider whether the key driver of potential impacts is the presence of high suspended sediment concentrations in the water column or excessive deposits of fine sediment within the channel. In the latter case, a higher sediment yield target might be appropriate if the catchment and hydrological characteristics of the catchment suggest that the sediment will be readily flushed through the system without deposition. If, however, concentrations are the key driver, deposition potential is of limited relevance. The classifications for the two categories of sensitivity would then be considered in combination, in order to assign an individual critical yield or rating curve target. A look-up table based on the example in Table 13 would be used for this purpose.

5.27 As outlined above, step 1 provides the facility for setting general sediment targets, according to catchment relief (ie upland and lowland) and size. With respect to this, it is important to note two key points. First, in view of the available data, the general targets are based solely on a general understanding of suspended sediment and its potential impacts within river channels. As such, it is recognised that general, rivers-based targets may not be applicable to all habitat types and their associated species. Moreover, in order to maximise the potential for compatibility with the WFD, there is a need to recognise the requirement to set targets for a range of different types of broad receiving water habitat (and their associated communities and species) in addition to rivers; such as lakes, transitional waters and wetlands. Second, the general targets are applicable on an annual basis and do not account for temporal variability in sediment impact.

5.28 In view of the general lumping implicit in step 1, step 2 of the matrix provides the opportunity to take account of the seasonal risk of sediment impacts on specific broad receiving water habitats, communities or species, thereby increasing the link between sediment impacts and ecology. The scope for refinement of the general, rivers-based targets depends on the availability of data. The matrix is flexible and step 2 can be extended to permit consideration of alternative (ie non-river) broad habitats, and any number of associated communities and individual species (two categories are shown in Table 12). In addition, a division of the year into two seasons is incorporated and has been selected on the basis of the ability to translate rating curve information meaningfully and the availability of data that quantify the links between fine sediment and aquatic ecology. In order to define targets under step 2, sediment yield and rating curve targets are first set for each season for each ecological category included. Second, the seasonal targets for each category are considered together to provide one overall sediment yield target and one overall rating curve target for each of winter and summer. The target will reflect the community or species with the highest sensitivity for each season and will this be the lowest value produced.

5.29 It is expected that at this early stage in the development of sediment targets, the potential for definition of specific targets under step 2 is likely to be severely limited. The lack of available data for quantifying the links between specific species and the impact of sediment presents a particular restriction. The potential methodologies for populating the matrix and associated issues of data availability and reliability will be considered further in Section 6.

Table 12 A proposed matrix for sediment target setting

Catchment type	Step 1: General				Step 2: Specific									
	Geomorphological/hydrological sensitivity	**Ecological sensitivity**	**Critical yield: annual**	**Rating curve**	**Eg habitat/community/species**				**Eg community/species**				**Critical yield**	**Rating curve**
					Season	**Risk**	**Critical yield**	**Rating curve**	**Season**	**Risk**	**Critical yield**	**Rating curve**		
Upland														
<10km^2	High	High	Value: see lookup table	Value: see lookup table	Summer	Low	Value	Value	Summer	High	Value	Value	Lowest value	Lowest value
	Medium	Medium			Winter	High	Value	Value	Winter	Low	Value	Value		
	Low	Low											Lowest value	Lowest value
10-100 km^2	High	High	Value: see lookup table	Value: see lookup table	Summer	Low	Value	Value	Summer	High	Value	Value	Lowest value	Lowest value
	Medium	Medium			Winter	High	Value	Value	Winter	Low	Value	Value		
	Low	Low											Lowest value	Lowest value
100-1000 km^2														
1000-10 000 km^2														
>10 000 km^2														

Table continued…

Catchment type	Step 1: General	Step 2: Specific
Lowland		
<10km²		
10-100 km²		
100-1000 km²		
1000-10 000 km²		
>10 000 km²		

Table 13 Example of a look-up table for Step 1

		Geomorphological/hydrological sensitivity		
		High	**Medium**	**Low**
Ecological sensitivity	**High**	**Lowest value**	Intermediate value	Intermediate value
	Medium	Intermediate value	Intermediate value	Intermediate value
	Low	Intermediate value	Intermediate value	**Highest value**

6 Towards estimates of generic critical sediment yields and rating curves

Overview

6.1 The aim of this section is to provide guidelines for generating best estimates of critical sediment yields for catchments of varying geomorphological and hydrological sensitivity, for populating the target framework described in the previous section. It provides an overview of the problems associated with quantifying sediment yield targets, guidelines for establishing sediment yield targets using the currently available data, and some preliminary estimates of such targets based on best professional judgement.

Problems of quantifying critical sediment yield targets

6.2 As indicated previously, values of annual sediment yield can be seen as affording an appropriate and convenient basis for setting standards or critical limits for sediment loads within a catchment. Such values have the advantage of providing a simple summary statistic or representation of sediment mobilisation, delivery and transport within a catchment. However, the limitations of such data, in terms of both their precision and their capacity to reflect the key linkages between fine sediment transport and ecological impacts must be clearly recognised.

6.3 The problems of obtaining **reliable** suspended sediment yield data have been outlined in Section 2, and these have important implications for both establishing critical sediment yields and for any subsequent measurement programme aimed at demonstrating or confirming compliance. Derivation of meaningful values of critical sediment yield through an assessment of the range of ecological impacts in catchments with known sediment yields must clearly be based on reliable data. Equally, if compliance is to be confirmed, the measurement programme aimed at generating the necessary information must be capable of providing reliable values of sediment yield.

6.4 In addition to these important **reliability** issues, the inherent statistical properties of sediment yield data must also be recognised. Thus, even if reliable sediment yield data are available, careful interpretation of such data is necessary. In the context of annual sediment yield data, the key factor is the inter-annual variability of annual sediment loads or sediment yields. It is well known that sediment yields are likely to vary from year to year and to be significantly higher in wet years than in dry years and that extreme events can cause marked departures from the 'norm'. Use of **mean** annual values of sediment yield provides a convenient means of addressing this problem and the foregoing discussion of using values of annual sediment yield to establish standards or critical limits has implicitly assumed the use of mean annual values.

6.5 Nevertheless, the inherent variability of annual sediment yield data introduces important constraints on the use of values of mean annual sediment yield. More particularly, the precision of such values will vary according to the period of record employed to establish the mean. If the period of record is short, the estimated mean annual sediment load may over- or under-estimate the true value. Similarly, if, as would seem to be very likely, a monitoring programme aimed at testing compliance extends for only one or two years, it could prove highly erroneous to assume that the value of mean annual sediment yield obtained from that short period of measurement can be directly compared with the critical or target value, in order to demonstrate compliance or non-compliance.

6.6 In the absence of long-term sediment load records for UK catchments, it is difficult to characterise statistically their inter-annual variability. However, records assembled by the authors for the Rivers Exe, Creedy and Culm in Devon, which in each case extend over 10 years (1994-2003), provide values for the coefficient of variation of annual sediment load values in the range 43 - 65% (Figure 14). These values are significantly greater than the equivalent values for annual runoff, which, as shown in Figure 14, are in the range 17 – 28%. If it is assumed that the values for the coefficient of variation of annual sediment load values are likely to be approximately double those for annual runoff values, some indication of the likely values of the former for British rivers more generally can be obtained by establishing the coefficient of variation of annual runoff series for UK rivers. Values for the coefficient of variation of annual runoff totals for a representative range of British rivers, based on 10 years of record (1994-2003), are shown in Figure 15, which presents a plot of the coefficient of variation values versus catchment area.

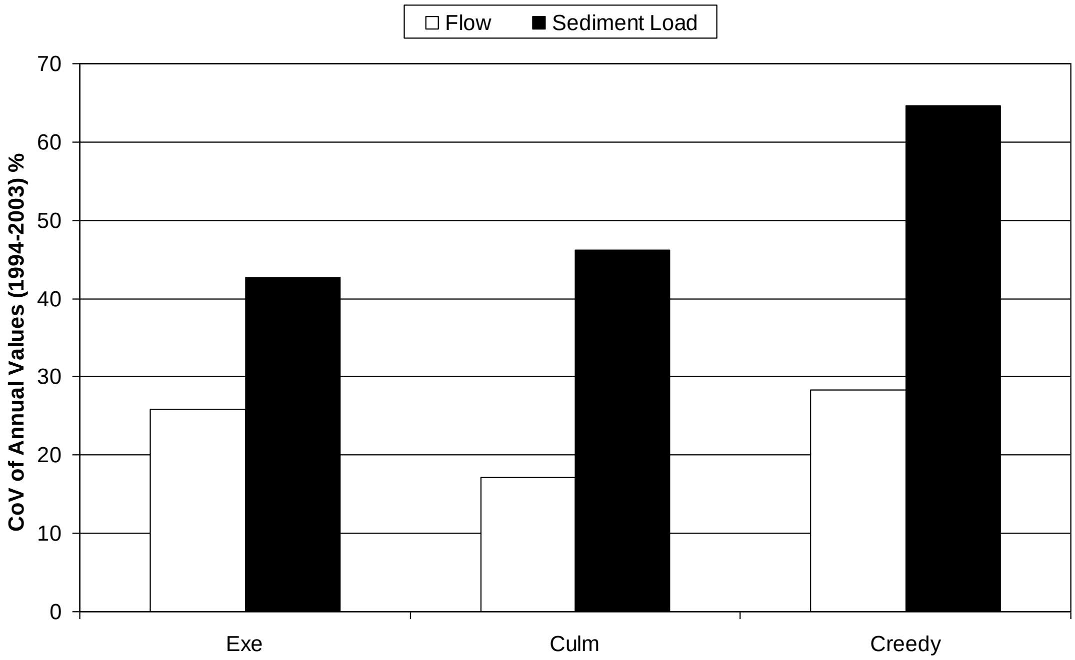

Figure 14 The coefficient of variation of annual values of runoff and suspended sediment yield for the period 1994-2003 for the Rivers Exe, Culm and Creedy

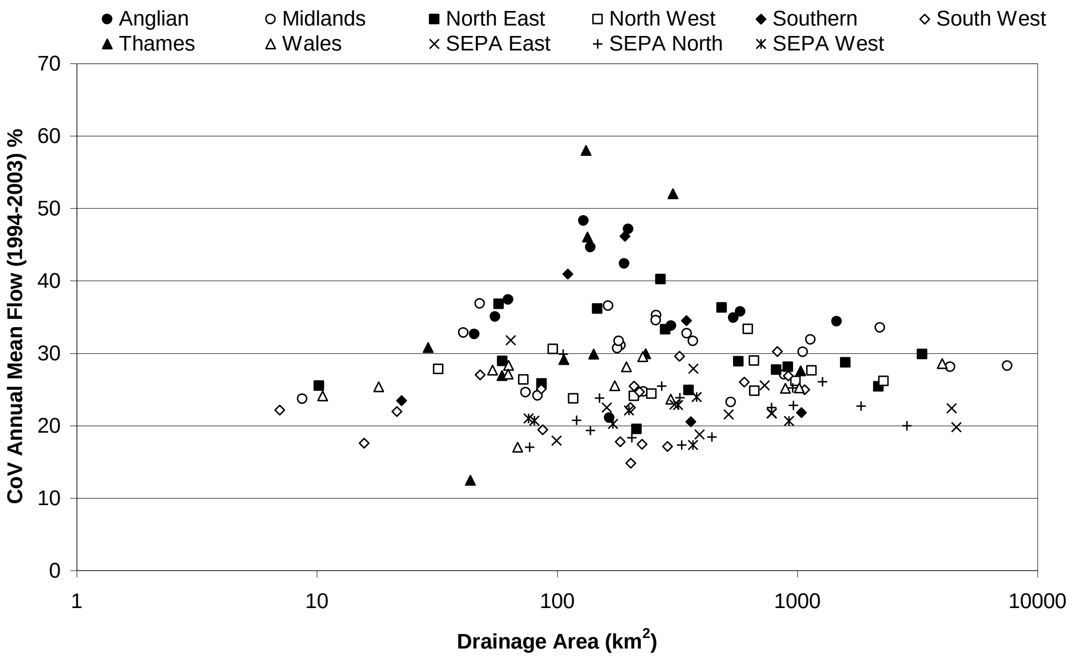

Figure 15 The coefficient of variation of annual runoff values over the period 1994-2003 for a representative selection of British catchments, plotted against catchment area

6.7 No clear relationship exists between the coefficient of variation of annual runoff and catchment area, but values for British catchments can be seen to fall typically in the range 20-40%. If it is assumed that coefficient of variation values for annual sediment loads are generally double those for annual runoff, it can be suggested that a typical value for the coefficient of variation of annual sediment yield values would be ca. 50 - 60%. The implications of the above for the precision of estimates of mean annual sediment yield, based on a short period of measurement, can be usefully demonstrated using simple standard error statistics. These indicate that a period of record of about 25 years would be required to estimate the long-term mean annual sediment load to within ± 20% of the true value, at the 95% level of confidence. Equally, if it is assumed that a catchment had been prescribed a target sediment yield of 50 t km^{-2} year^{-1} and that improved land management had enabled this target to be met, estimates of the mean annual sediment yield from the catchment based on 4 years of record could be expected to lie anywhere in the range 25 - 75 t km^{-2}year^{-1}, even though its actual long-term mean annual sediment yield was 50 t km^{-2}year^{-1}.

6.8 This simple analysis could be further refined, but the conclusions would not change greatly. They emphasise, firstly, that sediment yield standards cannot be defined in a highly precise manner, but should rather be represented as a range, and, secondly, that it is essential that any compliance monitoring programme should take careful account of the uncertainties involved in establishing the current sediment yield from a catchment, which is to be compared with the target value. In the latter case, it is likely that information of the magnitude of annual precipitation or runoff values in relation to the longer-term average would be available. Such information can be used to provide an indication as to whether the measured load is likely to have under- or over-estimated the longer-term mean.

6.9 In addition to the issues of precision outlined above, it is also important to recognise that a value of mean annual suspended sediment yield provides a very generalised and temporally lumped measure of the sediment response of a catchment. Thus, a sediment yield of a particular magnitude could be the result of a small number of high magnitude storm events characterised by high suspended sediment concentrations and loads or, alternatively, lower concentrations occurring over a more extended period and including all storm periods.

6.10 Clearly, these two potential scenarios could have significantly different ecological impacts and it is possible to conceive of situations where the first produced an ecological impact, whereas the second did not. Against this background it is important to recognise the potential limitations of a single value of mean annual sediment yield in providing an unequivocal standard or target. The use of sediment rating curve characteristics as an adjunct to simple yield targets seeks to address this problem.

Approaches to defining critical sediment yields

6.11 As indicated in Section 4, there have to date been very few attempts to establish quantitative links between the magnitude of values of annual sediment yield and the associated ecological impacts. To be comprehensive, such analysis would clearly need to cover a range of hydrological and geomorphological conditions, different habitats and different plant and animal communities and to take account of impacts associated with both excessive suspended sediment concentrations in the water column and excessive fine sediment deposition on the channel bed. The resulting information linking sediment yield magnitude and impacts must be seen as a key requirement for establishing meaningful values of critical sediment yield, which could be used to populate matrices such as those presented in Tables 12 and 13. Similar information is needed for rating curve characteristics, so that these can also be used to complement values of critical sediment yield in such matrices.

6.12 Assembling quantitative information on the ecological impacts of fine sediment, that could in turn be used to establish values of critical sediment yield or sediment targets for a range of hydrological and geomorphological conditions, habitats and species, must therefore be seen as an important research need. Arguably, further progress in establishing critical sediment yields or targets should await the products of that research. However, if a preliminary attempt to establish targets is to be made, alternative and more pragmatic approaches to generating estimates of critical sediment yields are required.

6.13 One possible approach to developing guideline targets could involve taking those rivers for which sediment yield data are available and attempting to distinguish between those where conditions remain semi-pristine and those where human impact, linked to land use and related activities, are likely to have caused increased sediment yields. If it is assumed that there is no ecological degradation in the catchments where conditions remain semi-natural, the sediment yields of those catchments could be used as an initial basis for defining critical sediment yields or targets. If the catchments embrace a range of different habitats and plant and animal communities, it should be possible to establish targets for different levels of ecological sensitivity.

6.14 Identification of semi-pristine catchments would, however, clearly involve a degree of subjective or ‘best professional’ judgement and the resulting dataset would be considerably reduced compared to the overall dataset for British catchments listed in Table 4. Furthermore, it may prove difficult, if not impossible, to identify semi-pristine catchments in some areas of the country. In order to provide more data for use in defining critical sediment yields, this approach could be modified to include an attempt to apportion the current sediment yields of catchments into a baseline or ‘natural’ component and an additional component associated with land use impact. Values relating to the baseline or ‘natural’ component could provide an additional basis for estimating the sediment yields of semi-pristine catchments. A greater degree of subjective judgement would necessarily be involved, but the analysis could be informed by existing understanding of the impact of land use on sediment yields and information on sediment sources, such as that presented in Table 6. The approach outlined above could be further informed by additional sources of evidence concerning the ecological health of particular river reaches or catchments, such as provided by River Habitat Surveys (RHS). However, such surveys will be sensitive to numerous potential controls on ecological health, many of which may be unrelated to sediment impacts, and a reduced RHS score cannot in itself be seen as evidence of a sediment impact.

6.15 Further work is required to implement the approach suggested above, but, to demonstrate its potential, an initial subjective attempt is provided in Table 14 for both upland and lowland catchments in the range 10-100 km². In this table, critical sediment yields are expressed as ranges, rather than as absolute values, in order to take account of the issues of precision and uncertainty outlined in paragraphs 6.2 - 6.10 above. However, when developing management strategies and using models to assess the impact of different land use scenarios and their potential to meet specific targets, it may prove more convenient to use a single value representing the mid-point of the range.

Table 14 A preliminary subjective attempt to populate the target matrix for **A** lowland and **B** upland catchments in the range 10-100 km² (values are best expert judgements of the authors)

Table A Lowland Catchments

		Geomorphological/hydrological sensitivity		
		High	**Medium**	**Low**
Ecological sensitivity	**High**	4-8	15-25	30-40
	Medium	15-20	25-35	40-50
	Low	20-30	35-45	50-60

Table B Upland Catchments

		Geomorphological/hydrological sensitivity		
		High	**Medium**	**Low**
Ecological sensitivity	**High**	10-15	20-30	50-60
	Medium	20-25	30-40	60-70
	Low	25-35	45-55	80-100

Values listed represent values of mean annual suspended sediment yield in t km^{-2} $year^{-1}$

6.16 Further work is again required to identify appropriate parameters for characterising the suspended sediment rating curve for a catchment and to establish critical values of these parameters for catchments of different size and with different ecological and geomorphological sensitivities, which can be employed to complement values of critical sediment yield. Figure 16 presents a selection of sediment rating curves for 17 British catchments, plotted in the conventional fashion on logarithmic coordinates. The discharge axis has, however, been plotted as specific discharge (m^3 s^{-1} km^{-2}), in order to facilitate direct comparison between the catchments.

6.17 It is clear that the individual rating relationships can be distinguished by both the slope or exponent and the intercept of the relationship. These two parameters would be sufficient to define a critical or target rating curve for a catchment, although it would be necessary to define a band surrounding the line, within which individual points (samples) would be expected to fall. As demonstrated in Figure 5, it would also be possible to refine further the definition of critical rating curve parameters by distinguishing summer and winter seasons, if these are characterised by different ecological and geomorphological / hydrological sensitivities. As with sediment yields, there would be a need to establish characteristic values of these rating curve parameters for semi-pristine catchments, in order to provide a basis for defining critical values.

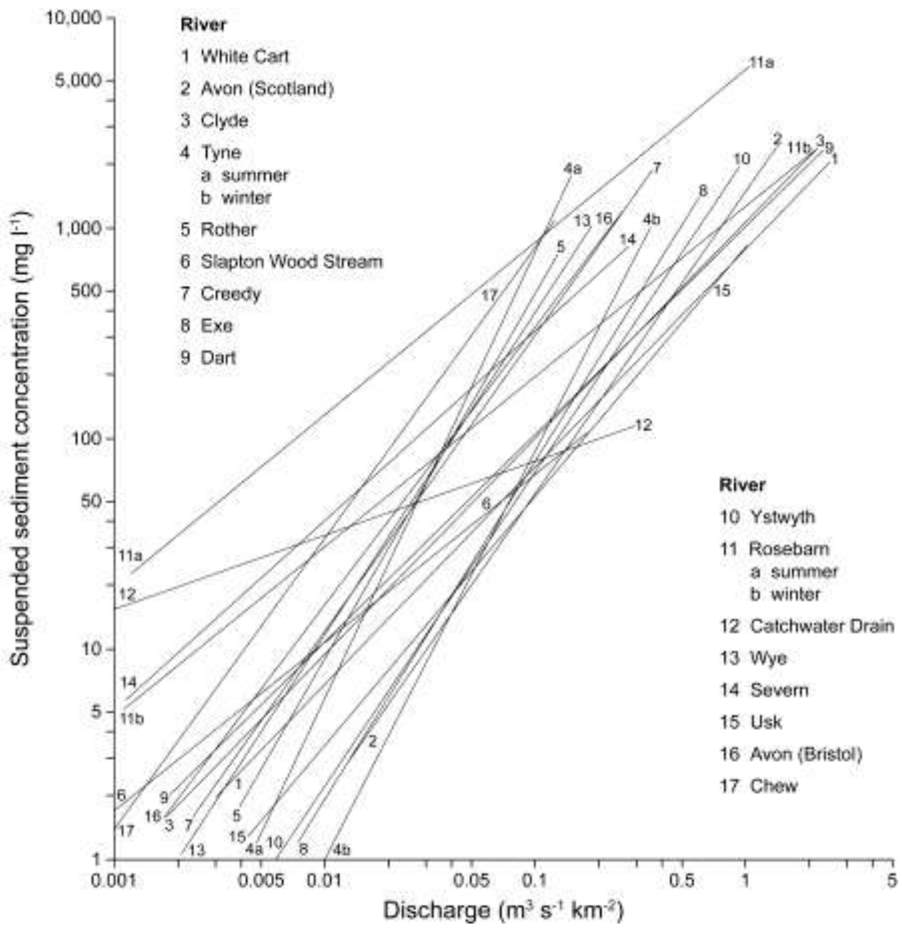

Figure 16 A compilation of straight line suspended sediment concentration / discharge relationships or rating curves for a selection of British rivers

7 Recommendations

7.1 Whilst this work has helped to highlight the serious ecological risks and impacts associated with excessive fine sediment delivery from catchments, and the consequent need to make progress with controlling fine sediment, it has also highlighted a lack of quantification of relationships between fine sediment delivery and ecological response. Recommendations are made below in two main areas:

- immediate work required to populate the target framework with best available judgements; and
- strategic work required to progress the development and application of sediment targets.

These two areas will be considered further in turn.

Populating the target framework

7.2 Clear guidelines should be developed for classifying both the hydrological and geomorphological sensitivity and the ecological sensitivity of a catchment, in order to identify the appropriate cell on a look-up table, such as that presented in Table 12. Linkage to other ongoing work may provide support for this process. For example, the Environment Agency is currently undertaking work on hydromorphological sensitivity as part of the development of the WFD Programme of Measures. In addition, work is in progress at Cardiff University in association with the Environment Agency River Habitat Survey Group, to compile evidence for links between morphology and ecology in terms of impacts and sensitivity.

7.3 An in-depth analysis should be undertaken of the available sediment yield data and information on rating curve characteristics for UK rivers, in order to develop an improved understanding of the key controls and to establish a means of estimating reference values that can be used to populate look-up tables, such as that presented in Table 12.

Strategic progress on the development and implementation of sediment targets

Sediment yield data

7.4 In view of the fundamental need for good quality sediment yield data and the limitations of the currently available data, the following recommendations are made.

- A national programme of suspended sediment monitoring is required, in order to improve data quality and availability and to support target setting. The monitoring strategy should aim to consider all types of receiving water and to include the following elements:
  a. a network of automated suspended sediment monitoring stations covering both key catchment outlets and a range of smaller 'representative' catchments, embracing a wide range of catchment characteristics and land use types (this could be designed to be consistent with WFD monitoring requirements).
  b. local monitoring of areas where specific risks have been identified (eg Figure 4) or where sediment management initiatives have been implemented (eg DEFRA's Catchment Sensitive Farming Delivery Initiative).
- Information on the magnitude of sediment loads and concentrations obtained from monitoring stations should be complemented by information on the grain size composition and organic content of the suspended sediment and levels of sediment-associated nutrients and

contaminants (eg N, P, pesticides, heavy metals), in order to provide a basis for target setting that incorporates sediment properties as well as fluxes.

Sediment and ecology

7.5 In view of the lack of quantification of relationships between sediment loads and concentrations with impacts on specific aquatic species or specific types of receiving water, the following recommendations are made:

- Further refinement of the preliminary sediment yield targets suggested in Section 6 and development of target rating curves to incorporate greater consideration of ecological sensitivity in the first instance and to permit their eventual application to specific receiving habitats or species.
- The incorporation of information on sediment quality as well as quantity into the target setting process.
- A programme of research to elucidate the ecological impacts of both increased turbidity and sediment deposition and their relative importance.
- A programme of research to elucidate the link between sediment yield/sediment rating curves/sediment quality and ecology in the full range of receiving waters.

Modelling tools

7.6 There is a need to further refine PSYCHIC to exploit fully its potential to provide an effective tool for supporting sediment management and control in catchments. More particularly, there is a need to incorporate sediment contributions from channel erosion into the model, so that predictions of the impact of changes in land use or land management relate to the overall sediment yield from a catchment rather than the contribution from the catchment slopes. Sediment impacts will commonly reflect the total sediment yield and sediment targets will also relate to the overall sediment yield from a catchment. PSYCHIC also needs to be able to simulate sediment delivery to the channel in a realistic way – making it a fully distributed model is a priority task.

Land use practices and sediment yields

7.7 In view of the lack of empirical evidence regarding the impact of improved land management or changed land use on catchment sediment yield, there is a need for a programme of research that:

- provides a review of available data relating to best practice to identify data gaps;
- considers the spatial and temporal efficacy of specific techniques; and
- considers the efficacy of techniques in combination at the catchment scale under a representative range of environmental conditions.

7.8 Defra's Catchment-Sensitive Farming delivery project provides excellent opportunities to improve our knowledge base in these areas.

Geomorphological techniques and their application

7.9 In view of the importance of a geomorphological understanding of fine sediment behaviour, the following recommendations are made:

- Training of personnel involved in implementation of targets in order to maximise awareness of the strengths and weaknesses of critical sediment yield and associated targets, and of the potential value of field-based geomorphological assessment, ie to place the management process within a geomorphological context.

- Development of guidelines to standardise the toolkit of available fluvial geomorphological approaches for catchment appraisal and target-setting, and to provide a protocol for selection and implementation of techniques under specified circumstances. In order to focus resources, priority catchments within which to test approaches could be selected from a representative range of categories (eg based on catchment type or scale) according to their risk of sediment-related problems.
- Standardisation of the range of geomorphological assessment techniques at the national level (cf. Walker and others, in press).
- Development of a national, comprehensive storage system for fluvial geomorphological data (cf. Walker and others, in press).
- Development of a comprehensive national policy on the application of fluvial geomorphology (cf. Walker and others, in press).

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Appendix 1 Evaluating fine sediment problems in freshwater ecosystems: a fluvial geomorphological perspective

Introduction

This contribution presents the somewhat skeletal understanding of the source-pathway-target for fluvial sediments derived from recently introduced geomorphological survey procedures. We cannot over-emphasize the fact that, until the end of the 20th Century, fluvial geomorphology played virtually no role in the management of freshwater systems in the UK. The UK therefore lacks the dense measurement/survey networks and long data runs that would greatly facilitate our understanding (Sear and Newson 2003). The translation of almost wholly academic knowledge and information into 'tools' for application to the range of emerging fluvial sediment management interests (inter alia physical habitat, flood risk management, water quality, climate change) must be managed with precaution and professionalism (Newson 2002). This translation is nowhere less certain than in relation to issues of biodiversity couched in terms of 'damage' (harm) to 'natural' or reference conditions (Large and Newson, in press; Newson and Large, in review).

State of the knowledge base: anthropogenic impacts on the fluvial sediment system in the UK

Siltation rates and levels in UK streams

This section presents available information on fluvial siltation in the UK. It should be seen against a backdrop of climate change predictions that suggest gross changes in catchment hydrological regimes that will have severe impacts on water-driven soil erosion and hence sediment delivery to rivers. For example, Reid and others (in press) clearly identify the very marked impacts of our best current estimates of future climate change in the sourcing and delivery of sediments in an upland catchment (Wharfedale, Yorkshire).

Rates of infiltration of fine sediment (particles <2mm) into coarse riverine substrates have been recorded for a range of UK river types. Comparison is made difficult by the variety of techniques used, season of measurement (high flows or low flows) and the time over which the measurements were taken. Figure A represents those datasets that utilise similar infiltration basket technology and whose timescale of measurement permitted standardisation. Although spatial variability in infiltration rate is evident even within the same broad stream type (eg chalk streams in Southern England), overall the pattern demonstrates an internal consistency with similar levels reported for streams in widely differing geographical locations and type. Average rates are around 2.49 $kgm^{-2}week^{-1}$ with a standard deviation of 1.89. Rates greater than 2$kgm^{-2}week^{-1}$ are likely to be indicative of high suspended loads and/or catchment lithology with high rates of sediment production.

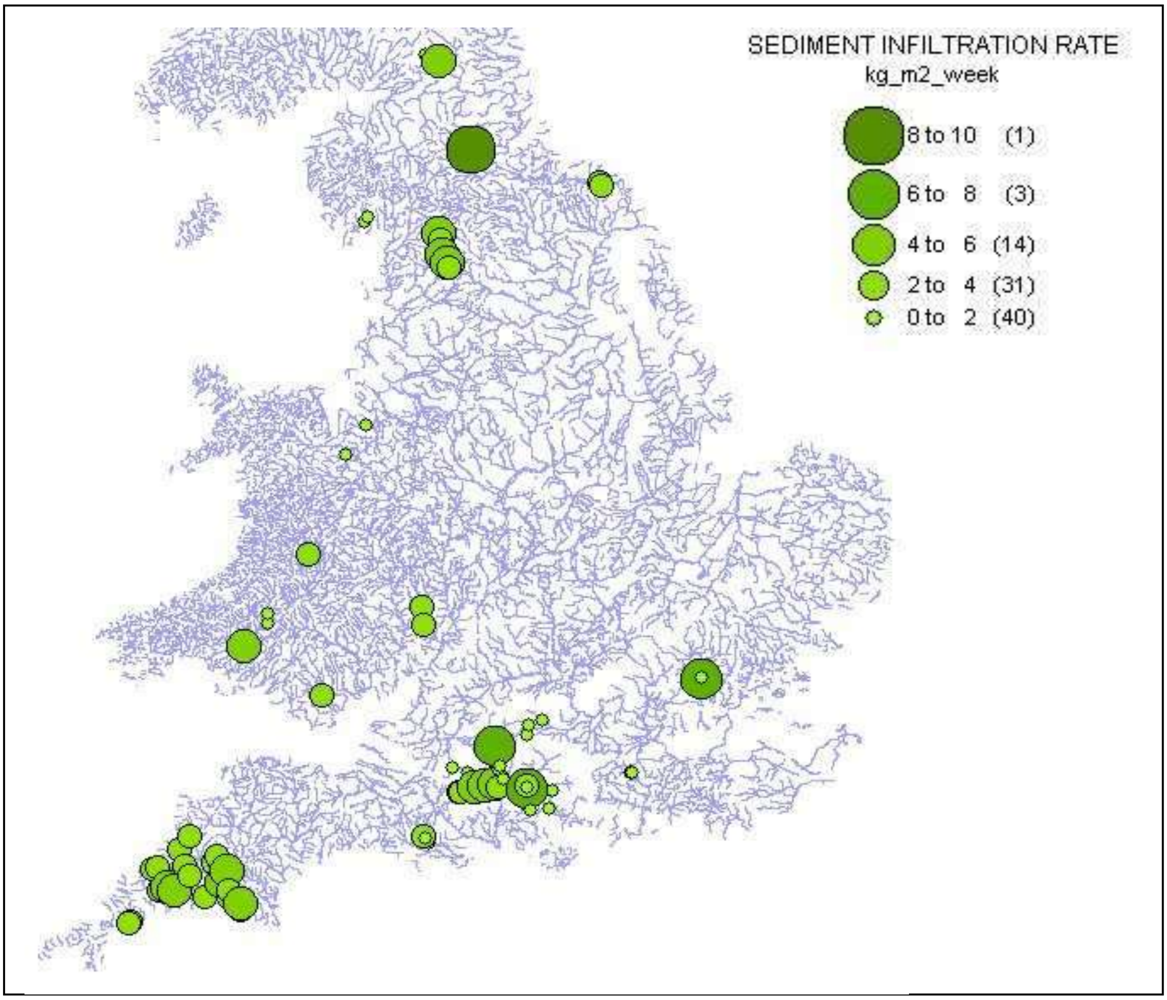

Figure A Fine sediment infiltration rates in UK rivers

(Source data compiled from CEFAS 2001 Sedimentation Database, EA 2002, Sear 1992, 1993, Sear & Acornley 1999)

Levels of fine sediment within gravels are highly dependant on the lithology of the catchment and the ability to flush the fines from the gravel beds. A review of 109 freeze core datasets of gravels within UK rivers is summarised in Table A below. The data have been separated into river channels in groundwater chalk catchments and those in upland runoff-dominated catchments. The distinction is largely one between those catchments that can flush their gravel beds and those that are unable to. There is a clear and statistically significant ($p<0.001$ Mann Whitney U-Test for non-normalised distributions) distinction between the levels of fine sediment within chalk streams and those in rivers with runoff-dominated hydrology. All data are for bulk cores and no distinction is made on the basis of surface or subsurface layers.

Table A Summary statistics for freeze core data collected from gravel beds within UK rivers

	Chalk	
	% < 1mm	%<2mm
Average	23.2	28.2
StDev	14.4	14.4
Max	69.8	73.4
Min	7.2	9.8
	Hard rock	
Average	10.0	15.4
StDev	4.8	5.8
Max	24.6	37.1
Min	0.5	7.8

(Data derived from CEFAS 2001 Sedimentation Database, Milan and others 2000, Carling & Reader 1982, Sear 1992, Acornley & Sear 1999. Number of Chalk samples = 78, Number of Hard Rock = 31)

Current Favourable Condition statements for SSSI rivers for fine sediment levels within the surface layers of gravels set a guideline target of <10% by weight of fines <0.85mm. Although the dataset is for bulk (surface and subsurface) it is instructive to note that fewer than 31% of sites have bulk fines contents <1mm at or below 10% by weight, and all these are from upland gravel bed rivers. No chalk or low stream power sites are close to this threshold (for this reason, Natural England allow for less stringent targets to be set for chalk rivers).

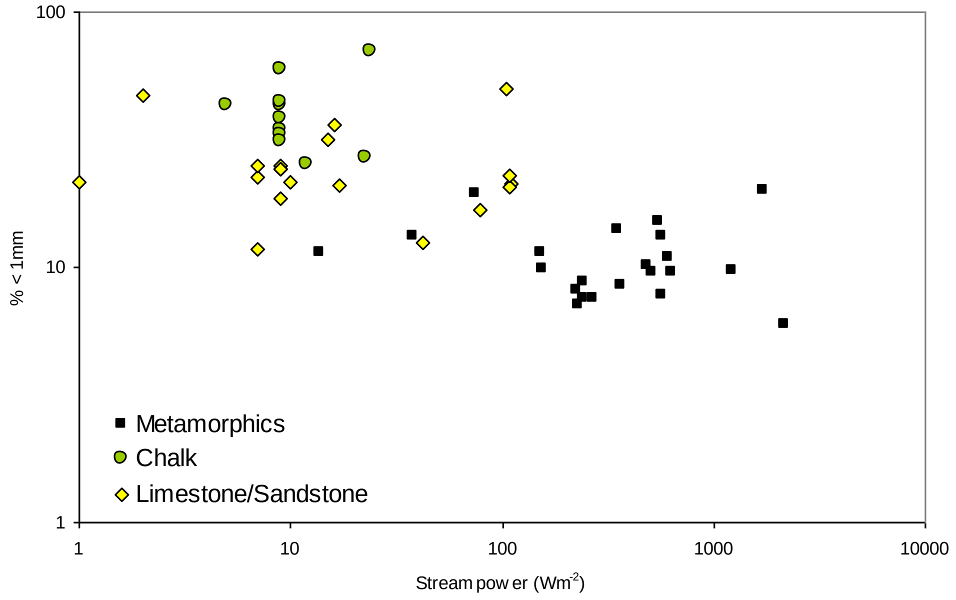

Figure B Relationship between stream power and the level of fine sediments recorded in freeze core bulk gravel samples (after Milan and others 2000)

(Groundwater dominated streams clearly stand out as low power, high fine sediment accumulated systems compared to runoff dominated streams where scour keeps the gravels clean)

A measure of flushing is provided by the stream power available for sediment transport in each stream. Unfortunately this is only available for half the total dataset. These data are plotted in Figure B which demonstrates the positive correlation between increasing stream power and lower levels of fine sediment within the gravel bed.

The presence of two distinct types of gravel bed river - those that mobilise their beds and those that have stable gravel beds results in different system sensitivity to fine sediment yields. Chalk streams and those with low stream power will be more sensitive to modest increases in fine sediment yield resulting in sedimentation of gravels compared to higher power rivers with periodically mobile beds. Lower limits for low stream power rivers might be around 15-30% fine sediment < 1mm within the bed whilst for more impermeable catchments this lower limit may be 5 – 10%.

A potential guide to assessing the sensitivity of rivers to siltation is based on the ability of a stream to mobilise the framework gravels. In the US, definition of flushing flows is well established and provides a conceptual model for managing the hydrology of regulated streams (Kondolf and Wilcock 1996). In the UK context, identification of natural ability for fine sediment flushing would be possible using Fluvial Audit-derived information. An example given below shows the predicted mobility of gravels within the River Nar in West Norfolk a chalk stream with sand/silt drift and a perceived siltation problem. Using information derived from cross-section surveys and a measure of the surface framework gravel population, it was possible to estimate the mobility of the bed substrate under bankfull flows. Figure C illustrates the lack of predicted bed mobility and hence absence of flushing of fine sediments from within the gravels.

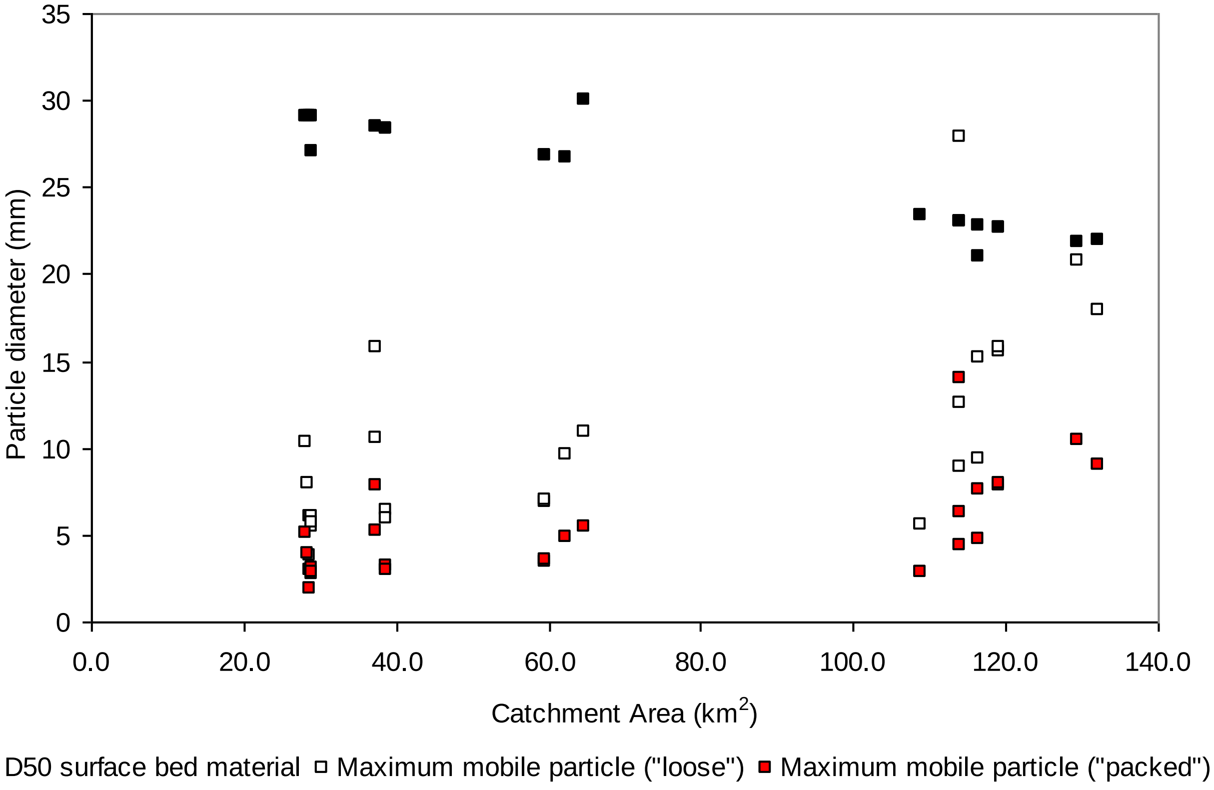

Figure C Gravel bed stability in the River Nar, Norfolk based on estimated maximum particle mobility using Shields entrainment function

Complexities in relationships between sediment delivery and ecological impacts

Physically, fluvial sediments are not 'conservative' pollutants. In the way that 'non-conservative' chemical pollutants translocate and transform in the pollution pathway, sediments interact together and also perform a 'relay race' by switching between storage and flux (deposition and erosion).

In this project we are mandated to deal primarily with the currently perceived problem of 'siltation' but the term itself strikes an impossibly reductionist position for fluvial geomorphologists. Instead, we are attempting to emphasize the importance of fine sediments within the full range of sediments in transport and storage and the resulting habitat templets created at various points in the system. This mesoscale morphological and hydraulic approach has been advocated as contributing to catchment-scale management processes (Newson and Newson 2000).

There are five main components to the complexity of relationships between sediment delivery and ecological impacts:

- **Catchment dependant –** for example, lowland chalk streams accumulate and store more of their catchment yield in the channel network than higher energy upland rivers. Catchment topography/lithology/land cover/climatic regime create different supply regimes.
- **Reach dependant** – some reaches throughput, others store. At a catchment scale this may in itself constitute physical habitat diversity (eg 1000 yr old ponded mill reaches on lowland rivers interspersed with short steep reaches produce arguably more varied habitat than might result from natural processes).
- **Sediment dependant** – fine clays and silts are especially deleterious to early life stages of biota that require oxygen diffusion and which lie within stable gravel beds. Similarly, the organic matter and associated contaminants are especially important. Sand becomes important for entombing and embedding substrates, reducing refugia/habitat for benthic invertebrates.
- **Biota dependant** – Different biota have different tolerances/requirements for fine sediment (eg salmonids/lamprey) and may be linked more or less through the food chain to other fine sediment-specific biota. Furthermore organisms can modifiy the fine sediments; for example by growth of biofilms or the re-working through ingestion and excretion by invertebrates.
- **Life-stage dependan**t – Different life stages are more / less sensitive to fine sediments within the river and floodplain ecosystem.

Thus a dynamic fine sediment load, interacting with a hydraulically variable river network, may result at the catchment scale in a more diverse range of habitats. In contrast, excessive delivery of fines to, or excessive storage of, fines within the river network may reduce the heterogeneity of the substrate with implications for the diversity of hyporheic exchange as a result of substrate accumulation (Greig 2004).

A further consideration is the type and magnitude of river management activity that may render reaches or indeed the river network more or less sensitive to sedimentation. Abstraction of water can exacerbate low flow problems resulting in increased rates of silt accumulation (Wood & Armitage 1999), channel maintenance can create extensive marginal deadwater zones or gross reduction in fine sediment transport rates leading to accumulation.

The controlling components of fine sediment problem situations, such as loads, sediment dimensions, sorting and permeability, are laid out by Reiser (1998) in Figure D. These are candidates for the kind of metrics required by those assessing impacts and setting up management regimes, although all of these have limitations. Combinations of the investigative techniques outlined can offer a 'general methodology' which is appropriate to particular cases (Table C). It must be said, however, that flow regulation is a much more important regulator of freshwater habitat quality in the USA (where Reiser's thinking has developed) than in the UK; the UK's 'hydromorphology' is generally more influenced by channel modifications than by flow regime.

A review by Diplas and Parker (1992) covers five field studies of the ingress of fine sediments into gravel river beds and five laboratory (flume) studies. The major findings of these studies are shown in Table D and they point up the essential elements of complexity to which we return below: the essential relationship between properties of the ingressing matrix fines and the 'host' gravel matrix and the vital role of river flow, in terms of its ability to mobilise different parts of the river bed at different rates and to different depths, within the same flood event.

Metric	Definition	Utility	How Measured	Limitations
Percent Embedded-ness	Degree to which larger particles in surface layer are buried by fine sediment	1) General index of sedimentation impacts to spawning, rearing, and food-producing habitats 2) Quick measure of sediment loading	1) Visual approximation 2) Statistical sampling of individual rocks	1) Not a good measure of sediment impacts to egg pocket 2) Requires visual calibration between multiple observers
Percent fine sediments, gravel, cobble, boulder	Percent of total stream bed area composed of specified facies group (size class)	Characterizing general spawning and rearing habitat quality and quantify in terms of general substrate types	Plan view mapping of substrate facies groups	Variable choices for size classes
Percentage of fine sediments < X mm	Percentage by weight or volume of sediments passing specified sieve size equal to X mm, to total sample weight or volume	Quantitative evaluation of salmonid embryo survival during incubation and to emergence from gravel	Physical gravel samples; Cumulative grain size distribution from sieving	1) Labor intensive to evaluate 2) Predictive survival relationships currently are of low accuracy with variable choice of X
D_{xx}	Particle size for which XX percent of particles are smaller	1) Simple characterization of substrate grain size distributions 2) Used to calculate other metrics (e.g. see below) 3) Extreme values of xx are useful measures for making comparisons of sediment loading 4) Incipient motion / bedload transport formulae (substrate stability, scour)	Physical gravel samples; Cumulative grain size distribution from sieving	1) Labor intensive to evaluate 2) Single values do not characterize complete distribution 3) Variable choices for XX
Geometric Mean Diameter (Dg)	Mean value of log-transformed particle diameters	1) Quantitative evaluation of salmonid embryo survival during incubation and to emergence from gravel 2) Simple characterization of central tendency of grain size distributions 3) Incipient motion/ bedload transport formulae (substrate stability, scour)	1) $\sqrt{D_{84}D_{16}}$ 2) $\sqrt[3]{D_{84}D_{50}D_{16}}$ 3) $D_1^{w_1} D_2^{w_2} \ldots D_n^{w_n}$ where w_n = fraction of weight of particles retained on nth sieve	1) No information on variance charactertstics of grain see distribution 2) Third formula needed for grain size distributions that are not distributed approximately lognormally 3) Labor intensive to evaluate
Geometric Standard Deviation	Relative measure of the magnitude of variation about the mean	1) Simple measure for how well sorted the substrate is 2) Evaluation of lognormality of distribution	$D_{84} / D_{50} = D_{50} / D_{16}$	Labor intensive to evaluate
Sorting Coefficient (So)	Relative measure of the magnitude of variation about the mean	1) Simple measure for how well sorted the substrate is 2) Used to calculate other metrics (e.g. Fredle Index)	$\sqrt{D_{75} / D_{25}}$	Labor intensive to evaluate
Fredle Index (Fi)	Measure of substrate pore size and permeability	Quantitative evaluation of salmonid embryo survival during incubation and to emergence from gravel	Dg/So	Predictive survival relationships currently are of low accuracy
Permeability /Apparent Velocity	Parameters of Darcy's Law	Descriptions of water flow through redd	Experimental application of Darcy's Law	Difficult to measure in field

Figure D Evaluation of sediment metrics (from Reiser 1998)

Cace Study	Problem Addressed	General Methodology
Sediment Monitoring and Flushing Flow Assessment below a Hydroelectric Project	Potential problem relates to sediment accumulation below hydroelectric project. Study designed to: l) Define flows or range of flows needed to mobilize and transport fine sediments from important spawning habitats and food production areas in the lower Madison River, Montana; and 2) Determine when flushing flows are needed and should be released from the project.	l) Flushing flows determined by: a) substrate core sampling and grain size analysis; b) hydrologic analysis natural hydrology; flood frequency analysis; c) geomorphic response analysis comparison of aerial photographs; d) sediment transport analysis stage:discharge determinations coupled with Shield's parameter; e) invertebrate sampling - define baseline conditions. 2) Need for flushing flows determined by annual monitoring program focused on: a) sediment - core sampling and scour chains; and b) invertebrates - Hess samples
Gravel Supplementation to Augment Salmonid Spawning Habitat	Hydroelectric project has cut-off upstream supply of gravel. This has resulted in limited amount of spawning gravels below dam. Feasibility study completed to evaluate gravel supplementation as means to increase spawning habitat. Focused on evaluating potential for supplemental	1) Develop Habitat Suitability Criteria (HSC) for spawning rainbow trout - site specific; 2) Define candidate sites for gravel supplementation that a) meet physical and hydraulic criteria for spawning fish; b) would be subjected to periodic flushing of fine sediments, without transport of gravels; 3) Field surveying of sites; 4) Develop alternatives for supplementation; S) Estimate construction costs; 6) Utilize PHABSIM model to determine quantity, and quality of habitat provided before and after gravel supplementation.
Estimation of Natural "recovery time" of Spawning Gravels Containing High Concentrations of Sediment	Historical land-use activities have resulted in excessive sediment deposition within river, which has degraded spawning, rearing and food production habitats. Study completed to estimate time to recovery of gravels back to conditions conducive to trout production.	l) Define existing substrate conditions (levels of fine sediments) via core sampling and grain size analysis; 2) Establish biological criterion for recovery (i.e. fine sediments (<0.84 run diameter) reduced to less than 10%; 3) Assume 50% sediment source control; 4) Integrate hydrologic records with sediment transport models (HEC - 6; ACRONYM) to estimate time to recovery.
Flushing Flow Determinations Below a Hydroelectric Project	Hydroelectric project has reduced frequency and magnitude of high flows; also isolated gravel supply. Study conducted to define magnitude of flushing flows that would maintain "clean" spawning gravels, without gravel loss.	1) Assess existing sediment levels via core sampling; 2) Define target level of fine sediment; 3) Collect depth/velocity data at 3 flows; 4) Apply Shield's parameter to identify mobilization flows of different size materials; 5) Develop "window of acceptability": provides for surficial flushing of fines without bed mobilization

Figure E Assessment of different sediment evaluation techniques in relation to generic case studies (from Reiser 1998)

Table B A summary of the review carried out by Diplas and Parker (1992) of the empirical evidence for 'siltation' processes

Authors	Study site	Major findings
Millhouse (1973)	Oak Creek USA	Sand (<2mm) concentrates below armoured bed surface: 12% a constant value
Adams & Beschta (1980)	Oregon Coast Range	Fines (<1mm) ingress varies between streams, riffles and parts of riffles. Flushing is vital. 'Normal' 19.4%, 'Impacted' 49.3%.
Frostick and others (1984)	Turkey Brook UK	Armour layer promotes ingress but flushing occurs to depth of twice the d_{90} bed material.
Lisle (1989)	Northern California	High energy locations 'drive' fines into bed to depth of 2.5 x d_{90}. 'Seal' formed. Processes of both infiltration and 'scour/fill'.
Alonso and others (1988)	Tucannon River USA	No 'seal' formed. Scour of eggs = importance. Too big difference between bed and 'silt' sizes.
Einstein (1968)	Flume	Silt 'flour' fills up gravel from bottom up. Too big difference between bed and 'silt' sizes.
Beschta & Jackson (1979)	"	Confirms 'bottom up' filling by sand in gravels but bed not moved.
Dhamotharan and others (1980)	" (model of Oak Creek)	Fines cause reduced bedload transport and collect between armour and sub-armour.
Carling (1984)	"	Bed not moved but ingress varied with concentration of the coarsest sand – formed seal.
O'Brien (1987)	Yampa River USA & model of same	Fines can be flushed from depths up to d_{50} without mobilizing bed material.

Understanding catchment-scale processes using geomorphological appraisal

Introduction

Unlike the behaviour of some conservative chemical pollutants in the 'pathway' between source and target, fluvial sediments experience and exploit the rich hydraulic diversity of the water flow regime between high hillside and river estuaries. Whilst channel storage of fine sediments may not be important (Lambert and Walling 1988) it is vital to the hydromorphological heterogeneity and dynamics that coarser sediments reach the coast only on a very 'jerky conveyor belt'. Fine sediments, however, are much more prone to the influence of flows modified on slopes and small tributary channels/drains, principally by local slope changes or by vegetation cover. It is the concept of this spatially-variable system of ‘delivery’ which we explore in this section.

Source-pathway-target in space and time

Evidence from a number of studies in the north west of England has identified a wide variety of dominant controls on sediment delivery at the catchment scale. These are easier to ascertain for coarse sediment than for fine since the evidence of coarse sediment transport/deposition is more obvious in the environment. To some extent the delivery of sediment reflects the dominant geomorphology and in upper tributaries this is related to the connectivity of the channel to surrounding steep slopes, sediment is usually delivered in intense rain events. The delivery ratio at the local scale may be highly dependent on the local vegetation cover and degree of channel activity at the base of the slope. To some extent upland tributaries are easier systems to budget for sediment sources and sinks.

In the English Lake District there are gravel traps and the relatively well-coupled slope and channel systems can be studied at the hillslope scale (eg Warburton and others 2003). There have even been relatively successful attempts to model these systems and their response to climate change (Reid and others, in review a; Reid and others, in review b). However, a gravel trap upstream of the village of Threlkeld (Kiln How trap) in the Bassenthwaite catchment was filled by mixed-calibre sediments in a single event in the summer of 2004; prior to this it had not been emptied for more than 20 years (Orr and others 2004 and NRA 1994). Sear and Newson (2003) also refer to the marked temporal variability of catchment yields in upland areas.

River channels and the sediment delivery system downstream of the upper tributaries can become much more complex. For example upper piedmont valleys may regularly supply small amounts of sediment from eroding bank margins, these systems have the potential to respond to rare events such that the entire valley floor becomes active and effectively a braided system (Wells and Harvey 1987). Such events may have a frequency of only 1 in 100 years; thus, average annual yield is an unhelpful way of conceptualising these systems; a widely-known recent example of such events is the Boscastle (Cornwall) flood of August 2004. The upland/lowland transition zone seems to be a particularly vulnerable location for highly varied but potentially very large sediment events. However new modelling work suggests that it may be possible to reduce source-area sediment yields with a riparian woodland in first/second order channels (Lane pers. comm.).

We have tended to assume that the uplands are the source areas for coarse sediment but extensive upland erosion and intensive grazing produce an unknown amount of fines, associated with unknown phosphorus budgets. The loss of organic-rich topsoil results in the exposure of subsoil material that can be rich in inorganic carbon. These changes set up the conditions for complex biogeochemical processes whereby carbon may be lost or accumulated within the soil-landscape irrespective of soil erosion, eg dissolution of primary carbonates, emissions of CO2, and formation of secondary carbonates (Quinton pers. comm.).

Steep bedrock and boulder gorges characterise the descent into the lowland reaches of heavily glaciated rivers where agricultural land has premium value and channelisation may have been extensive for hundreds of years. In the Bassenthwaite catchment 86% of channels are heavily modified and due to a reduction in engineering maintenance and an increase in flood activity many of these channels are now in a poor state of engineering. This has resulted in considerable instability and accelerated supply of fine sediment in many locations.

It is likely that sediment deposition on the floodplain has been limited where embankments have been in place – some of these were built before the C18th . It is less clear whether revetted channels reduce the entrapment and deposition of fines in the riparian zone and floodplain by reduced roughness and hence frictional resistance on the channel margins. The aim was increased in-channel conveyance; it is therefore likely that revetted channels offer less opportunities for marginal deposition, even in over-bank flows. Figure F is offered as a pictorial guide to the complexities of the fluvial sediment system, particularly as it effects the delivery of material from source areas in the uplands. It is these complexities which must be generalised by further survey/monitoring if a pollution control philosophy is to be applied to 'siltation'.

Geomorphological survey procedures: field identification of sources, pathways and targets

In recent years fluvial geomorphology has made increasing contributions to river management in the UK and, partly for reasons of professional accountability, it has become necessary to erect a terminology and equivalent standards for the procedures through which geomorphological expertise is applied (Newson 2002). In increasing order of complexity and cost, but decreasing order of geographical scale, these are known as Catchment Baseline Survey, Fluvial Audit, Dynamic Assessment and Environmental Channel Design (see also Sear and others 2003).

There is a further important survey technique, distinguished by its fusion of some of the principles of RHS and Fluvial Audit: geoRHS (Defra, EA, SNIFFER 2003). This system also uses a remote sensing component that allows a much broader, holistic, consideration of catchment conditions (principally the floodplain).

Geomorphological reconnaissance-type field surveys provide information on process-response feedback mechanisms up- and downstream of any site under investigation. There are alternatives eg monitoring and modelling but the UK information base is weak in both respects - hence the need for reconnaissance survey and monitoring (Sear and Newson 2003). Practically applicable geomorphological models are still limited to one dimension and largely straight channels and predictions that might be made from historical data assume constant drainage basin controls.

Early river reconnaissance approaches are covered by Kellerhals and others (1976) and subsequent variants have been devised to cover site, reach and catchment scales - e. g. studies by Downs and Brookes (1994), NRA (1993), Simon and others (1989), Thorne and Easton (1994) and Sear and Newson (2001). Reconnaissance surveys can be multi-functional and have been used for engineering-geomorphological analysis, stable channel design, assessment, modelling and control of bank retreat, to define the relationship between geomorphology and riparian ecology and as a component of statutory works assessments (Downs and Thorne 1996). The main advantage of stream reconnaissance surveys is that they are a coherent way of collecting field data, which can be easily stored and analysed using Geographical Information Systems (GIS). This may, perhaps, end the previous (notorious!) habit of river management agencies destroying paper-based surveys but also poses spatial-analytical opportunities and challenges not faced before in fluvial geomorphology because of the lack of extensive data (see below).

Fluvial Audit involves a complete walk-over survey from one bank in the field, using base maps at a scale of at least 1:10,000 to record sites and estimated dimensions of erosion and deposition. Audits are performed by experienced fluvial geomorphologists, allowing field interpretation of cause and effect, eg sourcing for sediment. The field data are presented in the form of a GIS, both as a permanent record of channel condition (permitting comparative re-surveys) and to aid managers' perception of the sediment system. Audits can be extended to detailed bank profile examination using the field survey protocols developed by the Environment Agency's own Research and Development programme - the Waterway Bank Protection approach (EA 1999). Many Fluvial Audits also have access to the Agency's River Corridor Surveys (RCS - see NRA 1992) carried out in the 1990's; despite reservations from other geomorphologists about the usefulness of these surveys (Gurnell and others 1994) they contain helpful reconnaissance-level data of relevance to fluvial geomorphology, eg on channel dimensions and riparian land use. RCS is also a continuous survey technique, unlike the stratified random, transect-based River Habitat Surveys (RHS).

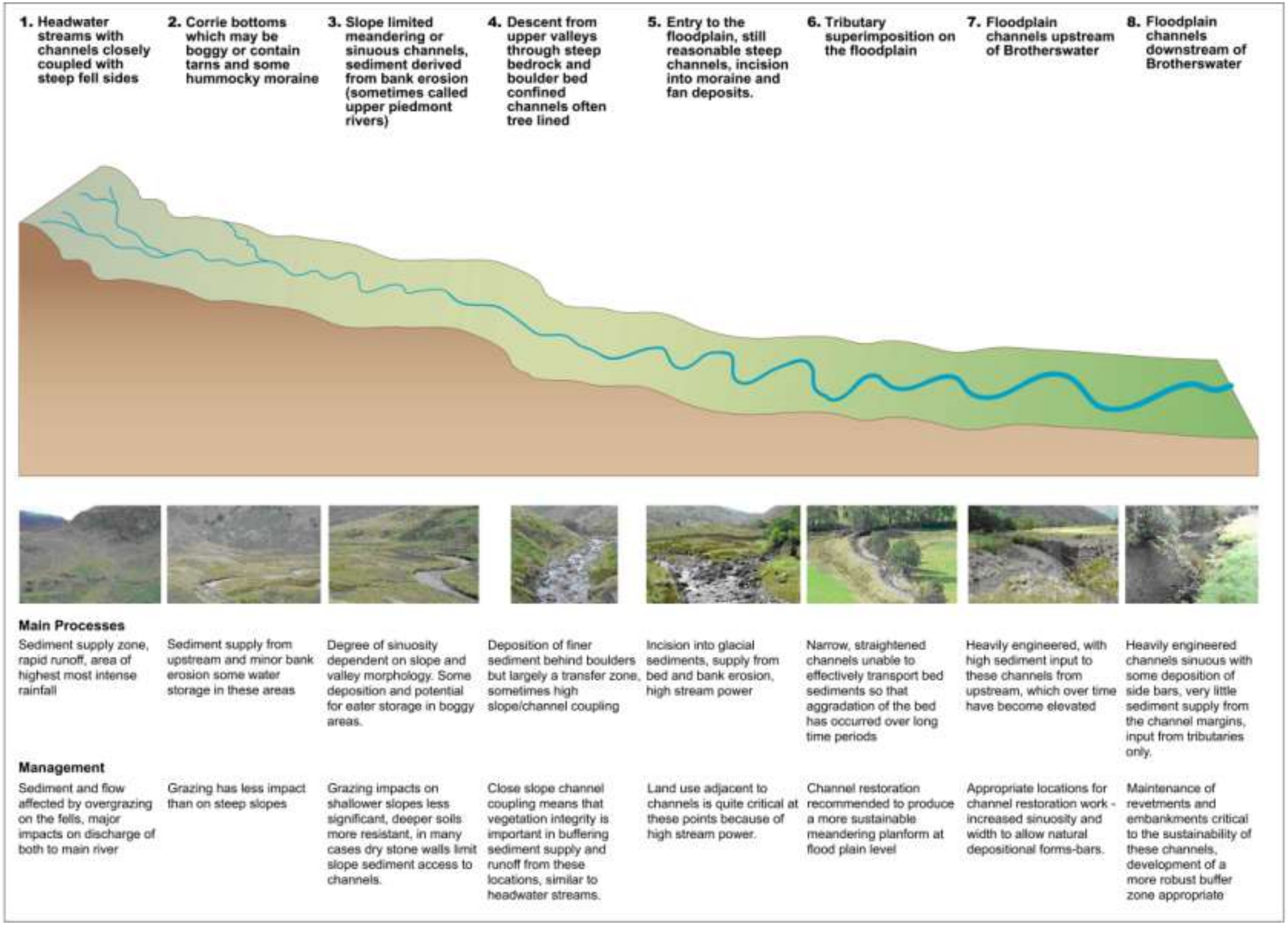

Figure F A typology of the upland sediment delivery system: Goldrill Beck (source Orr 2003a)

It is a bias in Fluvial Audits that sediment sources are underrated, except for bank erosion (see below), because the technique involves field survey of channels, not remote hillslopes or agricultural land. Nevertheless, some sponsors of Audits have specified 'siltation' as a problem and this has necessitated approaches that are additional to the standard procedure laid down (Sear and others 2003). Additionally, Fluvial Audit's special concern for the extent of bank erosion is relevant in that, if not a significant source for 'siltation' problems, supply from 'soil erosion' can be inferred, even if not identified in the field (it often is identified). New EA procedures for managing bank erosion (EA 1999) can be annexed to Fluvial Audit to identify a causal chain and help to suggest remedial action.

The dominant processes causing bank erosion and failure can be hard to identify and are likely to be highly dependent on location within the catchment; rates of bank erosion are also highly variable over space and time (Hooke 1980), and depend to a large degree on the stage of development, for example, of meanders and the amount of bank vegetation (Beeson and Doyle 1995). Past engineering works may also have a dominant role in the distribution of bank erosion in British rivers (Brookes 1988 and 1995).

Bank erosion is only one aspect of channel morphology and change but it is given a high profile in river management. Bank erosion may be a major source of sediment. Damage from river bank erosion has been priced at $270 million per year in the U.S.A. (Lawler 1993); the figures for the UK was £40 million in 1980 (Newson 1986a). The control of bank erosion is a major component of applications for land drainage consent received by the Environment Agency, particularly in rural areas.

Surveys of bank erosion, within Fluvial Audits, have tried to consistently record the predominant bank material size, the height and length of erosion features and some comment on local causes eg poaching, vegetation cover, flood defence management, structures, revetments etc. Information is also recorded on deposition features which indicate process and channel storage and potential supply sites (Table C). These are all marked on basemaps at a scale of 1:10,000 and then transferred to GIS databases.

Table C Bank sediment sources identified and recorded during Fluvial Audits

Feature	Dimensions	Other attributes
Erosion	Bank length Average bank height	Predominant material, Cause of erosion, type of bank failure.
Deposition	Length and width of bars	Predominate material Type, eg side bar, point, bar, discrete deposit
Structures	Bank length	Type, eg revetment (material and condition), weirs, groynes and informal bank protection
Management Issues affecting channel form	Reach length affected	eg overgrazing, unrestricted stock access, fallen trees.

The simple value of this procedure is that the accumulating survey evidence from the somewhat serendipitous distribution of completed Fluvial Audits can be compared on a national scale, indicating the widespread variability of bank erosion sediment source rates at a coarse scale (Table D).

The most relevant element of Fluvial Audit to a management regime for 'siltation' is that it is able to compare catchment-scale and reach-scale processes by inference from field observation, particularly if a Catchment Baseline Survey has also been completed to serve up a catchment scale backdrop to field observations and eg a 'diary' of significant fluvial influences such as flood schemes and rare flood events. Table E lines up the comparison between the two scales of identification for changes in sediment supply.

Table D Eroding and revetted bank lengths assessed by Fluvial Audit in England

River	Source	Location within catchment	Percentage of 'serious' bank erosion	Percentage of banks with revetments
River Lune	Orr 2000	Main river (100 km)	7%	12%
River Lune	Orr 2000	Floodplain only (15 km)	18%	26%
River Kent	Orr and others 2001	Main river	13% (minor erosion 42%)	Not recorded
River Ure	Sear and others 2000	Main river	6% (minor erosion 58%)	Not recorded
Goldrill Beck	Orr 2003	Main river	2.5%	8%
Till	Newson and Orr 2003	Sample lengths of main river (78km)	10%	2.4%
Upper Deben	Newson 2001	Main river	1.4%	Not recorded
Upper Stour	Newson and Block 2002	Main river	1.1%	Not recorded
River Pant	Newson and others 2002	Main river	3.1%	Not recorded
River Blackwater	Orr and others 2002	Main river	1.5%	Not recorded

Table E Dynamic controls on sediment supply

	Increase sediment supply	Decrease sediment supply
Catchment scale	Gripping (upland drainage) Mining (hushes and spoil heaps) Afforestation Agricultural drainage Land use change Accelerated soil erosion Climate change (>rainfall) Soil erosion	Dams/regulation Changes in agricultural practice Cessation of mining Sediment management Climatic change (<rainfall) Vegetation of slopes and erosion scars
Reach scale	Channel straightening Agricultural runoff Upstream embankments Upstream erosion Supply from tributaries Bank collapse	Sediment trapping Bank protection Dredging Weir/mill stream Upstream deposition Vegetation of banks Channel widening upstream

Specific Fluvial Audits in catchments with sedimentation problems

Catchment specific analysis within fluvial audits, using combinations of remote sensing of soil erosion/landslips and field reconnaissance, can be used to confirm risk-based analysis of erosion achieved by modelling. Figure G shows the output from a field and aerial photography assessment of sediment sources and routeways for the River Britt (Dorset). Identification is based on observations of soil erosion and critical conditions for soil erosion, together with localised mapping of routes from the fields to the watercourse. In this instance additional confirmation was generated by storm event surveys and consultation with stakeholders.

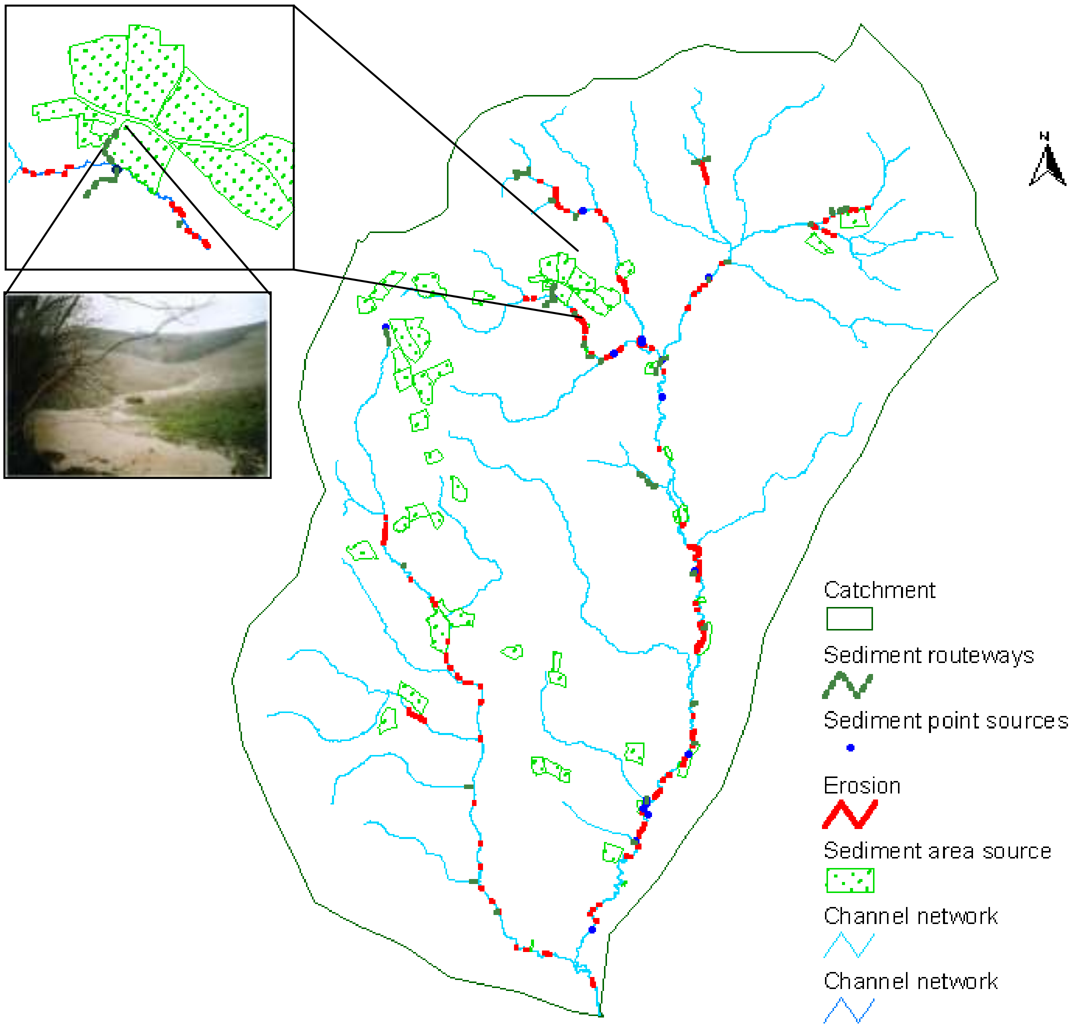

Figure G Example fluvial audit of sediment sources and routeways identified by field reconnaissance and air photo interpretation. (Ground-truthing during storm events and by stakeholder interviews provide higher levels of confidence)

Whilst source-area erosion assessments are not part of the formal brief for Fluvial Audit (Sear and others 2003), the ‘siltation’ problem has required it as ‘bolt on’ for several recent cases. Digital aerial photography is relatively easily available; however extracting information on bare ground (potential sediment sources) requires considerable digitising time. By contrast, oblique aerial photography, used in the Eden catchment proved expensive and also requires considerable digitising and GIS analysis to extract information on channel sediment storage.

Remote sensing is potentially less time-consuming, data on landuse, eg CEH Landcover maps from remotely sensed data are available from 1990 and 2000. However, work on Bassenthwaite identified under-representation of bare ground to a very considerable extent. For example the area of bare ground and inland bare rock in Bassenthwaite catchment for the year 2000 identified from digital aerial photography was 3168ha compared with 138ha identified from the Landcover map (Orr and others 2004).

Risk-based modelling is another approach to looking at sediment sources and the bare ground dataset from the digital aerial photography in Bassenthwaite catchment was a unique dataset which could be used to assess attempts by other researchers to model erosion and sediment delivery risk. Vulnerability to erosion based on soil classes was compared to the bare ground data set, captured from aerial photography and the observed bank erosion data from the fluvial audit. This was found to show a very weak relationship (Nisbet and others 2004). Environment Agency data showing the distribution of predicted erosion vulnerability for 1-in-10 year events within the catchment was compared with the national context in order to identify areas associated with causing unacceptable problems of diffuse sediment pollution (McHugh and others 2002). The connectivity ratio was used to show how high the risks were of sediment being transported to the river system. The 1km resolution limits the application of this method. A simplified approach to this method was then carried out using the soil association classes as it was observed that the predicted erosion vulnerability model correlated closely with the soil associations. This highlighted two main soil association types as high risk for erosion A similar approach was then taken in examining bank erosion. These were assigned to high, medium and low risk classes of bank erosion, respectively.

The distribution of the classes and the observed reaches exhibiting significant channel and bank erosion were then able to be mapped. A total length of 61 km and 138 km of stream/river are considered to be at high and medium risk of damage, respectively. The majority of soils within the high risk area are also at a very high risk of structural damage by poaching.

Accumulation of fines within the river network can be monitored again using fluvial audit mapping to identify silt-rich and silt-poor areas of channel, and to build up a broadscale understanding of the causes of fine sediment storage. Analysis undertaken on the River Wylye as part of the Life in UK Rivers project (German & Sear 2003) mapped fine sediment storage (Figure H), dominant bed substrate together with erosion and the location of silt ingress points along the river network (Figure I). This methodology demonstrated the lack of channel sources for fine sediment, the relatively high levels of silt accumulation in the upper reaches (impacted by abstraction) and the importance of larger scale structures (mills/sluices) for increasing fine sediment accumulation within the Wylye channel.

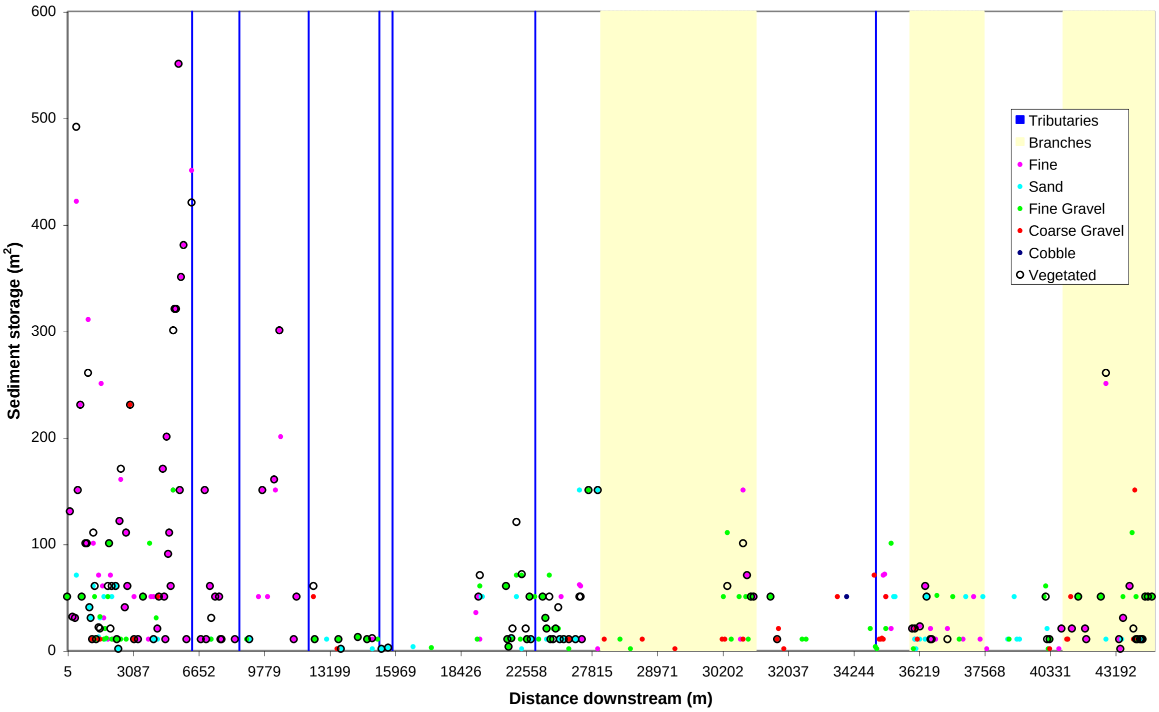

Figure H Fine sediment storage on the River Wylye (part of the River Avon SAC)

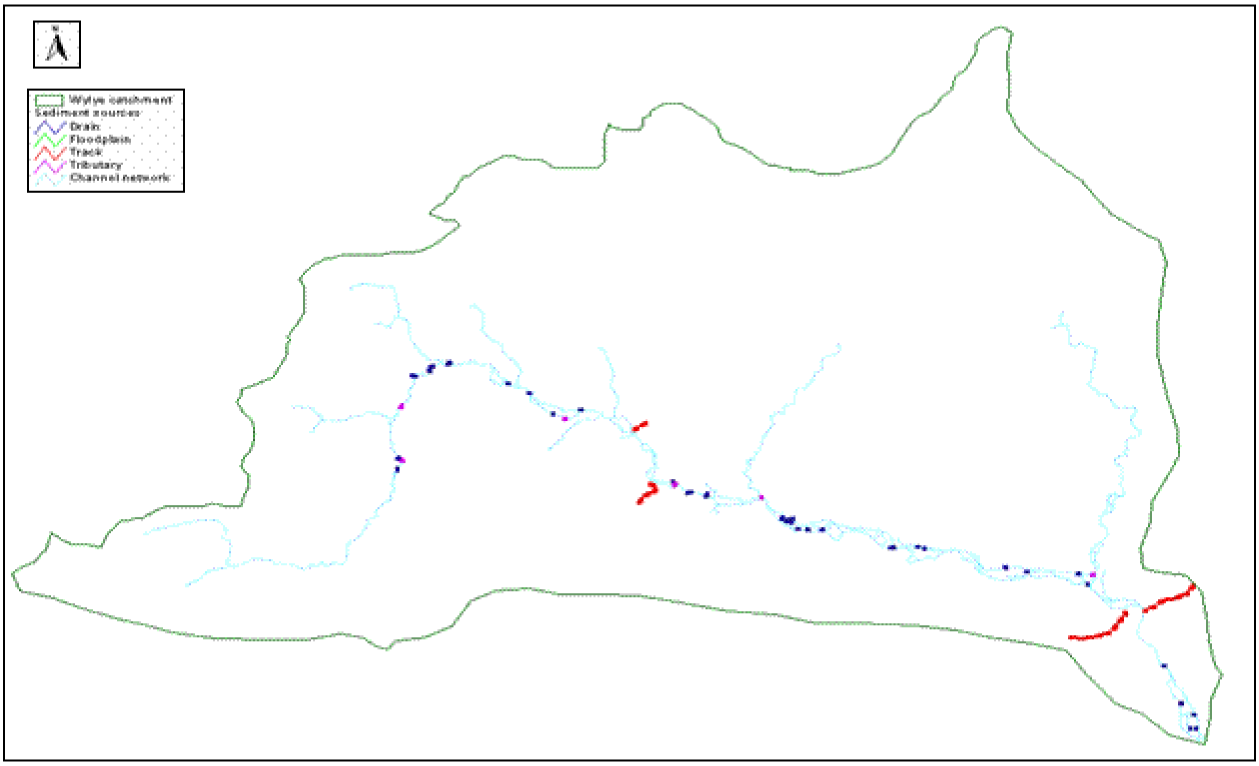

Figure I Fine sediment sources on the River Wylye (part of the River Avon SAC)

The value of such fluvial audit approaches is not only catchment-specific but through compilation of similar data from a range of fluvial audits, can be used to distinguish between catchment types in terms of silt storage and potential sources. Table F demonstrates the process distinction between lowland rivers with catchment-dominated silt sources and upland catchments with significant contributions from bank erosion, but relatively little accumulation on the channel bed.

Table F Summary information derived from Fluvial Audits, demonstrating the variability in bank erosion and fine sediment accumulation between upland rivers (grey shaded boxes) and lowland river systems

Catchment	% of Bank Eroding	Dominant Bank Erosion Process	Fine Sediment Storage (% Channel bed area)	Dominant Flow Type
Caldew	14.8	Fluvial	4	Run
Wharfe	18.7	Geotechnical	3	Run/Glide
Swale	25.2	Fluvial	11	Run
Dee	18.2	Fluvial	0.8	Glide
Highland Water (New Forest)	9.4	Fluvial	2	Riffle
Britt (Greensand/Chalk)	6.0	Poaching	38.6	Glide
Wylye (Chalk)	4.2	Weathering/poaching	25	Glide

In addition to field-based mapping, quantitative estimates of silt accumulation at network and reach scales can be achieved through analysis of existing bespoke topographic survey. Many existing surveys undertaken for flood defence contain estimated levels of silt within the channel that can be scaled up between cross-sections to provide an estimate of silt volume stored within the network. This information is again amenable to visualisation and spatial analysis within a fluvial audit GIS framework.

Remote sensing under clearwater conditions can be used in larger watercourses (> 5m width) to identify areas of different substrate, though this requires spatially consistent levels of turbidity and an algorithm that accounts for depth changes (Gilvear & Bryant 2003). The utility of remotely sensed information for assessing hydromorphological condition has been published recently (Gilvear and others 2004).

The detailed level of investigation associated with quantitative estimation of fine sediment characteristics tends to be undertaken at the site level, though sampled according to the channel typology derived from fluvial audits. Such an analysis was undertaken on the River Wylye, where the aim was to determine the performance of rehabilitated reaches in terms of ability to:

a) mobilise bed material;
b) route incoming sediment through the reach with minimum accumulation; and
c) increase physical habitat diversity.

The data was integrated within the fluvial audit GIS (German and Sear 2003) – a summary table for the rehabilitated reaches is shown in Table G. The methodology utilised rapid topographic survey and field mapping coupled to a modelling algorithm to estimate sediment mobility and transport rate.

Table G Summary performance data for rehabilitated reaches on the River Wylye (German & Sear 2003)

Site	Processes			Form		Habitat		
	Bed Mobility	Sediment Continuity	Bank Erosion	x-Section	Diversity	Hydraulic variability	Depth variability	Substrate
Gt. Wishford (a) 4-Copse Rehabilitation	Limited	No (increased)	Yes	Variable	Increased	Decrease	Increase	Size+ Fines – Diversity -
Gt. Wishford (b) Rehabilitation	No	Yes (increased)	No	Simple	Limited	Decrease	Decrease	Size – Fines + Diversity +
Chilhampton Rehabilitated	No	Yes (increased)	No	Simple	Increased	Increase	Increase	Size + Fines + Diversity +

Summaries from other Fluvial Audits with relevance to fine sedimentation

River Kent
The River Kent was assessed for coarse sediment delivery from the entire catchment to the flood relief channel in its lower reaches (Orr and others 2001). The role of mine waste and weirs in controlling delivery of coarse and fine sediment dominated many of the main channels, but in one third of the catchment cattle damage to banks was the dominant factor (Sprint subcatchment). The geomorphology of the Sprint is different to the rest of the catchment and more suitable for cattle grazing, soils may also be different and potentially more poachable.

Goldrill Beck
Goldrill Beck was assessed for the coarse sediment accumulation in elevated channels and the contribution to increased flood frequency (Orr 2003a). There were no obvious problems with fine sediment but coarse sediment accumulation as a result of build-up over 100s of years combined with a reduction in more traditional channel maintenance has lead to elevated channels and overtopping in places (similarly Borrowdale in the Lake District).

Bassenthwaite
Bassenthwaite was assessed primarily to explore potential sources of fine sediment (Orr 2003b; Orr and others 2004). Limited lake cores covering the period 1880 to 1995 indicate that sedimentation rates are shown to increase steadily between 1900 and 1940 (from 0.05 to 0.14 g cm^{-2} y^{-1}) reaching a peak between 1945 and 1965 and continuing to the present day at a rate of ~ 0.1 g cm^{-2} y^{-1} (Bennion and others 2000). Cranwell and others (1995) describe a similar rapid increase in accumulation rate of sediment from a late 19th century value of 0.05 cm yr^{-1} to a modern value of 0.11 cm yr^{-1}. This increased rate is also supported by changes in diatom assemblages that indicate a likely increase in lake turbidity after the late 19th century (Cranwell and others 1995). Studies of sedimentation rates since 1994/95 are inconclusive regarding suspected rapid accumulation of sediment in subsequent years (Hall and others 2001; Parker and others 1999).

The protected vendace fish is in decline and is threatened by: eutrophication; siltation; predation; competition from other species for food and climate change (Winfield and others 2003). The resident population is believed to be unsuccessful in spawning partly due to excessive siltation of the spawning grounds. In other aspects the environment of the Lake is close to the threshold conditions suitable for vendace survival eg dissolved oxygen content (Winfield and others 2003). Following a geomorphological audit, modelling of erosion risk and sediment supply risk mapping exercise, the Bassenthwaite Restoration Group (under the umbrella of the Still Waters Partnership) are keen to set sediment objectives. One proposed route was to adopt a late 19th century accumulation rate. However this is problematic, the numbers are based on a Pb210 dated core from 1880 so there is no indication of accumulation rates prior to this and re-coring may not be sufficient to indicate a change in accumulation rate in the short-term since the top few cms of cores are often highly disturbed.

Work is currently underway to determine the long-term (10000 year) accumulation history of the lake and continuous suspended sediment sampling has been set up at 2 locations to determine sediment budgets at the main lake inflows. These may have the potential in the future to set objectives based on the suspended sediment concentration. A research consortium has been established to collaborate on future research to understand and quantify processes in the catchment which deliver sediment and phosphorus to the lake and forecast their effect on lake function. The aim is to deliver guidance to those agencies responsible for monitoring.

River Lune
The Lune was assessed partly to identify the drivers of channel change throughout the catchment (Orr 2000, Orr and Carling 2006). In the Lune the role of channel enlargement through changes in the flow regime has lead to increased bank erosion and this is exacerbated by stock damage and loss of riparian vegetation, channelisation and bank structures in many locations – mainly on the floodplain (1000km2). The Lune has a large floodplain and is extremely active in its upper sections which may correspond to Lawler's peak in stream power. Further down the floodplain channel planform change has been relatively limited in the last 150 years. There appears to be more extensive erosion and a complete loss of riparian vegetation in many locations. In several locations the impact of channelisation and revetments continue to cause erosion and instability up and downstream for many kilometres. Thus key drivers of erosion (no data on yields) are climatic variability, exacerbated by land use changes, the effects of past engineering and management and local riparian land management practices (Orr and Carling 2006).

River Deben
The Deben Fluvial Audit was commissioned with apparently opposite aims to this project, but in fact creating a highly relevant context. Flood Defence operations over post-War decades have widened the Deben channel; together with high rates of water abstraction this has created fluvial habitat problems including siltation (Newson 2001). Whilst the Audit did not measure the extent and rates of silt accumulation, it employed source maps for sand and silt as a guide to where restoration of 'berms' of inset deposits might narrow the channel and create more streampower to reduce gravel siltation. The impact of milling upon fine sediment accumulation and habitat connectivity was discussed and a field experiment using millpond scouring (a traditional practice) designed; this was not followed up by EA.

River Waveney
The River Waveney did not receive a Fluvial Audit; rather it was subjected to Catchment Baseline Survey (more intensive than normal) and the Dynamics Assessment of potential restoration sites to achieve silt-free riffle conditions (Newson and others 1999; Sear and Newson 2004). It is interesting to note that, in a contract for surveying the Waveney channel operated by ADAS, it was required to indicate the depth of the channel as 'depth to silt' and 'depth to firm base'. These data allowed Newson and others to calculate a volume of $73{,}000^{m3}$ of silt in the Main River sections of the Waveney, mainly held in reaches ponded upstream of mills. It was again suggested that trial openings of mill hatches to replicate the traditional flushing practices would create an ideal field experiment to address the questions of mill 'retirement' or flood flow operations.

Stour/Pant/Blackwater
Fluvial Audits of these lowland rivers (Newson and Block 2002; Orr and others 2002) were only peripherally concerned with 'siltation'. However, by using measurements of the extent of bank erosion and its geometrical 'style' (according to a specific survey technique – EA 1999) these Audits establish the role of modified flows, riparian land management and catchment processes on all sediment yields. Once again, in a lowland context, the influence of milling backwater hydraulics was paramount on fine sediment accumulation.

Upper Derwent
There are considerable 'siltation' problems, with measured habitat impacts, in the Upper Derwent catchment. A Fluvial Audit (Arup 1999) revealed, however, that two major fine sediment sources in the catchment – bank erosion in 'unstable' reaches and cattle poaching were, alone and together, insufficient to create the problem. Rather, the causes of sedimentation were identified as reduced gradient, luxurious macrophyte vegetation (induced by nutrients) and flow abstraction/reduction by flows sinking into limestone.

A note on the future of Fluvial Audit and the use of geoRHS

Whilst Fluvial Audit is accepted by river managers as standard procedure, in practice they vary its specification to meet the particular aims of catchment management, including erosion control (within flood risk management) and river restoration. Its inclusive costs, often between £300-£400 per channel kilometre, can be reduced by such a local specification (even though these do not seriously exceed those of survey techniques such as RHS and geoRHS).

This lack of a rigorous and completely replicable format means, however, that any national adoption of Fluvial Audit may increase costs by reducing flexibility, the gain being completely comparable Audits. Comparability is a feature of the survey techniques RHS and geoRHS: every category on the survey form receives an entry, thus suiting national aims for inventories and databases. At the time of writing it is difficult to assess whether or when EA will deploy geoRHS nationally for the sort of annual programme that has yielded in excess of 6,000 RHS surveys to date. By contrast, the rate of deployment of Fluvial Audit is likely to remain episodic because it is problem-orientated.

The point of this brief outline is to help characterise the utility of field monitoring for siltation problems and their resolution. As presently constructed, Fluvial Audit has the advantages of comprehensive main channel coverage in a catchment (geoRHS segments the network into 500m lengths) and of interpreting sediment sources, pathways and targets (as the above examples very briefly demonstrate). However, any national application of a management regime for 'siltation' cannot await a full national coverage of Fluvial Audit and may gain, therefore, from a collaboration with the eventual programme of geoRHS deployment.

The relevance of geomorphological appraisal to fine sediment management

The importance of in-channel characterisation of fine sediment problems

In view of the previous sections it can be demonstrated that sediment yields are in themselves a poor metric for defining environmental status since they are an aggregate measure of the delivery of erosion products from a catchment. Their utility is in relation to monitoring change in catchment sediment delivery rather than defining ecologically acceptable fine sediment loads. Rather, of ecological concern is the location and residence time of different critical size fractions of fine sediment within the river network and floodplain, together with their associated contaminants and nutrients. Of management concern is the location of input points within the river network and sources of fine sediments within the wider catchment.

The corollary of this argument is that, in terms of ecological monitoring and condition assessment, evaluation of the amount and characteristics of fine sediment accumulation within the river environment cannot be replaced by targets for sediment fluxes per se. However, information on the fluxes is also required in order to monitor the effectiveness of any catchment remediation of loads should these be the dominant source.

Two key ecological distinctions exist between river environments:

- The ability to flush, on an annual basis, the deposits of fine sediment within a reach/river network.
- The mobility or not of the bed substrate.

In fine sediment river systems with sand or silt bed material, the question of the ecological role of fine sediments is poorly defined and most probably relates to questions of nutrient and contaminant sorption on the sediment surface, and in flocs. In these systems fine sediment transport is a key determinant of residence time for these contaminants, and ideally some measure of transport rate and the conditions under which transport occurs should be established. Mode of transport may also be important, with some observers reporting a “turbidity” current of high concentration close to the bed in lowland fine sediment rivers (Johnes, pers comm.).

Flushing of fine sediments from the surface and margins of a river tend to relate to the transport capacity of the stream and the opportunity for stable accumulation. Thus Wood & Armitage (1999) document the progressive accumulation of fines within a ponded reach of chalk stream in response to a drought, but at a reach-scale demonstrated the relative mobility of fines in the areas of faster flow. Kondolf and others (2003) identify the role of complex channel morphology in creating opportunities for fine sediment accumulation through the provision of more areas of slackwater per unit length of channel compared to the simplified conditions associated with managed reaches of the same watercourse. German & Sear (2003) highlight the need to consider habitat rehabilitation in this light, and report increased silt accumulation in those reaches that as a result of rehabilitation contained more opportunities for silt storage (Figure J).

Gravel and mixed gravel-sand bed rivers represent the dominant channel type within UK rivers in terms of total length (Raven and others1998). These rivers can be differentiated in terms of their ability to mobilise their gravel beds under current flow regimes. Chalk streams are sensitive to fine sediment accumulation primarily because they lack the ability to flush fines from within the gravel substrate. In contrast, higher energy upland channels are often able to mobilise bed sediments at bankfull discharge and can flush fines from the surface layers. This may represent a critical ecological threshold at least for those biota that utilise open gravel interstices and coupled channel:hyporheic flows. In the UK, gravel mobility is poorly monitored and relatively under-researched. It is however, relatively simple to estimate (Komar 1987).

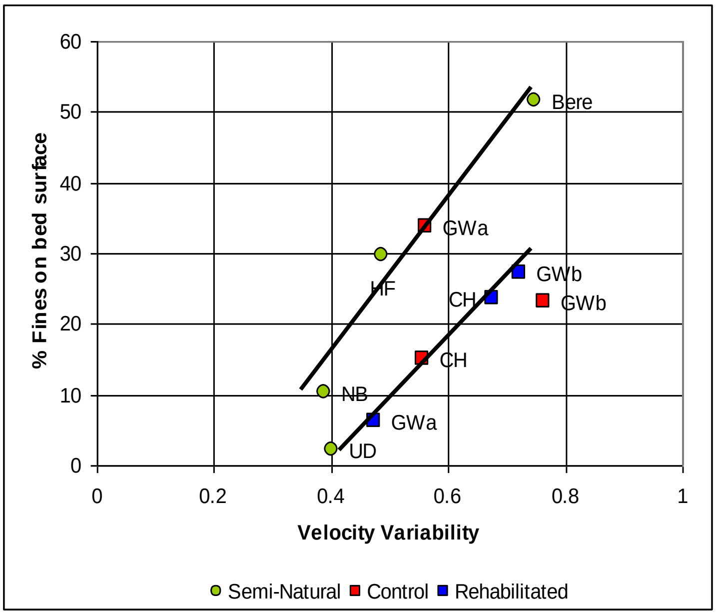

Figure J Relationship between the quantity of fine sediments on the surface of the river bed and the degree of hydraulic variability in a reach. The two curves, have similar slopes, but are offset due to differences in fine sediment loads in each reach . The Bere stream represents the morphologically most diverse of instream habitats (German & Sear 2003)

A rationale for assessing fine sediment accumulation

Fluvial Audit techniques are in need of two extensions in order to support management strategies for fine sediment. In the first case they need rapid national application – this is being achieved via the development and application of 'geoRHS' as a regular survey procedure. Whilst RHS claims to be able to identify severe cases of 'siltation' (recent Newsletter), the more comprehensive assessment of catchment sediment budgets proposed for geoRHS is likely to provide more relevant information. In the second case, Fluvial Audits must be backed by or incorporate elements of the Dynamics Assessment procedures, normally applied to reaches for which engineering options are required. Dynamics Assessment identifies the nature of river bed/bank sediments (particularly size) and links these to the driving variables for sediment entrainment/transport/deposition via accepted sediment transport theory (notably stream power).

Combining the two procedures, the emphasis on monitoring fine sediment in aquatic ecosystems should focus on the following factors:

- The level of accumulation in the river network both surficially and within the substrate (critical levels need to be determined).
- The ability to mobilise bed substrate under annual flow regimes.
- The composition of the fine accumulated sediments (organic matter/sand, silt,clay).
- The source of the accumulated sediments (channel, bank, catchment).
- The location and severity of input points for fine sediment into the river network.
- The geochemistry and biochemistry of the accumulated sediment (Sediment Oxygen Demand, associated nutrients/pesticides/herbicides etc.).

Critical to these is the need to improve our understanding of the relative impacts of each on the ecological functioning of UK rivers. However for the present there is a need to develop an approach that takes the best practicable available options whilst developing the underpinning research to deliver a UK capability to model and monitor fine sediment accumulation and ecological impact.

A range of techniques exists to determine the magnitude, location and source of fine sediment within the aquatic environment (Naden and others 2003). What is required is a framework for integrating these techniques and summarising the information in a succinct and readily understandable format. The best format at present is the Fluvial Audit methodology developed for the NRA flood defence function by Newson and Sear (1991) and modified for SAC monitoring by German & Sear (2003) and in parallel by Orr, Newson and Block (2004). Within this framework it is possible to nest a range of techniques of differing sophistication for the analysis of bed sediment loading and ecological impact (Kondolf and others 2003).

Approaches to the quantitative assessment of bed sediment storage of fines have been reviewed by Naden and others 2003. Though several techniques exist, most are relatively expensive and or time consuming to undertake in anything other than a research mode. A promising approach that is based on Lambert and Walling (1987) technique has recently been piloted on the River Nar and River Wensum (Plate 1, Sear & Newson in prep). This technique utilises a stilling chamber cut into the gravels. The surface of the bed is disturbed and a record made of the suspended solids concentration using a pre-calibrated turbidity probe. The bed material is then disturbed down to salmonid egg burial depth (0.1- 0.2 m) and the concentration again determined. A standpipe is inserted 0.15m into the river bed adjacent to the stilling well and measurements made of the water temperature, Dissolved Oxygen concentration, and intragravel flow rate. Standard values of fine sediment loading in units of kgm^{-2} can be estimated for the bed surface and subsurface and correlated with other biologically relevant datasets for those sites. Note this approach is unable to sample the coarser sands that might cloak the bed and are transported as bed load. Using this approach up to 10 sites per day can surveyed by two people, performing replicates at each site.

Plate 1 Use of bed material disturbance within a stilling well - River Nar, Norfolk: location on spawning riffle (left) and detail of dissolved oxygen meter (right)

Modelling fine sediment accumulation and its ecological impacts

Opportunities for fine sediment accumulation within a reach are broadly associated with hydraulic capacity for transport. These are poorly represented by conventional 1-dimensional hydraulic models. Instead, 2-dimensional or even 3-dimensional approaches are needed in order to account for the important secondary flow structures that lead to the creation of dead waters and associated sedimentation (Booker and others 2001). As a result the assessment of fine sediment storage is not simulated as part of river management activity in contrast to coastal and estuarine management where such models are becoming routine. Protocols have been developed and tested and modelling capacity is being improved through research programmes (eg LOCAR). However their application is unlikely to be widely adopted in the short - medium term owing to the relative expense of model development and application.

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