Natural England Research Report NERR008

Development of guideline sediment targets to support management of sediment inputs into aquatic systems

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Development of guideline sediment targets to support management of sediment inputs into aquatic systems

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with ecological narratives provided by
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Natural England

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A summary of the findings covered by this report, as well as Natural England's views on this research, can be found within Natural England Research Information Note RIN008 - Development of guideline sediment targets to support management of sediment inputs into aquatic systems.

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Summary

Establishing quantitative environmental targets to protect against the adverse ecological effects of excessive fine sediment delivery to aquatic ecosystems is a major challenge facing environmental managers. This report details progress made in this area through work undertaken on behalf of Natural England in collaboration with the Environment Agency. It builds on initial investigations described in Walling and others (Natural England Research Report 007), which proposed approaches based around the development and use of targets relating to sediment yield and relationships between suspended sediment and river flow.

We have developed an evidence-based typology for sediment delivery using the high quality data presented by Walling and others. The typology is based on elevation, HOST soil classification and standard percentage runoff, with individual types identified by statistical 'tree' analysis. Lower and upper quartiles of the annual sediment yield distribution for each type are suggested as 'target' and 'investigation' thresholds. The typology has been mapped for England and Wales and compared with a sediment pressure map in current use by the Environment Agency.

In seeking reference conditions for the typology we have investigated historic data series from lake cores, determining changes in yield over years or decades. These time series show a trend of increasing sediment yields over time, with historical yields tending to support the use of the lower quartile of the frequency distribution of observed values as a guideline target to protect against enhanced fine sediment delivery (subject to further local validation). However, this appears to generate an overly liberal target for some individual catchment types. The analysis also suggests that the typology might be extended to include woodland as a separate type, given sufficient calibration catchments. An analysis of anthropogenic activity within types, based on land cover statistics, reveals no clear association with sediment yield. This is partly because land cover is a very crude measure of anthropogenic activity and partly because such influences are largely accommodated between types as land cover is highly correlated with other catchment characteristics.

Ecological narratives associated with the proposed typology have been contributed by Chris Mainstone of Natural England, to place local target-setting into the context of the specific ecological vulnerabilities that are likely to be operating on the ground. Operationally, it is suggested that these narratives are used to help characterise risks and impacts in the catchment of interest .

The typology has been defined using continuous data which give a close-to-accurate measure of yield over the monitoring period. It is recognised that such accurate measurement is resource-intensive for assessment of new catchments against targets. We suggest alternative yield estimation techniques, including both weighted means and rating curves. These are more readily computed, but provide statistical rather than exact values of yield. The performance of these techniques is compared with exact measurement for a small number of catchments and methods for dealing with temporal variation are proposed. Rating curves, in the broadest sense of the term (ie suspended sediment/flow relationships), also provide a means of understanding the nature of sediment delivery in a way that is more ecologically meaningful and more sensitive to changes in delivery. Their use in defining typology, setting targets and assessing change needs further investigation.

Suggestions are provided for how this work might be applied operationally to inform management decisions in the short-term. A catchment appraisal involving an analysis of sediment-related risks and impacts, and a local analysis of suspended sediment and flow data, is recommended to set context and ascertain the local relevance of the guideline targets suggested. This may result in modified targets being set, in addition to other targets relating to the suspended sediment concentration/flow relationship. However, the limitations of the approach must be recognised – understanding of the quantitative link between sediment delivery, sediment deposition and biological impacts remains poor, and should be the focus of strategic R&D to refine the framework for target-setting in the medium-term. Recommendations for such research are made.

Contents

Appendices

List of tables

Appendix 1:

List of figures

Appendix 1:

1 Introduction

1.1 The detrimental effects of anthropogenically-enhanced sediment loads on aquatic habitats are well documented in terms of both increased water turbidity and the clogging of interstitial habitat in coarse substrates (eg Wood and Armitage 1997; Milan and others 2000, Walling and others 2007). The relationship between fine sediment delivery from the catchment and adverse ecological effects in receiving habitats is known to be complex and highly variable, making the definition of management targets difficult (Walling and others 2008). Nevertheless, management decisions still need to be made in the face of this uncertainty.

1.2 In defining conservation objectives for sites specially designated for wildlife (such as nationally designated Sites of Special Scientific Interest and European-designated Special Areas of Conservation), Natural England specifies ‘Favourable Condition’ through targets for a range of environmental and biological attributes. These objectives drive status assessments of sites and also inform site management. Natural England has a pressing need to refine the approach to suspended sediment and siltation within the framework for setting conservation objectives. In parallel, under the requirements of the Water Framework Directive (WFD), the Environment Agency is involved in the process of defining High and Good Ecological Status for water bodies and environmental conditions to support these. Suspended material is one of a number of pollutants specified under the WFD for which critical values may ultimately need to be set. For both Natural England and the Environment Agency, targets or critical values need to be couched in practical terms which can be related to catchment management.

1.3 Initial investigations have already been carried out into the most effective way of making the link between catchment management, sediment targets and ecological requirements (Walling and others 2008). One of the recommendations from this earlier work is that generic guideline values of both sediment yield and rating curve characteristics would be useful for target setting and management guidance. This is because sediment yield can be readily related to catchment management, through models such as PSYCHIC (Davison et al. In Press), whilst rating curve characteristics are more closely connected to ecological requirements.

1.4 The current project has sought to build on the earlier work of Walling and others, through a detailed analysis of available data, to develop practical sediment targets that can be applied in the management of sediment inputs into aquatic systems. The aims of the project are to:

- Refine the catchment typology generated by Walling and others.
- Analyse data on sediment yields and rating curves and identify best estimates of values consistent with near-pristine (reference) conditions with which to populate the refined typology.
- Consider ecological information on the sensitivities of biota to enhanced siltation/sediment delivery and identify (where possible) values of sediment yield and/or rating curves likely to protect against impacts, according to the refined typology.
- Devise a statistical rationale and process for comparing observed values of sediment yield and shape/position of rating curve with reference/critical values.

1.5 It should be noted that throughout this report, the data on suspended sediment used to derive yields and investigate rating curves strictly relate to total suspended solids. The data, therefore, include both organic and mineral fractions and both allochthonous and autochthonous sources. There are few datasets which separate out these fractions or which include particle size information, ie proportions of sand, silt and clay. Clearly, in looking at ecological impacts, the differential risk posed by different particle size and quality (Newson and others in Walling and others 2008) will in future need to be properly recognised.

2 Refining catchment typology for sediment yield

Background

2.1 Catchment typologies can be useful in a management context. They group together catchments that have similar characteristics, which can then potentially be considered and managed in a similar way. The extent to which a typology can provide this type of service in relation to silt control depends on a range of factors, including its ability to discriminate between natural and anthropogenic differences in fine sediment delivery. It is important that any typology is fit for purpose and the potential pitfalls of its use are known as well as the potential benefits.

2.2 Sediment delivery from a catchment is a function of catchment characteristics and prevailing weather conditions, primarily precipitation. Two summary statistics of sediment delivery have been proposed as target indicators: the yield and the rating curve (Walling and others 2008). Total yield is generally a function of catchment area, and the time period over which sediment delivery is measured. Some standardisation is achieved by expressing yield in dimensions $[M][L]^{-2}[T]^{-1}$, that is to say mass per unit area per unit of time, as exemplified by kg ha^{-1} yr^{-1}. The rating curve is the relationship between simultaneous measurements of suspended sediment concentration and discharge at a selected location on a river. Other summary statistics of suspended sediment delivery may also be of environmental concern. These include the occurrence, magnitude and duration of extreme high concentrations, or events where there is significant net deposition of fine sediment. The magnitude of high concentrations and the discharge at which they occur will be apparent from the rating curve; the potential for net deposition may be investigated by considering the hysteretic behaviour of rating curves over individual events.

2.3 It was initially proposed to classify sediment delivery regimes, as defined by summary statistics, using the standard Water Framework Directive (WFD) reporting typology (UKTAG, 2003). This typology is based on three catchment characteristics, each split into a number of classes:

Altitude
The mean catchment altitude defines three altitude classes: <200m (LOW), 200-600m (MID) and >600m (HIGH)

Dominant geology
Geology has been classified by the BGS as siliceous (SI), calcareous (CA), organic (OR) or saline (SA) (Kinniburgh & Newell, 2003). The siliceous and calcareous classes relate to solid geology, while the organic and saline are based on near-surface characteristics.

Area
The division is into those catchments which have area <10 km^2 (XS), 10-100 km^2 (S), 100-1000 km^2 (M) and 1000-10000 km^2 (L) and >10000 km^2 (XL).

2.4 The 60 WFD types generated by this classification are selected to be relevant Europe-wide, and some are poorly represented or absent from the UK.

2.5 The altitude, geology and area data for British catchments, given the location of their outlet, are generally available from national georeferenced databases. It is therefore possible to readily assign a type to any catchment, and to consider the extent to which sediment yields from a sample of catchments are related to typology.

2.6 Walling and others (2008) have identified a different grouping of types based on the altitude, area and anthropogenic impact (rather than dominant geology) classes. Altitude is split between lowland (<200 m) and upland (>200 m). In effect these are the WFD LOW and MID classes; British catchments above 600m altitude have a very limited extent. Area follows the WFD divisions, and impact is characterised as “low”, “agricultural” or “urban”. The replacement of geology by impact in Walling and others’ typology broadly replaces “siliceous” and “organic” by “low impact”, and “calcareous” by “agricultural”, with the “urban” classification being entirely new.

Data

2.7 In exploring the relationship between sediment yield and catchment characteristics, the data used are suspended sediment yield estimates from over 100 catchments in Great Britain. These include the majority of those investigated by Walling and others that were identified as medium or high quality, with additional catchments from the NERC-funded Lowland Catchment Research (LOCAR) study (6 catchments) (URL://www.nerc.ac.uk/research/programmes/locar/), CEH Bradford catchments (2 catchments) monitored under the NERC-funded URGENT programme (URL://urgent.nerc.ac.uk/) and CEH Plynlimon catchments (2) (Neal, 1997). At all the new catchments, data collection was of a standard consistent with Walling and others’ medium or high quality. The locations of the catchments are shown in Figure 1, with attributes and references given in Tables A and B of Appendix 1.

2.8 Figure 1 includes some nested catchments, particularly in the Pennines. The extensive coverage of part of Yorkshire and the Midlands reflects the comprehensive sampling of large catchments in the region during the NERC-funded LOIS study (Wass & Leeks, 1999). This also accounts for much of the coverage in southern Scotland. Scattered catchments in southern England are the focus of a number of individual smaller scale studies. Large areas in northern Scotland, Wales and eastern England are rather poorly represented.

2.9 The catchments for which we have yield data were not selected to provide estimates of delivery for particular typologies. They are essentially opportunistic, derived from numerous individual studies often made at locations convenient for researchers. Many catchments are grouped, so that we have good information where a group falls within a single typology. Nevertheless, the group location may be geographically limited, and for this reason the data may fail to reflect nationwide variability of yield within typology. Worse is the situation where example catchments for a particular typology are virtually absent, in which case we have no statistical indication of type-specific sediment yield. The lack of a designed survey specifically to consider typology behaviour is a clear limitation on the characterisation of sediment delivery by typology. As is evident from Figure 1, the most obvious information gaps lie in East Anglia and the south east of England.

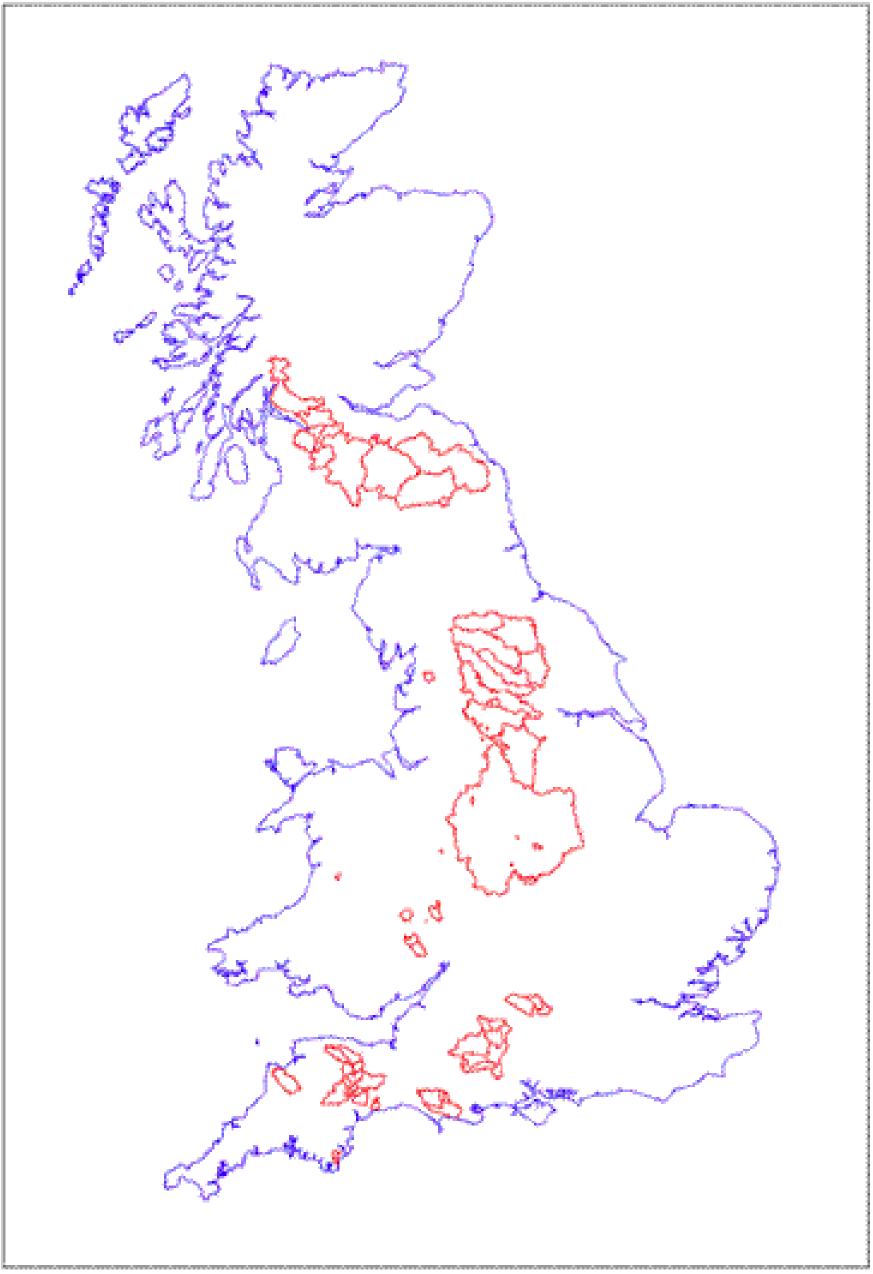


Figure 1 Catchment locations

2.10 Catchment characteristics have been determined using a GIS analysis based on a digital elevation model (DEM) (Morris & Flavin, 1990) and national GIS databases. First an outlet has been identified for each catchment. The outlets are not always well-identified from the published literature, and in these cases an inferred approximate outlet has been selected, usually based on known catchment area. This area can be equated to the DEM-based area upstream of a candidate location for the catchment outlet. This is not guaranteed to give an accurate estimate of the true sampling location, but is thought in the vast majority of cases to be good enough for present purposes.

2.11 The DEM catchment area is assumed to contribute to the suspended sediment yield through the catchment outlet. Where the catchment drains to a lake or reservoir, it is assumed that the estimated yield relates to the sum of the yields from all catchments draining to the water body. Note that, if reservoirs have catchwaters (low-gradient channels constructed to intercept water from streams which naturally drain outside the topographic catchment) then the drainage area derived from the DEM may bear no close relationship to the true area draining to the reservoir.

The unnatural hydraulic properties of the catchwaters may also potentially influence sediment delivery by, for example, not providing a source of bank-eroded sediment.

2.12 The period of data record and method of yield estimation vary between sites. At some catchments a stream monitoring site has been identified, and instrumentation installed to measure flow and suspended sediment concentration semi-continuously. Other catchments drain to lakes or reservoirs, and the yield has been estimated from sediment accumulation on the bed of the water body. This is done either by coring bed sediments, or by bathymetry, ie estimating the volume of the water body some years apart. The difference gives the accumulated sediment. The sources of estimation error vary considerably between these estimation approaches. There has been some limited comparison of some of these estimation techniques on a small number of catchments (Foster, 1995).

2.13 The parameter of interest in associating sediment delivery with typology is the long-term average yield scaled by time and area. In this context, long-term means over a period sufficient to factor out seasonal weather effects, but short enough not to be influenced by climate or land use change. The between-year variation in sediment yield may be substantial, and a yield estimate based on a single year’s data may give a much less reliable estimate of the long term yield than one based on several years’ data. A longer record can also be used to quantify between-year variability, from which the variability of the true long-term yield may be estimated. Available data on the variability in fluxes shows these to be very large and also poorly related to mean annual river flow. Measurements made on the Swale and Calder in Yorkshire, the Tweed in southern Scotland and the Cyff and Tanllwyth in Wales (Wass & Leeks, 1999; Bronsdon & Naden, 2000) show differences of up to a factor of 5 in sediment yields with 3-6 complete years of monitoring. Inspection of these data shows that the highest annual sediment yield does not necessarily correspond with the highest annual discharge. While these data are sufficient to demonstrate the magnitude of between-year differences, they are insufficient to relate these in a predictive fashion to annual discharge.

2.14 Yields may also be regionally correlated, since weather conditions which give a depressed annual yield in one catchment may give a similarly depressed yield nearby. Comparison of yields between catchments, made over different years, may therefore be deceptive.

Assessment of the Walling and WFD typologies in relation to sediment yield

2.15 Figure 2 and Table 1 show the distribution of yields by type for Walling’s preliminary classification, each type being a component of a typology. Note that the catchments included are those appearing in Tables A and B of Appendix 1. They are not the full suite of Walling and others’ original catchments shown in their Table 2.4. Catchments with low quality data and a number of very small agricultural catchments are excluded. The Walling and others types for new CEH catchments have been identified, and these added to their abbreviated list.

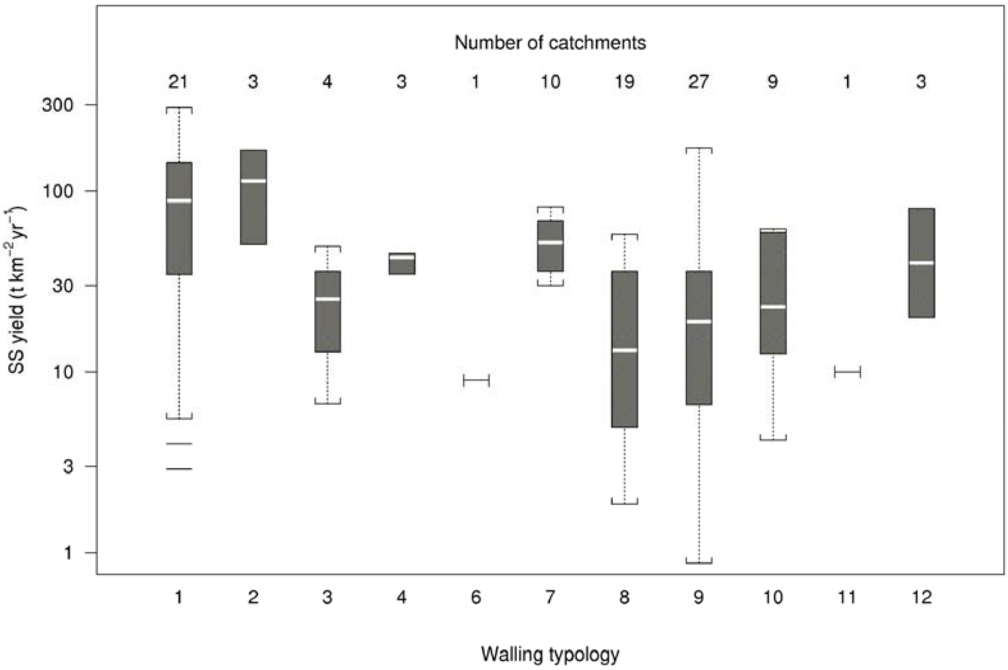


Figure 2 Boxplots of sediment yield by Walling typology

Table 1 Distribution of catchment sediment yield by Walling typology

Type	Altitude	Impact	Size	Yield t km^{-2} yr^{-1}						Total
				<3	3-7	7-23	23-56	56-90	>90	
1	MID	LOW	XS	1	2	2	2	5	9	**21**
2	MID	LOW	S				1		2	**3**
3	MID	AGRIC	XS		1		3			**4**
4	MID	AGRIC	S				3			**3**
6	LOW	LOW	XS			1				**1**
7	LOW	AGRIC	XS				7	3		**10**
8	LOW	AGRIC	S	3	2	6	7	1		**19**
9	LOW	AGRIC	M	3	4	9	7	2	2	**27**
10	LOW	AGRIC	L		1	4	1	3		**9**
11	LOW	URBAN	XS			1				**1**
12	LOW	URBAN	S			1	1	1		**3**

2.16 Types that are represented vary greatly both in the number of example catchments and in their geographical distribution. Low-altitude agricultural catchments of very small to medium size are well-represented and have a good geographical spread. Mid-altitude, very small low-impact catchments, also well-represented, are located mainly in the Pennines. In both these major groups sediment yields appear very variable, ranging over two orders of magnitude.

2.17 Visual inspection of Table 1 suggests no discrimination between types 8 and 9. Statistical analysis shows that types 1 and 2 are indistinguishable, as are types 3 to 12. Upland low-impact catchments are significantly different from the remainder, which are indistinguishable amongst themselves (p=0.2 with a random effects model).

2.18 The WFD typology based on the characteristics altitude, area and geology generates 60 types. Of these 60, sixteen are present in our sample of catchments with medium or high quality sediment yield data (Table 2). Note that the typology numbering of Table 2 may not be consistent with other sources (UKTAG, 2003).

Table 2 Distribution of catchment sediment yield by WFD typology

Type	**Altitude**	**Size**	**Geology**	**Yield t km^{-2} yr^{-1}**						**Total**
				<3	**3-7**	**7-23**	**23-56**	**56-90**	**>90**	
1	LOW	S	SI			2	1	1		**4**
2	LOW	S	CA	3	2	4	8			**17**
4	LOW	M	SI			1	1	1		**3**
5	LOW	M	CA	3	4	3	2		1	**13**
8	LOW	L	CA		1	4	1			**6**
10	MID	S	SI				3		2	**5**
11	MID	S	CA		1		1	1		**3**
13	MID	M	SI			4	2	1		**7**
14	MID	M	CA				2		1	**3**
16	MID	L	SI			1		2		**3**
17	MID	L	CA					1		**1**
37	LOW	XS	SI				2			**2**
38	MID	XS	SI	1	2	1	4	2	6	**16**
40	LOW	XS	CA			3	2	3		**8**
41	MID	XS	CA				2	2		**4**
44	MID	XS	OR			1	1	1	3	**6**

2.19 The highest WFD altitude and size classes are entirely unrepresented, as are examples of catchments with saline geology. Other combinations are absent, such as any catchments classified as organic, other than those <10 km^2 at mid altitude. The WFD classification gives more types than Walling and others. The main reason for this is the higher correlation between impact and altitude/size than between geology and altitude/size. Table 1 therefore has more missing, empty potential types.

2.20 Figure 3 shows boxplots of the data by WFD typology. There is again considerable overlap between types. Analysis of variance using a random effects model gives a between-group mean square of 3.9 and a within-group of 1.5. An F-test with 15 and 85 degrees of freedom gives a p-value of 0.01, suggesting some differences between groups. That is to say, the yields within types do not appear completely random.

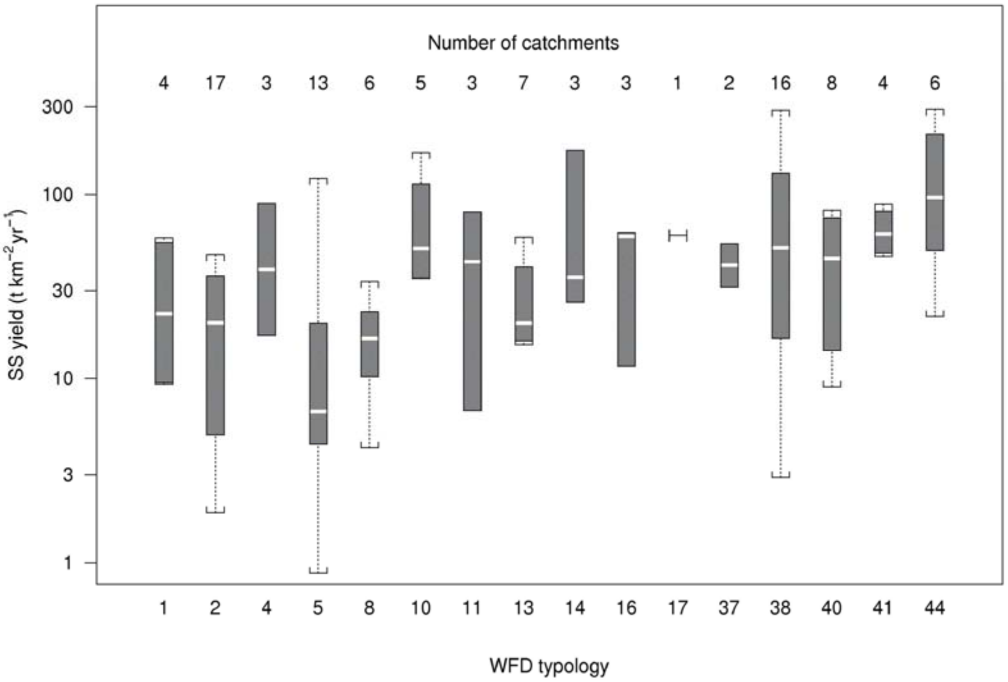


Figure 3 Boxplots of sediment yield by WFD typology

2.21 Individual boxplots by altitude, area and geology are shown in Figure 4. Analysis of variance suggests each of these classifications individually gives significant differences between groups, but because of correlations between the classes, there is no improvement in fit by using more than one class. Once one effect has been removed, removal of further effects does not give better explanatory power. Differences are dominated by the effect of very small, mid-altitude, organic catchments which tend to have high yields. The classifier which gives the best predictor in terms of the Akaike Information Criterion (AIC) is altitude, but this is clearly not in itself a driver of sediment yield.

2.22 Although catchment size is not identified as a significant predictor of sediment yield, it has been observed by Walling and others that larger catchments sometimes have lower sediment yield than smaller ones, because of the potential for greater storage, possible deposition in the floodplain and decoupling of slopes and river channels in floodplain areas. While it is true that none of our larger catchments has high sediment yield, many smaller catchments also have low yield. A relationship between yield and catchment area may exist, but be too complex to be identified in a simple classification.

2.23 There are sufficient data from some types to provide insight into the sources of within-type variability. Type 38 of Table 2 is classified as mid-altitude, very small, siliceous. Yields in this type cover two orders of magnitude. Sites are essentially moorland, rough grazing or forest, with examples from Exmoor, Plynlimon (mid-Wales) and the Pennines. There is wide variation in yields within this type. The Exmoor catchment has little sediment generated, the Plynlimon catchments intermediate yields, and the Pennine catchments have a wide range of yields, up to some 300 t km^{-2}yr^{-1} It is well known that many Pennine catchments are badly eroded, and this is most likely to be due to a combination of local conditions which may not be captured by the WFD typology. In addition, all Pennine catchments drain to reservoirs, and sediment yield has been estimated bathymetrically to provide volume changes, with estimation of the bulk density of material added to the reservoir bed to provide an estimated mass of accumulated sediment. In 3 cases out of 28, this method of estimation suggested negative sediment loss from the catchment, leading to some doubt over the accuracy of estimates for the remaining catchments.

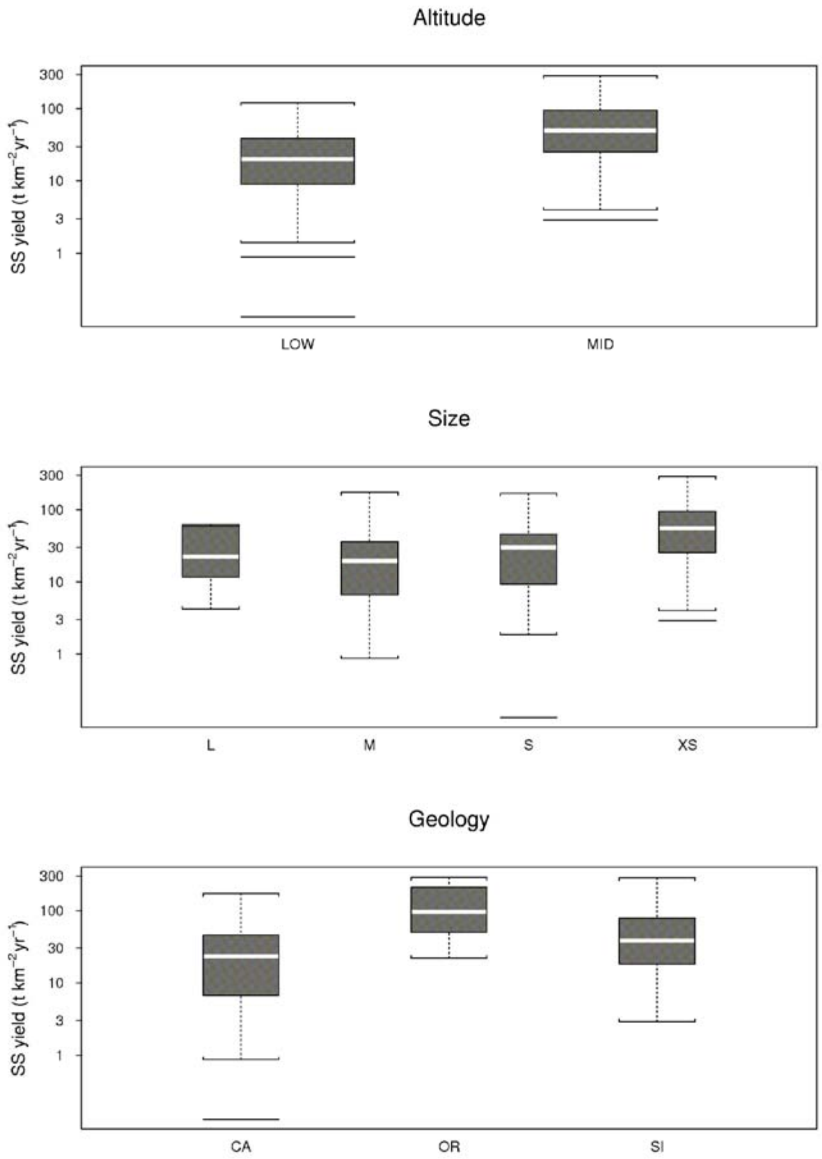


Figure 4 Boxplots by components of WFD typology

2.24 Types 2 and 5 are small and medium sized, low altitude, catchments on calcareous geology. The calcareous classification is based on geochemistry and covers a very wide range of geologies in terms of hydrological properties. These include very permeable chalk, sandstones, and some less permeable geology. Much of lowland agricultural Great Britain is included. Of the sample catchments in this type, several are chalk, and this seems to have much lower sediment yields than other catchments with different geology but classified as calcareous. This is particularly true of some Scottish catchments such as the White Cart where distinct hydrology and land use generate quite different sediment yields compared to the chalk catchments in southern England.

Development of an improved typology

2.25 In developing an improved typology for defining sediment targets, we would ideally choose to separate out natural and anthropogenically-induced variation eg through the use of sites at reference status. With such an approach, between-type variation is driven by intrinsic (natural) differences in catchment characteristics, and within-type variation is driven by differences in the level of level of anthropogenic activity causing fine sediment delivery. However, in practice, available data are limited and there is a close correlation between natural characteristics and land use such that reference status for many landscapes is illusive. In generating a typology using all the available data, we seek to minimise the within-type variability in order to bring out the dominant catchment types. In so far as this is broadly based on an underlying natural variability, we would then hope to be able to define targets for each of the identified types that have relevance to managing anthropogenic activity.

2.26 The catchment characteristics included in the WFD are easily computed, and are established as classifiers in other contexts. However, they are a limited subset of the catchment characteristic data that are readily available for British catchments, and which might prove better classifiers of sediment yield. There is good evidence from other studies that soil and land use influence sediment yield, and we might therefore expect that more detailed discrimination between these might yield better predictors of catchment sediment yield (but bearing in mind that land use is an anthropogenic influence and therefore not ideal for use in a typology underpinning catchment management decisions). Weather and morphological features of catchments may also have a significant influence.

2.27 The main classification of soils in Great Britain is by soil association. There are several hundred associations, and the classification scheme differs between England and Wales and Scotland. Data at this level of detail might well give useful prediction of erosion, particularly at local level. However, we have selected the Hydrology of Soil Types (HOST) classification (Boorman and others 1995) as the basis for investigating soil class and sediment yield relationships. The twenty-nine HOST classes are essentially hydrological, but include many of the features associated with sediment yield, particularly the availability of runoff to erode soils and transport eroded material. The HOST classification provides some distinction between soils of different textures, since these have differing permeabilities. Data are available by proportion within a 1km square. This can give poor definition for small catchments, where the location within a 1km square of particular HOST classes may be unclear.

2.28 Land cover data at European scale are available as the CORINE classification, which would be a candidate for investigating links with sediment yield. Within the UK, the Land Cover Map 2000 (LCM2000; Haines-Young and others 2000) is available at a 50m grid scale. There are 27 LCM2000 land cover classes.

2.29 Drainage characteristics and long-term climate data are included in the Flood Estimation Handbook (FEH) statistics (Reed and others 1999), which in addition to altitude and catchment area include standard annual average rainfall (SAAR), slope, base flow index (BFI) and standard percentage runoff (SPR). These statistics are derived from national rainfall databases, HOST classes, and the DEM and are used in catchment-scale flood estimation. Given the relationship between high discharge and high suspended sediment transport, some of these FEH statistics would seem potential predictors of sediment yield.

Relationship between sediment yield and catchment characteristics

2.30 In seeking effective new typologies using 29 HOST classes, 27 LCM2000 classes and 6 FEH classes, we have first eliminated all HOST and LCM2000 classes which never comprise more than 10% of any of the sample catchments. While their influence may be significant, this cannot be determined in the absence of catchments containing substantial areas of these classes. In addition, the inclusion of poorly represented classes can seriously distort statistical analysis. Following the removal of these variables, the importance of the remainder is explored using stepwise regression. In this and subsequent statistical analysis we have worked with logged values to stabilise the variance properties of the data. Stepwise regression eliminates variables which individually appear to have little influence on sediment yield. It will also tend to eliminate variables which in isolation are associated with sediment yield, but which are highly correlated with other variables. For example, upland peat soils have characteristic vegetation. On the basis of statistical analysis alone, either the vegetation or the soil may appear to be influencing sediment yield. Stepwise regression will tend to eliminate one or other of these.

2.31 Stepwise regression has been performed separately on the three groups of potential influential variables. Analysis of the FEH group eliminates area, SAAR, altitude and slope, retaining BFI or

SPR, which are highly correlated with each other. This suggests a measure of catchment permeability and ability to generate runoff is an important indicator of sediment yield, with more permeable catchments having lower yield. This conforms to expectations. The apparent absence of a significant influence of altitude, rainfall and slope is of some interest.

2.32 Of the 27 LCM2000 classes, thirteen are so poorly represented as to be eliminated prior to analysis. Stepwise regression removes a further 10, leaving four classes associated with variation in sediment yield. These are: “cereals”, “improved grassland”, “dwarf shrub heath”, and “bog”. Dwarf shrub heath is generally Calluna, Empetrum and species of similar habit. Loosely, the four classes may be identified as arable, pasture, moorland and peaty moorland.

2.33 Of the 29 HOST classes, eighteen were retained following initial screening. These were reduced by stepwise regression to HOST classes 1, 10, 15, 25 and 29. HOST class 1 is almost exclusively soil over Chalk. Class 10 represents poorly drained agricultural soils over sandstones, class 15 mineral but peaty soils, generally in the uplands. Class 25 has the poor drainage characteristics of class 10, but over clays rather than sandstones and class 29 is “raw peat”. In comparing the LCM and HOST classes retained we can relate arable to Chalk, pasture to HOST classes 10 and 25, moorland to HOST class 15, and peaty moorland to HOST class 29. Both stepwise regressions give results which are broadly similar and have some scientific interpretation.

2.34 In a final stepwise analysis the retained HOST and LCM classes and the full suite of FEH statistics are used as an initial set of variables. Stepwise regression reduces these to “improved grassland”, “dwarf shrub heath”, and four of the five HOST classes, excluding class 15. All the FEH statistics are eliminated. The effective groups remaining seem to be “chalk arable”, “permeable wet pasture”, “impermeable wet pasture”, “moorland” and “peat”.

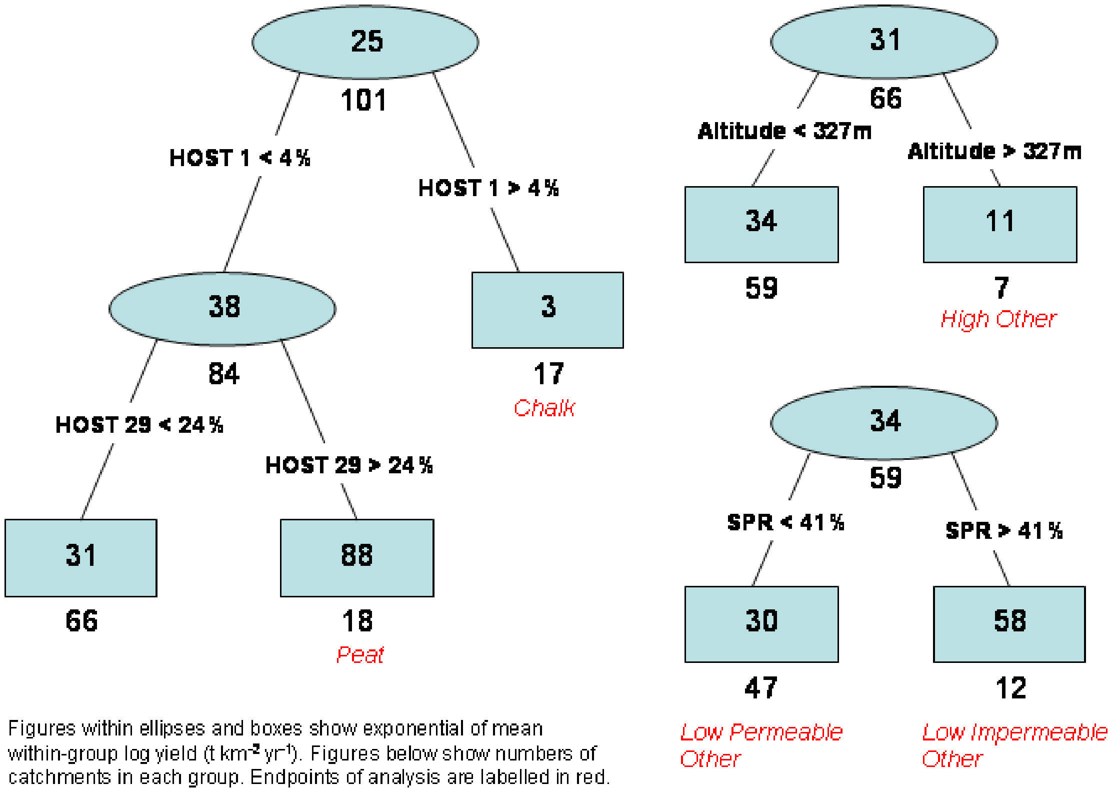
2.35 The regression analysis provides useful information on the key associations in the data, but typically treats the driving variables as continuous. If we seek an alternative classification to that provided by the WFD, we are really interested in defining discrete classes on the basis of catchment characteristics. In the context of regression analysis this means treating levels of a characteristic as factors. For example, the proportion of peat in a catchment may be classified as low, medium or high, in which case peat becomes a factor with three levels. We may also want to determine where to split the proportion of peat to provide the most useful factor levels for classifying sediment yield. This generates a classification problem, essentially attempting to minimise the within-group variability of a number of groups, while most variability is accounted for between groups.

2.36 An attractive and relatively new method of doing this is through recursive partition or “tree” analysis (Venables & Ripley, 1994), in which successive groups (types) are split into two components on the basis of a single characteristic. This generates a bifurcating “tree”. The procedure stops when the within-group variance is sufficiently small.

2.37 Recursive partition has been implemented within the statistical software package Splus, using cross-validation to determine the tree size, and admitting all FEH statistics, and the previously identified HOST and LCM classes output from the stepwise regression. This generated a tree with only three partitions, these being based on HOST class. Essentially catchments were divided into those associated with peat, those associated with chalk, and the remainder. This is consistent with the stepwise regression analysis, but more parsimonious. It splits off the low-yielding chalk catchments, the high yielding Pennine peat catchments, leaving a large number of catchments as an undifferentiated group. Note that the tree analysis identifies the location of splits used to define groups.

2.38 Enforcing a further tree structure on those catchments which are neither chalk nor peat, and including only FEH and LCM variables as potential discriminators, suggests that the next most significant classifier is altitude. Higher altitude catchments in this group have rather lower yield than low altitude catchments, where altitude is split at around 300m. In the stepwise regression, altitude was eliminated as a significant variable. Note that in the recursive partition, altitude is only used as a discriminator after the chalk and peat catchments have been partitioned off. Any effect of altitude within the chalk and peat groups is not considered, and may in principle be quite different from the altitude effect in the remaining catchments. The tree analysis is effectively allowing interaction between altitude and the HOST classifiers, which is not considered in the regression analysis implemented.

2.39 A further splitting of the remaining low altitude catchments suggests that standard percentage runoff is the next discriminator, with high SPR catchments giving higher sediment yield than low SPR. This is consistent with scientific understanding, since catchments with higher levels of surface run-off would be expected to generate higher levels of soil erosion (ignoring the influence of other factors). We therefore now have the basis for a simple 3-way classification using three HOST-based soil classes, two altitudes and two permeability classes based on SPR. The tree structure selected is shown in Figure 5.



Figures within ellipses and boxes show exponential of mean within-group log yield (t km^{-2} yr^{-1}). Figures below show numbers of catchments in each group. Endpoints of analysis are labelled in red.

Figure 5 Tree structure for classifying new typologies

2.40 The criterion for identifying “chalk” catchments requires only that 4% of the area be HOST class 1. Such a low threshold cannot be identified with a causal mechanism, but is acting as an indicator of more general conditions - it is therefore unlikely to be robust. Use of a threshold of 25% HOST 1 transfers a single catchment out of the original classification, with little change in the within- and between-type variances. We have also rounded the SPR threshold of 41% and elevation threshold of 327m shown in Figure 5 to 40% and 330m respectively for further development. These changes result in reclassification of a small number of catchments. Following this modification, the final criteria for defining the new typology are defined by:

- HOST class: HOST 1 > 25% (CHALK); HOST 29 > 25% (PEAT); remainder (OTHER)
- Altitude: >330m (HIGH); <330m (LOW)
- SPR: >40% (IMPERMEABLE); <40% (PERMEABLE)

2.41 The catchment types are labelled alongside the relevant endpoints in Figure 5. Subdivisions not identified within the tree analysis either have the same sediment yield characteristics or are not present in the available data. The distribution of catchments amongst the twelve provisional new types, following adjustment for rounding, is shown in Table 3, with boxplots in Figure 6. These may be compared with Tables 1 and 2 and Figures 2 and 3. Analysis of variance using a random effects model gives a between-groups mean square of 18.6 (cf 3.9 for WFD typology, 4.6 for Walling typology) and a within-groups of 0.76 (cf 1.5 and 1.5). An F-test with 6 and 94 degrees of freedom gives a p-value of 0.0. The new typology gives much better discrimination between groups than the WFD typology or the Walling and others preliminary typologies.

Table 3 Distribution of catchment sediment yield by new typology

Altitude	**Permeable/Impermeable**	**Geology**	**Index**	**Yield tonnes/km^2/year**						**Total**
				<3	**3-7**	**7- 23**	**23-56**	**56-90**	**> 90**	
LOW	PERMEABLE	CHALK	Lpc	6	7	3				**16**
LOW	PERMEABLE	OTHER	Lpo		1	16	19	5	2	**43**
LOW	IMPERMEABLE	OTHER	Lio			3	5	8	1	**17**
LOW	IMPERMEABLE	PEAT	Lip				1		1	**2**
HIGH	PERMEABLE	OTHER	Hpo	1			1			**2**
HIGH	IMPERMEABLE	OTHER	Hio		2	1	2			**5**
HIGH	IMPERMEABLE	PEAT	Hip			1	4	2	9	**16**

2.42 Numbers of catchments within each grouping remain very variable, in fact more variable than in the WFD typology. Unrepresented types include unlikely ones such as high (>330m altitude) permeable chalk. Other new types, eg low impermeable peat and high permeable other, are poorly represented in our catchments, and in most cases the catchments concerned have characteristics only just outside the limits defining a commoner type.

2.43 An altitude of 300-400m approximates to the upper limit of improved grassland and arable in much of England and Wales. An altitude split at 330m in defining types therefore has some natural interpretation. The WFD split at 200m lacks any obvious interpretation in England and Wales. Using a split at 200m in the new typology, while retaining the other criteria unchanged, removes any distinction between typologies other than “high impermeable peat” and “low permeable Chalk”, and is therefore difficult to justify.

2.44 The suitability of the new statistically-based typology for catchments generally requires further investigation. In our analysis the value of data from all catchments is treated equally. To take an example of a possible type which has not been identified, we may suspect differences in sediment delivery in urban areas. While we have some catchments with significant urban areas, identified through the LCM2000 class, the presence of urban development does not figure as a significant influence on sediment yield. Similarly, catchment size is not identified as a factor, although the relative importance of a number of erosion and deposition processes in large and small catchments varies greatly. The new typology is essentially identified statistically using yield estimates at the available catchments over the available time periods. It should be seen as provisional, subject to revision in the light of new data.

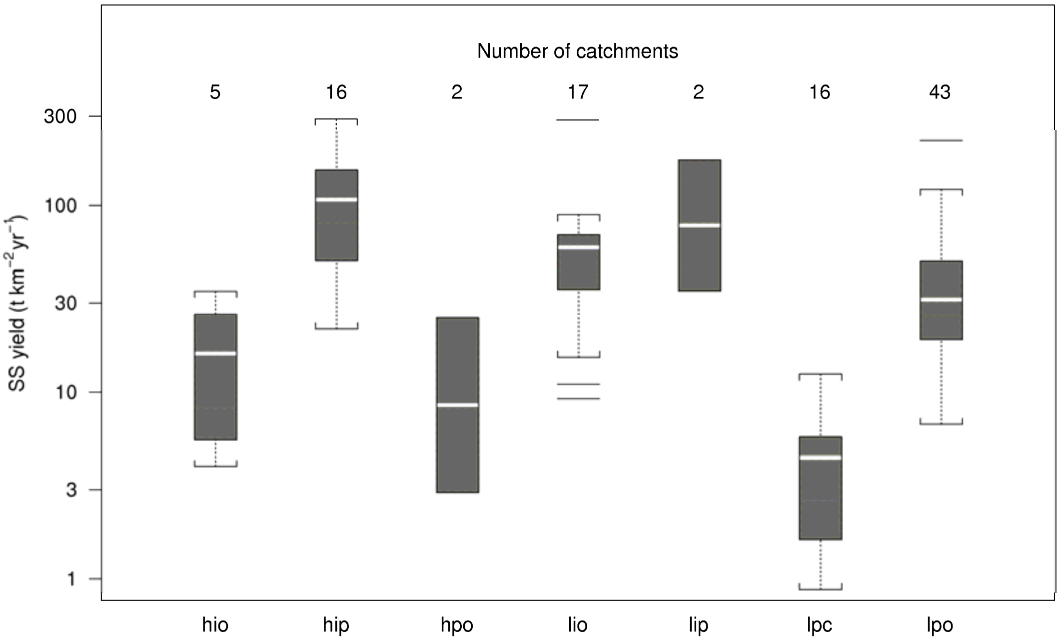


Figure 6 Boxplots of sediment yield by new typology

Selection of target sediment yields for catchments

2.45 The new typology classifies the sample catchments into types which tend to have on average greater or smaller yields. Within each type there is residual variability, with some catchments having greater yields than others. Higher yields within a type may be due to poorer land management, though there may be other reasons for this such as temporal variability, in-stream or localised sediment sources or measurement uncertainty. This is inevitable, but we might hope that within types some of the higher yields might be reduced by catchment management. This hope is based on the assumption that, all other things being equal, catchments in the same type should have similar yields. One difficulty is that if a large number of catchments are suffering excessive erosion due to land management practices, then using the sort of statistical analysis described, these catchments might be identified as a type with high erosion as “natural” if they can be sensibly grouped with the catchment descriptors available within the analysis.

2.46 Nevertheless, there is some value in suggesting target values of sediment yield for each type. Catchments whose yield is well above the target can then be identified and investigated. It may be that investigation will reveal some unavoidable factor generating excessive sediment, perhaps necessitating reclassification or an updating of the typology. Alternatively, some management factor which can be dealt with may be causing high yields. In selecting targets, we also need to be aware that some lower values of sediment yield may also be due to local anomalies, particularly a short data record over a dry year or years.

2.47 The main catchment types are considered in turn below, some of which have been paired up due to data limitations. In each case, we have suggested target yields and possible thresholds above which investigation might be considered. Figure 7 shows the distribution of catchment sediment yields within each of the single or paired types below, with the location of the upper and lower quartiles. We have defined the suggested target as the lower quartile and the investigation threshold as the upper quartile of the data, rounded to a greater or lesser extent depending on the number of catchments within each type. The use quartiles is based on an assumed data model in which the dataset for each catchment type contains data from catchments covering the complete spectrum of anthropogenic pressure from near-pristine to heavily impacted. Under this model, a lower quartile figure might be expected to represent a condition of moderate anthropogenic elevation of fine sediment delivery, whilst an upper quartile figure might be expected to represent a condition of considerably elevated delivery. However, the extent to which this data model holds true varies considerably between catchment types, as is evident below. For this reason, the suggested targets and thresholds should be treated with caution.

High impermeable peat (and low impermeable peat) - 18 catchments

2.48 Statistical analysis shows this to be the highest-yielding type with lower and upper quartiles of 50 and 150 t km^{-2} yr^{-1}. However, with one exception (the Swale), data are from the southern Pennines, catchments are small, and estimated yields are derived from reservoir bathymetry. Furthermore, many of the catchments are known to be highly eroded due to both over-grazing and footpath erosion, severely affected by loss of Sphagnum due to industrialisation, and subject to moorland gripping and heather-burning (Tallis 1998). Thus, the high yields seen in these catchments may not be typical, and the frequency distribution of data within the type may therefore not reflect a good range of anthropogenic pressure from which to select targets based on the lower quartile.. For example, Carling (1983), using discontinuous monitoring but covering the major storm events, gives a value of suspended sediment yield of 12 t km^{-2} yr^{-1} for Great Eggleshope Beck in the northern Pennines (grid ref. 398500 528750) in 1980. This catchment type should, therefore, be viewed as requiring further investigation prior to defining target values.

Low impermeable other – 17 catchments

2.49 These are low permeability catchments at low altitude. This class covers a very wide geographic area, and the catchments with data are also well-distributed. They have very varied size. The yield at the Reva reservoir looks anomalously high for this typology.

Target 40 t km^{-2} yr^{-1}; investigation threshold >70 t km^{-2} yr^{-1}

Low permeable other – 43 catchments

2.50 Higher permeability catchments, excluding chalk. These have lower sediment yield than their impermeable equivalents.

Target 20 t km^{-2} yr^{-1}; investigation threshold >50 t km^{-2} yr^{-1}

High impermeable other (and high permeable other) – 7 catchments

2.51 These types are represented by a small number of fairly pristine sites in upland areas, free of peat. These have low sediment yield. It would be useful to have more examples of this type.

Target 10 t km^{-2} yr^{-1}; investigation threshold >20 t km^{-2} yr^{-1}

Low permeable chalk – 16 catchments

2.52 These catchments deliver little sediment, although some of the data cover dry years, and over a longer period the target might be ambitious.

Target 2 t km^{-2} yr^{-1}; investigation threshold >5 t km^{-2} yr^{-1}

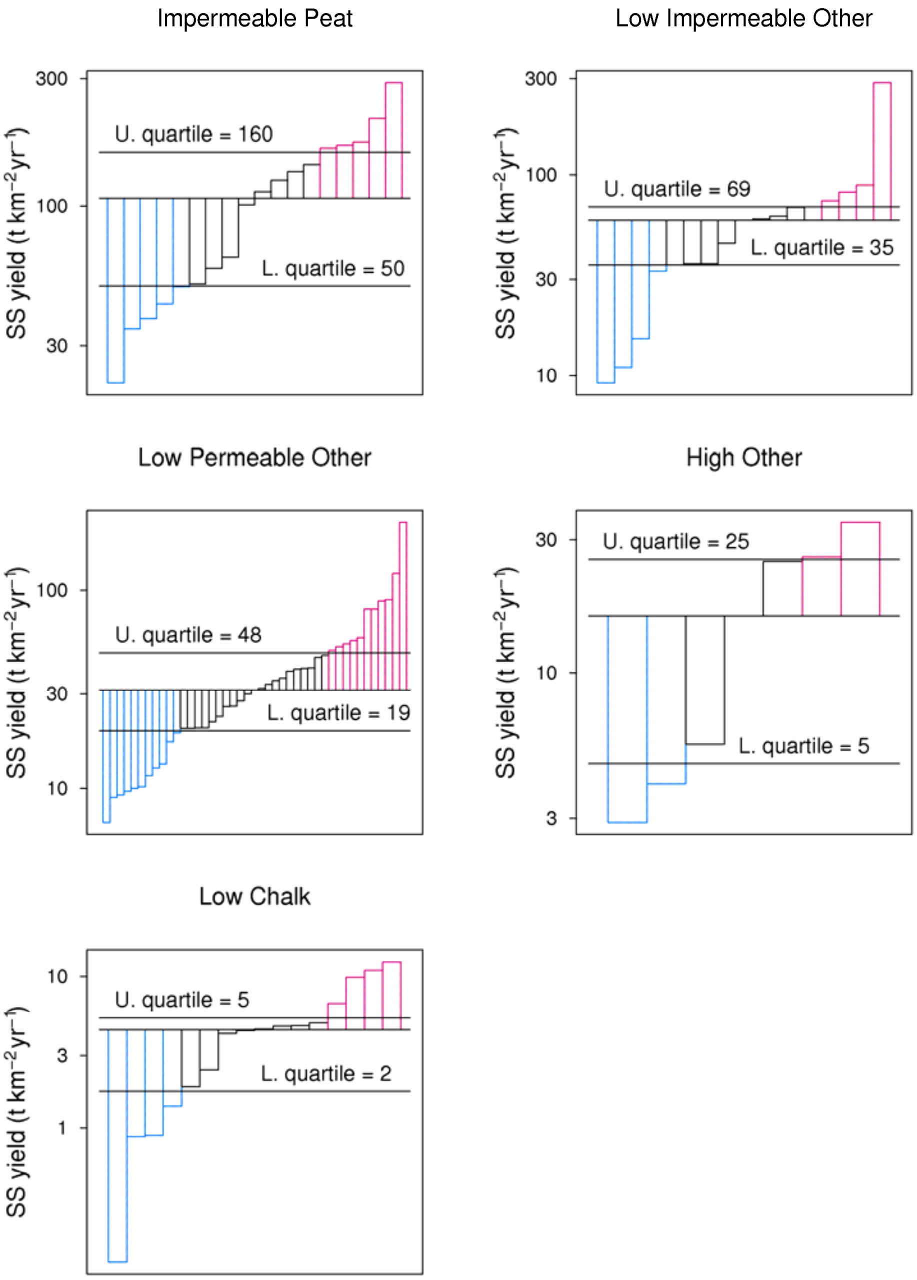


Figure 7 Distribution of sediment yields by new typology

Assessment of the improved typology and proposed target values

2.53 The coverage of types has been computed for all 1km grid squares in England and Wales using national databases and is shown in Figure 8. While there will be some differences at the boundaries between this mapping and a mapping based on catchments, it allows us to examine the general distribution of catchment types. The key features are the upland peat and non-peat areas, the chalk, and the bulk of lowland England and Wales divided on the basis of Standard Percentage Runoff, which in effect constitute the drainage characteristics of the soil.

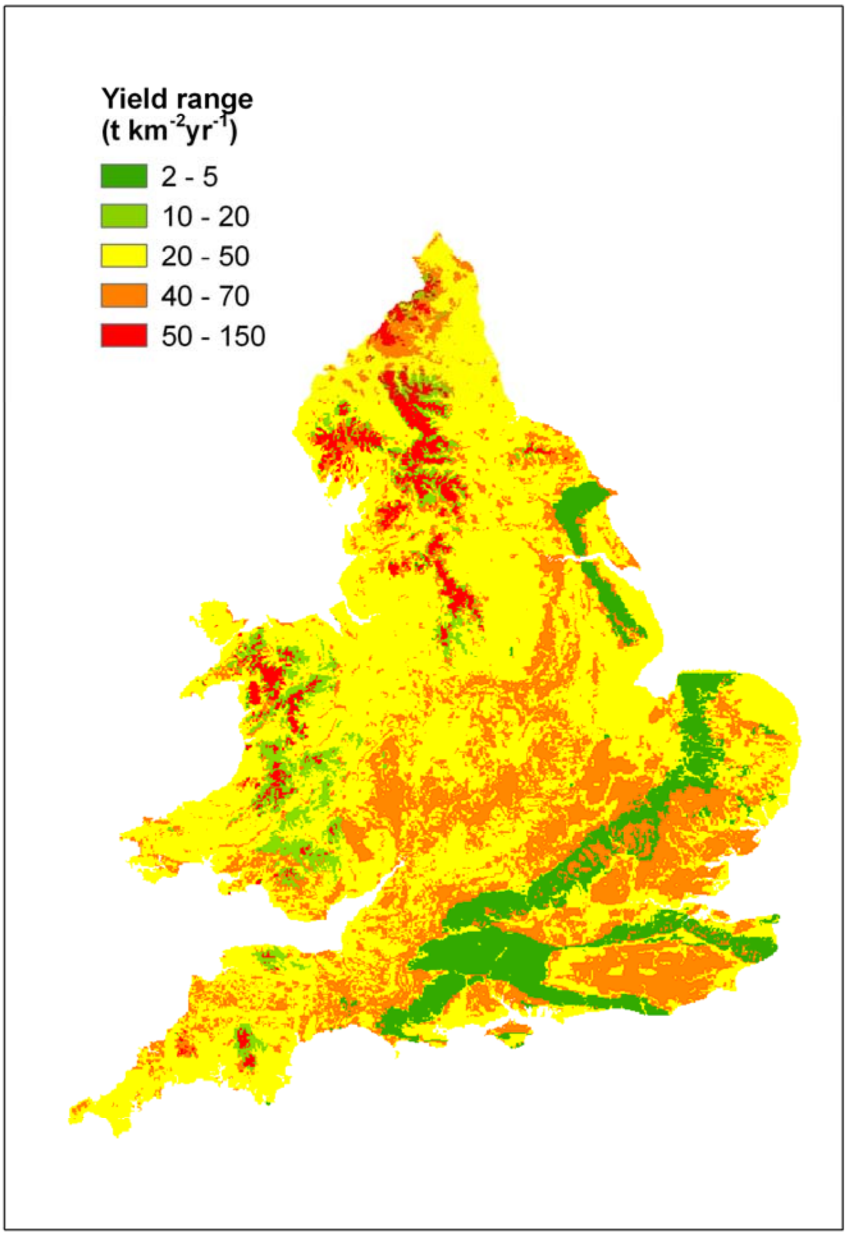


Figure 8 Sediment yields for types, showing estimated interquartile ranges

Comparison with other classifications

2.54 The England and Wales sediment yield classification shown in Figure 8 is not the first to have been presented. Most recently, the Environment Agency (pers. comm.) has identified risk classes for soil erosion. These are intended as an aid to catchment management to meet WFD standards. Relative pressure class, shown in Figure 9, is estimated as a combination of vulnerability and land management. The vulnerability is essentially a measure of the erosion potential of the soil, due to slope, soil characteristics and the extent of surface runoff. Transport of sediment to rivers is included by use of drainage density. The land management score is based on cropping and the density and type of livestock. The pressure classes are qualitative estimates, and the lack of any quantification makes them unsuitable for target setting and compliance testing. Nevertheless, we might expect some broad correspondence between pressure classes and sediment yield derived from an analysis of river suspended sediment data.

2.55 The EA classification follows on from a more quantitative analysis of erosion rates by McHugh and others (2002a), drawing on earlier work by Fraser and others (2000), Harrod (1998) and Harrod and others (2000) and it is worth first comparing our analysis with the results of the

McHugh and others study. Their approach to estimating sediment yield, which excludes any reference to land management, is through plot-scale erosion measurements rather than direct measurement of sediment in rivers. Their first objective is to determine erosion rates as a function of landscape characteristics, and they provide a single-valued estimate based on soil, slope and elevation/land use. This is broadly equivalent to the more recent vulnerability classification of the EA. Elevation/land use is classified as “lowland arable”, “upland” and “lowland grassland”. Data for arable and lowland grassland are Harrod’s, while McHugh and others use data from 206 new measurement sites to estimate erosion from upland soils (McHugh and others 2002b). Within each of the three classes, erosion is estimated according to soil group and slope, and the authors provide estimates for three return periods, 1, 5 and 10 years. The return periods are calculated by fitting a Poisson distribution to erosion measurements at different locations, and assuming space/time substitution can be made. This assumption should be considered a first approximation, and while the Poisson distribution has an appropriate discrete positive-valued statistical structure, it is clear that this distribution provides a poor fit to their data, and the return periods generated are not well-estimated.

2.56 Not all material eroded from the land reaches water courses, and as an aid to estimating stream losses McHugh and others consider the connectivity of slopes and channels. The key parameter is a “connectivity ratio”, which is high where slopes are greater, and where soils are less permeable. By combining estimated erosion rates with connectivity ratios, estimates of losses to the stream network are found. It is these estimates of stream losses which might be expected to be similar to estimates using our typology.

2.57 In general it appears that stream losses estimated by McHugh and others are considerably less than the catchment yields implied by load estimates in rivers. However, because their results are presented in terms of return periods a comparison is difficult. Furthermore, as Walling and others. note, bank erosion is known to be a major contributor (up to 50%) to suspended sediment loads in streams, and this is a likely source of part of the discrepancy. The authors identify peat as the most vulnerable upland soil, and chalk as the most vulnerable lowland – a distinction which is consistent with our typology. Standard percentage runoff, used in our typology, is related to McHugh and others’ connectivity and slope, these being comparable indicators of hydrological influence. Their “upland” is actually defined by land cover, and includes all woodland at whatever altitude, and some lowland heath, scrub and bracken. This is effectively low productivity agricultural land, excluding urban areas. Our typology would not distinguish lowland land use classes, with differences in delivery based only on chalk and soil runoff properties. They identify high sediment yields in north Norfolk and in the south-west. They do not identify a low delivery upland component where peat is absent, and the marked difference between chalk and other catchments which we identify is not a feature of McHugh and others’ analysis. In peaty upland areas, McHugh and others’ estimates look particularly low compared to ours. The effect of moorland burning, gripping and extensive erosion in the southern Pennines may be responsible for the high recorded sediment yields found in our analysis.

2.58 McHugh and others’ point estimates are not in themselves suitable for judging the status of individual water bodies since they provide only an average yield, with no indication of variability about this average. There is no means of assessing the yield of an individual water body in relation to the yield of other water bodies in the same typology. The usefulness of a statistical classification scheme such as ours is that it allows an estimate of within-class variability, which provides for realistic assessment of status that takes account of this variability.

2.59 A comparison of our sediment yield map with the relative pressure map in Figure 9 also shows a number of similarities but also some distinct discrepancies. In chalk areas, Figure 9 shows low relative pressure, consistent with our identification of low yields. The high yields assigned to upland peat in our analysis of available data are not reflected in a high relative pressure class in Figure 9. Fairly level blanket peat is assigned low vulnerability by the EA mapping, and livestock numbers are generally relatively low. Despite this apparent lack of pressure, sediment yields in the peat catchments of the southern Pennines are undoubtedly high, although this may not be true in other areas of peat cover in upland Great Britain. As noted above, the highly eroded nature of the southern Pennines is largely a result of centuries of high anthropogenic impact

(Tallis, 1998). Within the EA analysis, management influence is judged particularly high in dairying and beef cattle areas. This factor can give high sediment pressures in areas where slopes are steep, so that pressures are estimated to be high in the South-West, much of Wales, the northern Lake District and the West Midlands. These areas are not distinguished in our classification. Our classification in the lowlands is based solely on permeability rather than a combination of surface runoff with slope, soil type and land management. This means that under our typology, fairly flat clay soil areas tend to have the higher yields amongst lowland catchments whereas the EA identifies lower pressures for such catchments. Areas around the Wash and in Cheshire have quite different estimates of sediment yield and relative pressure, and these areas would merit further monitoring to determine the true situation in the field.

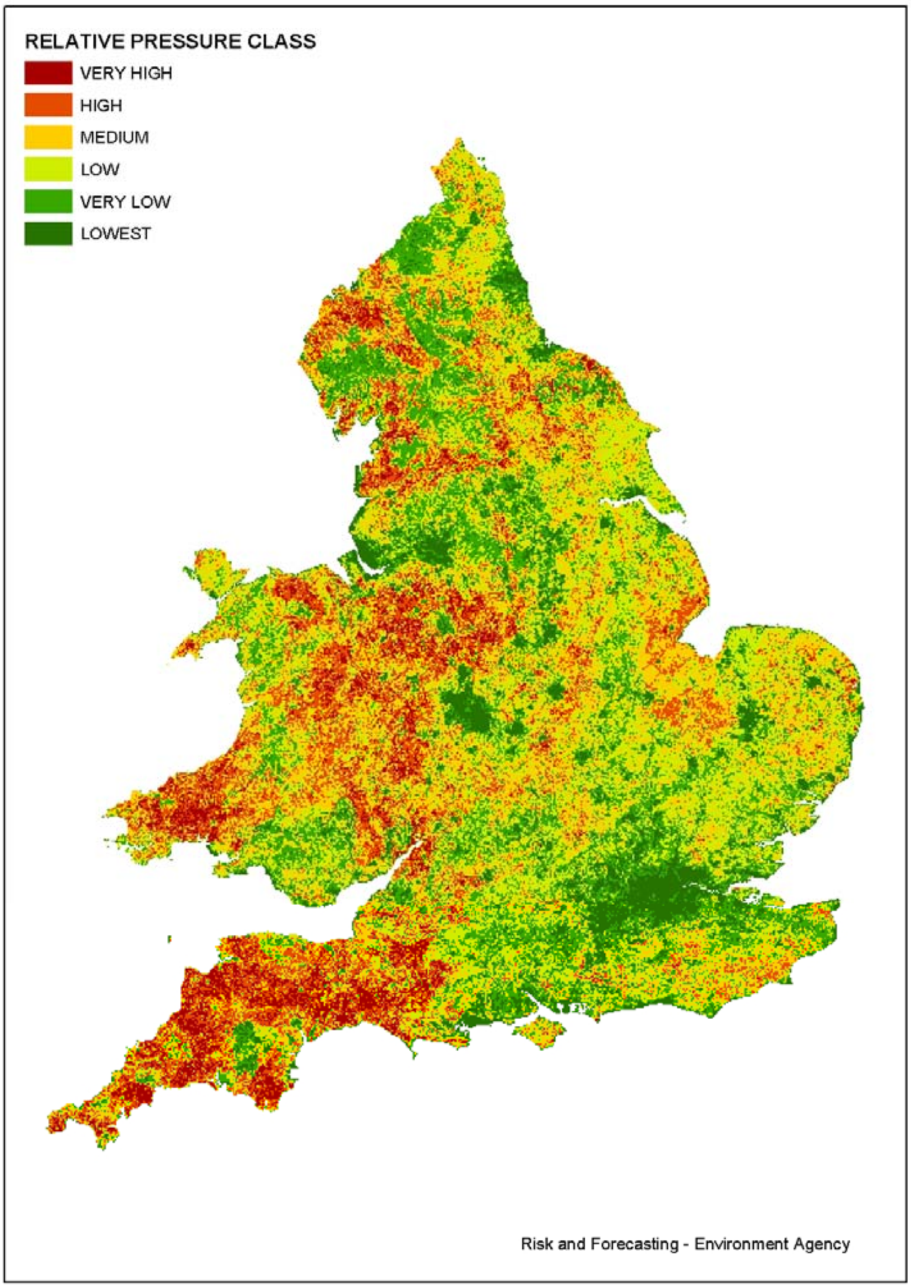


Figure 9 Sediment pressure map (Environment Agency 2004)

2.60 The analysis undertaken by McHugh and others and subsequently by the EA effectively takes a bottom-up approach, using scientific understanding at small catchment and slope scale to estimate losses. There has to date been no validation against river loads, and McHugh and others acknowledge that they have not accounted for in-river processes which might influence concentrations. Indeed, Warburton and others (2003), in a critique of McHugh and others' assessment of soil erosion in upland England and Wales, question the basis of estimating sediment yield from soil erosion, calling for a proper sediment budget assessment of such catchments. Nevertheless, there is likely to be some correlation between river loads and erosion losses from the land surface and the sediment yield estimates provided here might provide a basis for validation in cases which are well-supported by calibration data.

Anthropogenic impact and historical evidence for target values

2.61 The new typology and the suggested target values are based on the high quality sediment yield data collated by Walling and others (2007). The catchments used include many with considerable anthropogenic influence. Land cover characteristics – one indicator of anthropogenic influence – were included in the analysis but were not identified as significant in the typology. This is thought to be partly due to the correlation between land cover and other catchment variables such as altitude and soil type. Given that we are concerned to provide target values in relation to reference conditions, the issue of anthropogenic influence needs further investigation.

2.62 Possible indices of anthropogenic influence are being developed within the EU-funded REBECCA project (URL://www.ec.europa.eu/research/fp6/ssp/rebecca_en.htm) which aims to define relationships between the ecological and chemical status of surface waters. Part of the REBECCA project has been seeking to predict good and bad ecological status from catchment characteristics, notably land use (Anderson and others 2004). The work is based on biological data and is not specifically related to sediment impacts. Initial investigations by Wasson and others (2004) on data from 3600 French sites suggest that sites with <2% urban land use are likely to have good ecological status and those with more than 6% urban land use are likely to have bad ecological status. For those catchments with between 2 and 6% urban land use, the ecological status is dependent on the percentage of cropped land – if less than 3.5% cropped land then the status is likely to be good.

2.63 Looking at the data analysed here, nearly all categories in the new typology include some catchments which fall into the French definition of low anthropogenic impact – largely because they satisfy the urban criterion whereas the percentage of cropped land can be substantial. Further analysis of the catchments within each typology, indicates that there is no general association of high sediment yield with either the percentage of cropped or urban/suburban land uses. For example, Figure 10 shows sediment yield against the proportion of cropped land for three of the defined types: Chalk, low permeable other and low impermeable other. The symbols have been shaded according to the proportion of urban/suburban land use with the lower two classes matching the French percentages. It clearly shows that catchments with low anthropogenic influence, as measured by proportions of land use type, can have high sediment yields and catchments with high anthropogenic influence can have low sediment yield. This partly reflects the fact that a catchment percentage of cropped or urban/suburban land use is a very crude estimate of anthropogenic influence. It does not take into account different crops, livestock, land management practices, proximity of sediment sources to the river system or the effect of other activities on sediment yield.

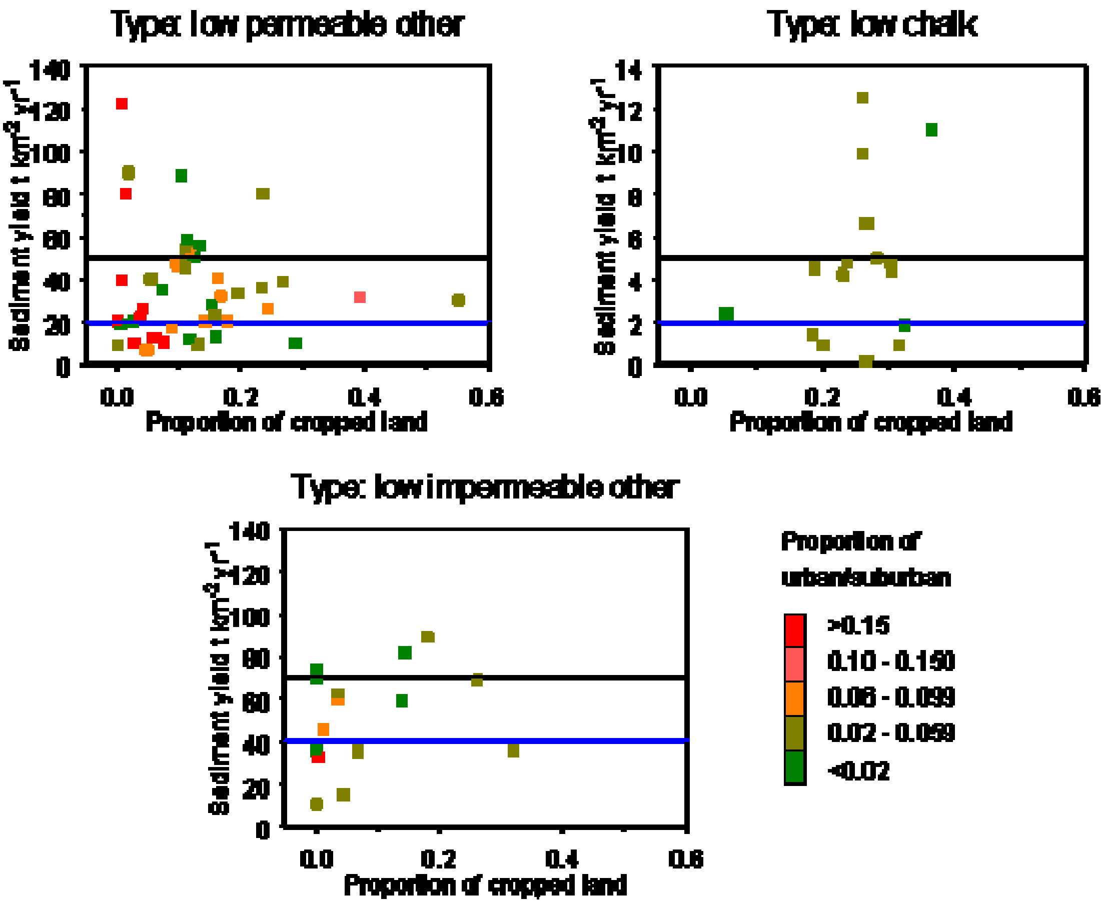


Figure 10 Within-type sediment yield against the proportion of cropped land with target yields (blue line) and investigation thresholds (black line)

2.64 An alternative approach to investigating anthropogenic influence, with a view to improving the definition of targets in relation to reference conditions, is through either long-term records of suspended sediment or through analysis of sediment cores from lakes or reservoirs. We are not aware of any long-term high-quality suspended sediment datasets and, due to budget constraints, did not pursue this further. We have Environment Agency data for some sites which go back over 30 years but data are approximately monthly and yields calculated include sources of variation not present in the high quality continuous data used to define target values thus far. Thirty years is also a relatively short time-scale for defining reference conditions. Published data from sediment cores have, therefore, been investigated for evidence of changes in sediment yield due to anthropogenic influence over longer time scales.

2.65 Historic and recent suspended sediment yield data, all estimated from lake cores, are presented for several catchments in Table 4. Target yields (lower quartile) and investigation thresholds (upper quartile) are also presented. In general, suspended sediment yields are higher in recent years and in most cases the changes have been attributed to changing land use and land management practices. Climate may have some influence but as the data presented are long-term averages, there is not the same sensitivity to individual wet or dry years. It should also be noted that the values given here for Silsden differ substantially from the value given by Butcher and others (1993) of 221 t km^{-2} yr^{-1} which is the substantial outlier in our “low permeable other” category. In this context, Foster and Lees (1999) urge caution over estimates based on reservoir resurvey especially when using an assumed original storage volume rather than measured sediment thickness.

Table 4 Historical changes in sediment yield derived from sediment cores

Lake/Reservoir	Landuse	Grid Reference	Target Yield (lower quartile) t km^{-2} yr^{-1}	Investigation threshold upper quartile t km^{-2} yr^{-1}	Estimated yields "past" t km^{-2} yr^{-1}	Estimated yields "recent" t km^{-2} yr^{-1}	Notes	Reference
Llyn Geirionydd, North Wales	Conifers	276550 361550	40	70	<10 (Prior to 1650)	15 to 18 (1915 to 1985)	18 t km^{-2} yr^{-1} (in times of mining)	Dearing (1992)
					2-5 (three periods in Holocene)			Snowball and Thompson cited in Dearing (1992)
Old Mill Reservoir, East Hams, South Devon	Pasture	285100 521500	20	50	20 (1942-1953)	90 (1997-1991)	Pasture areas main source: increased livestock numbers	Foster and Walling (1994)
Fontburn, Font river basin	Coniferous woodland	404800 593800	40	70	8.2 (Pre 1963)	11.2 (Post 1963)		Walling *et al.* (2003)
Boltby, Swale river basin	Coniferous woodland	449700 488500	10	20	11.5 (Pre 1963)	22.3 (Post 1963)		Walling *et al.* (2003)
March Ghyll, Wharfe river basin	Moorland	412350 451000	40	70	43.7 (Pre 1963)	18.9 (Post 1963)	Agric expansion in post war years and subsequent reduction	Walling *et al.* (2003)
Silsden, Aire river basin	Pasture	404450 447650	20	50	16.8 (Pre 1963)	21.7 (Post 1963)	Conversion to grassland to support more cattle.	Walling *et al.* (2003)

Table continued…

Lake/Reservoir	**Landuse**	**Grid Reference**	**Target Yield (lower quartile) t km^{-2} yr^{-1}**	**Investigation threshold upper quartile t km^{-2} yr^{-1}**	**Estimated yields "past" t km^{-2} yr^{-1}**	**Estimated yields "recent" t km^{-2} yr^{-1}**	**Notes**	**Reference**
Fillingham, Trent river basin	Arable	493850 385900	20	50	14.2 (Pre 1963)	18.4 (Post 1963)	Moorland to arable	Walling *et al.* (2003)
Merevale Lake, North Warwickshire	Forested: Oak and conifer	429850 296600	20	50	~5 (1879 – 1905)	6.48 (1982 – 1983) Based on river monitoring)		Foster *et al* (1985)
Kyre Pool, Worcestershire	Pasture 49% Woodland 33% Arable 18%	363300 264800	40	70	32 (1920 – 1960)	78 – 120 (1960 – 2000)	Land drainage	Foster *et al* (2003)

2.66 Looking in detail, the high recent yield derived from the sediment record from the Old Mill Reservoir in Devon has been attributed to an increase in livestock numbers over this period (Foster and Walling, 1994). Similarly, the fourfold increase in sediment yield found from Kyre Pool in Worcestershire post 1960 (Foster and others 2003) has been attributed to land drainage – a factor not specifically included in our catchment analysis due to the lack of a national dataset (although there would be partial correlation with soil type). Both these catchments would fall into our category of needing further investigation. The exception to higher sediment yields in recent times is March Ghyll. Here, the high yields prior to 1963 have been attributed to post-war expansion and subsequent reduction of agriculture in this catchment (Walling and others 2003). These attributions take the form of probable or most likely causes, not necessarily implying actual cause.

2.67 With the exception of March Ghyll, comparing the historic yields with our targets, we see that sediment yields are either close to or below the suggested targets. A number of the catchments are woodland and these can have substantially smaller yields (less than 10 t km^{-2} yr^{-1}). For the cases which are not woodland, the historic yields are closer to the proposed targets eg around 15 t km^{-2} yr^{-1} compared to a target of 20 t km^{-2} yr^{-1} for the “low permeable other” category and 32 t km^{-2} yr^{-1} compared to 40 t km^{-2} yr^{-1} for the “low impermeable other” category. It is possible that the sediment core data underestimate the suspended sediment yields perhaps due to post-depositional erosion or degradation of organic compounds. Changes in climate over the historic period may also have influenced yields. A further possible cause of the discrepancy is a difference in the subpopulations of these lake catchments and the catchments used in typology definition.

3 Sediment rating curves

3.1 The previous study by Walling and others (2007) suggested that rating curves, or more broadly sediment/flow relationships, might also be defined for each of the catchment types and that this would provide a better link between sediment delivery and ecological sensitivity. The shape of such relationships might be used to set useful management targets and monitor trends. Just as catchment types may be associated with different yields, there may be characteristic rating curve shapes for different catchment types. The basis for this assertion comes from plots like Figure 5.3 in Walling and others which show ratings – but not the points to which they have been fitted – for a number of British rivers. Further subdivision into seasonal relationships and different curves for rising and falling limbs of a hydrograph are also quoted in the literature (eg Walling and Webb, 1987).

3.2 While the use of rating curves as indicators of sediment behaviour is well-established, it is recognised that measurements often show no very close law-like simple relationship between suspended sediment concentration and river flow (discharge). Factors other than flow often have a very significant influence on concentrations, to the extent that discharge alone may be a poor predictor. For instance:

- The same river flow can be generated by widely different spatial and temporal patterns of rainfall in the catchment, patterns which can generated very different levels of sediment delivery.
- The catchment is in a different hydrological condition for each rainfall event, with differing availability of sediment both on the land surface and in the river channel.

3.3 These factors can generate significant statistical variability in the relationship between concentration and discharge.

3.4 Nevertheless, scatter plots of suspended sediment concentration against discharge can provide useful qualitative insight into sediment transfer processes. Further, it may not be necessary to fit a curve through discharge/suspended sediment data to obtain useful quantitative information. Suspended sediment concentrations within particular flow ranges may be of great ecological significance and scatter plots provide an indication of how these vary. They may also have the potential to be linked to changed catchment management practices for controlling sediment delivery. These aspects of the discharge/suspended sediment relationship may be at least as useful as the derivation of a parametrised rating curve.

3.5 When focused at the level of an overall typology, an important consideration in using parameters from the discharge/suspended sediment relationship for sediment transport characterisation is that these parameters are not measurements of a variable, but have a statistical definition. In contrast, the sediment yield of a catchment over a given period is a fixed quantity which can be measured with increasing accuracy with sufficient instrumentation. Even with perfect continuous data, there is no goal of precise and accurate error-free estimation of rating curve and related parameters. Nevertheless, it is in principle possible that within a typology the statistical properties of such parameter estimates are consistent within types. If this is the case, then rating curve or related parameters may be of use in characterising typologies.

3.6 The quality of parameter estimates depends on the data used and the suitability of the parameters chosen. The range of sample flows should include as far as possible the complete range of flows in the river including both rising and falling limbs for a range of storm sizes at differing times of year, under differing antecedent conditions. This ensures that the full range of behaviour of the discharge/suspended sediment relationship is captured, and aids in choosing a suitable parameterisation. Use of both parameters derived from discharge/suspended sediment relationships and sediment yield for typology definition requires the use of a multivariate extension of the tree analysis described earlier. This is not demonstrated here, but can be achieved following De'ath (2002), using his routines written in the R statistical programming language (URL://www.r-project.org/).

3.7 Even if not used in defining typologies, rating curves and other parameterisations derived from the discharge/suspended sediment relationships are likely to be useful in characterising individual catchments/sites within a type. The statistical distribution of a selected parameter within a type could be estimated, and used as an additional basis for catchment management. For example, the magnitude of concentration scatter within a particular flow range might be selected as a parameter. Low scatter might be thought desirable, and a target could be based on, for example, the lower quartile of the scatter distribution.

3.8 With regard to the use of discharge/suspended sediment data to generate rating curves, we have identified catchments from a number of groupings for which either parameterised curves, or data suitable for generating such curves, are available. All the yield data sequences of Table A1 are derived from data which would have been suitable for deriving a rating curve, although in most cases we have not had access to the necessary raw data. In some cases parameters of the fitted rating curves are available, but their standard errors or indications of the adequacy of fit are not. Data from numerous other locations are also suitable for estimating rating curves. These include, for example, data from Harmonised Monitoring sites (URL://www.defra.gov.uk/environment/statistics/inlwater/iwhmsdb.htm), EA monitoring data (subject to approximate co-location of associated discharge and water quality monitoring sites and coverage of discharge range) and data from a wide range of research studies. Rating curve estimates are potentially available for the groups of catchments shown in Table 5.

Table 5 Available rating curve data

Source	Number	Location	Information	Uncertainty
LOIS EA	22	Yorkshire	Single line; potentially raw data	SEs given
LOIS NERC	13	Yorkshire	Raw data	Available
Walling	10	Nationwide	Some multiple lines	No SEs presently available
LOCAR	4	S. England	Raw data	Available
Bradford	2	Yorkshire	Raw data	Available
Plynlimon	5	Wales	Raw data; patchy	Available
Imeson, 1970	3	Yorkshire	Raw data	Available
Psychic	9	Wales and S. England	Raw data	Available
Kennet	2	S. England	Raw data	Simultaneous flow and concentration not available
Other EA	> 57 high quality	Patchy in England	Raw data	Available

3.9 Figures A to D (Appendix B) show example plots for some (24) of the Table 5 sites. A range of behaviour is evident from these curves. Many show a general increase in concentration throughout the range of flows observed. This is particularly the case for the LOIS catchments. Others apparently start to respond once a discharge threshold has been reached. The chalk catchments monitored within the LOCAR programme show complex effects due to differing sources of water at high flows. It is clearly not appropriate to fit a single rating curve to data from these chalk catchments.

3.10 It is possible that most catchments have a response threshold, but that in some catchments flows are always above this threshold, and in some always below. Under this hypothesis, most of the LOIS catchments, which are large and agricultural, have flows which are always above the threshold. There is always ample available mobilisable sediment in the catchment or in the channel of these rivers, and the greater the flow the more is mobilised. In the Plynlimon catchments, sediment is not available until flows are higher than some threshold. The stream bed itself lacks significant mobilisable sediment, and sediment must be derived from out-of-bank sources. In the chalk catchments, if river rise is due to groundwater this has no significant effect on suspended sediment concentrations. On the other hand, if some of the rise is due to storms, then surface sediment is mobilised, and some of this reaches the river. Figure 11 shows examples of apparent threshold behaviour, and the poor association between discharge and suspended sediment concentration in the Pang at Frilsham, a chalk stream. Figure 12 shows the response of the Pang at Frilsham as time series of discharge and suspended sediment concentration. Higher sediment concentrations at Frilsham are associated with storms which generate near-surface runoff, while the main hydrological response is due to groundwater, which does not generate high sediment concentrations.

3.11 Analysis of the data for different seasons and for different parts of the hydrograph may help to reduce scatter but this is not always the case. Monthly scatter plots for the Tweed and Teviot given in Bronsdon and Naden (2000) do not show a substantial improvement. If a time line is included in a scatter plot, the data are generally highly structured, showing hysteresis for individual storms, and also variation in the absolute concentrations for particular discharge values, generating significant between-storm variability. This is shown for the Ouse at Skelton in Figure 13. Similar plots are presented on a storm-by-storm basis for the Swale at Catterick and Leckby Grange in Smith and others (2003). Changes in hysteresis are often related to the location and exhaustion of different sediment sources. For the larger catchments in Yorkshire, it was argued that different tributaries respond during different events according to the different spatial distributions of rainfall. Hysteresis curves are also available for the Torridge (Nicholls, 2001) and Hampshire Avon (Heywood, 2002). These again show complex behaviour, rather than a tendency towards a particular pattern. The study of hysteresis within an individual catchment can provide valuable insight into the type of events which may lead to deposition of fine sediment. It should, therefore, be investigated in cases where further understanding of the impact of sediment and a need to manage sediment inputs is required. The examples quoted demonstrate that simple indices or analysis of hysteretic behaviour are not so helpful in the context of setting generic catchment type-specific targets, although they might be useful in defining catchment-specific targets.

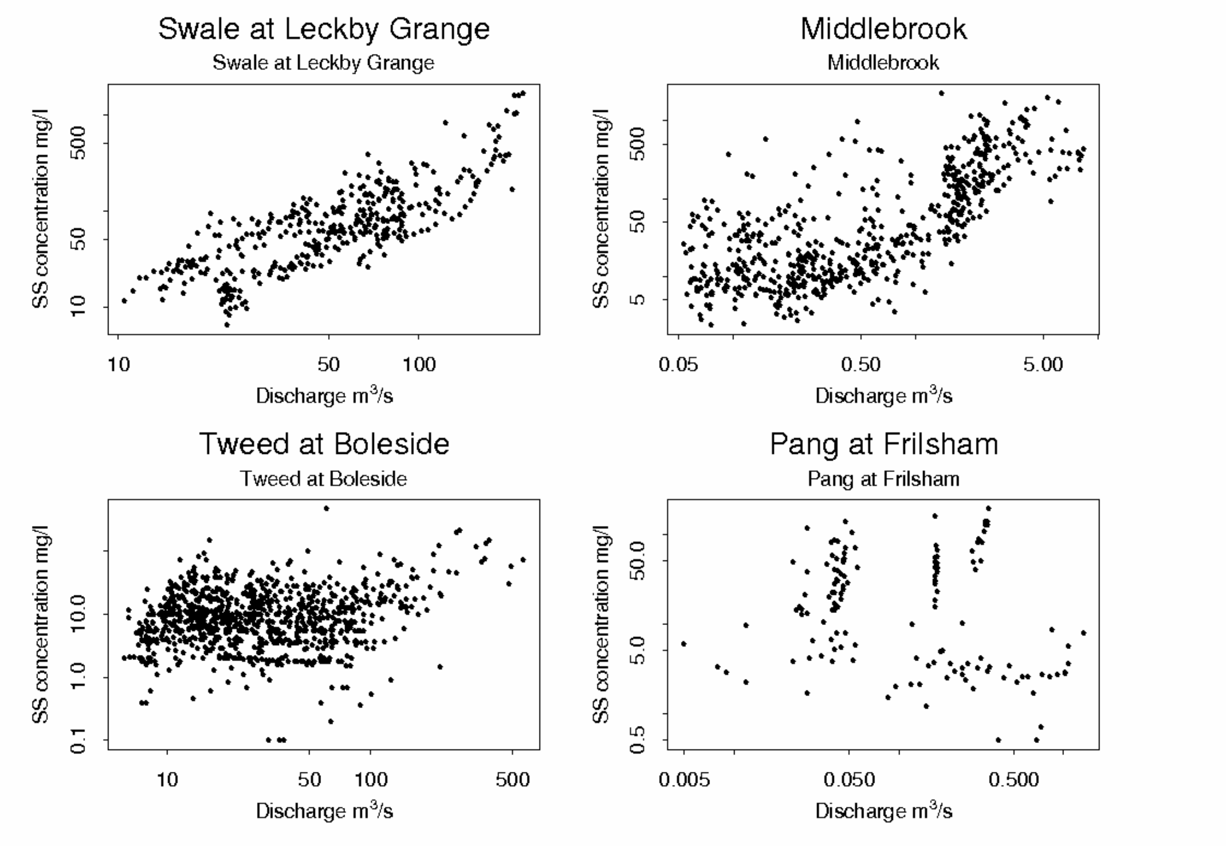


Figure 11 Example sediment rating curve data

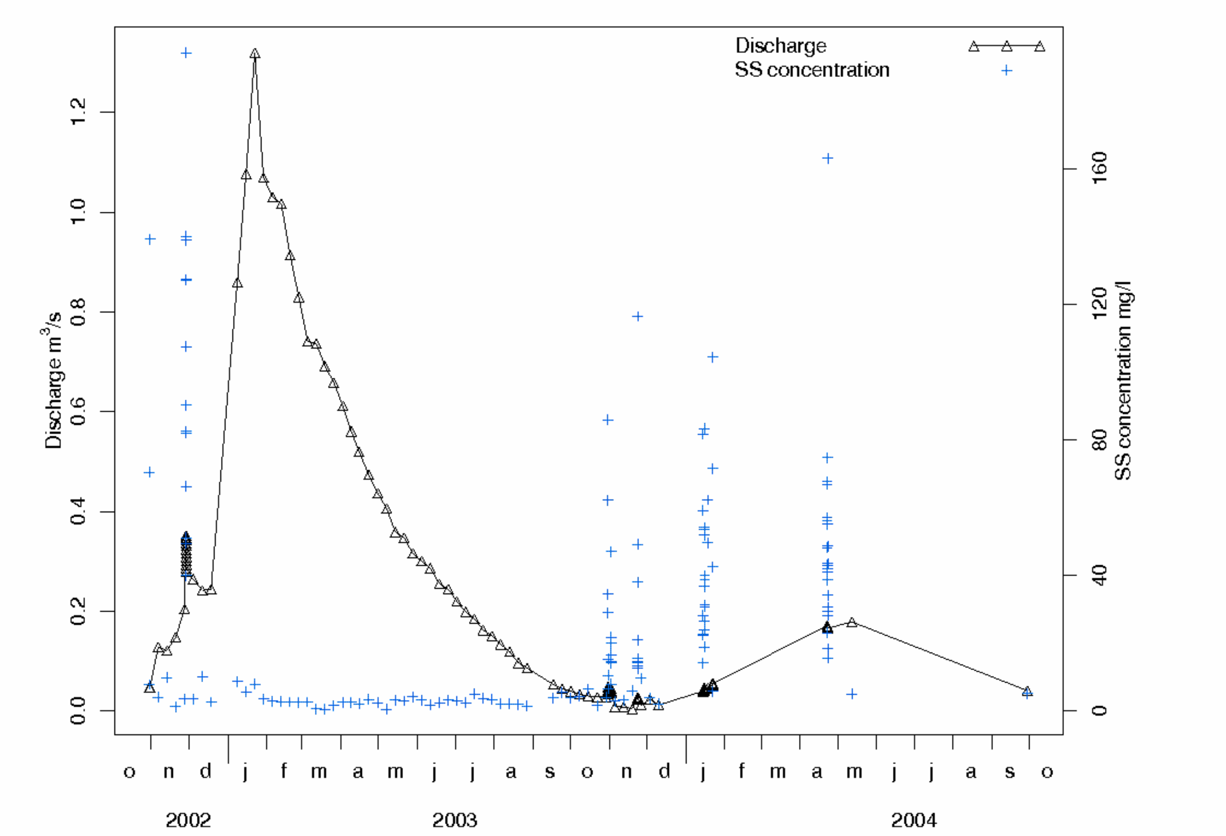


Figure 12 Time series of discharge and suspended sediment concentration on the Pan at Frilsham

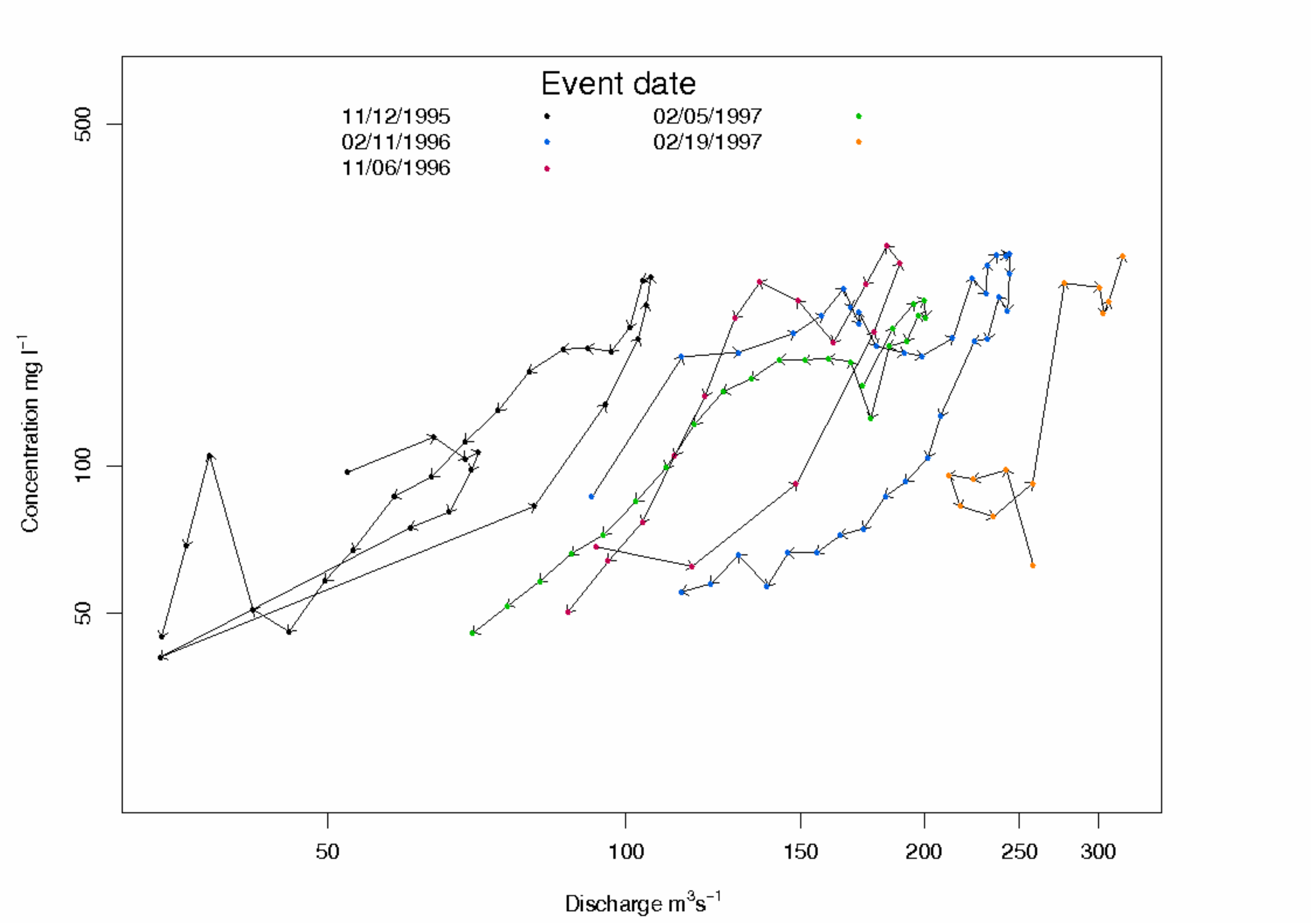


Figure 13 Hysteresis loops for events on the Ouse, Skelton

4 Consideration of ecological linkages

4.1 The link between biota and sediment is a continuing area of research. Newson and others (in Walling and others 2007) point to five dependencies which operate at different space- or time-scales – catchment, river reach, sediment characteristics, biota and life stage. In this study, generic targets for sediment yield have been suggested at the catchment level, based on catchment characteristics and available data, with a view to relating this to catchment management. The basis for this rests on the argument that, in general, aquatic biota characteristic of a catchment type are adapted to the lower sediment yields found in past records and less anthropogenically-impacted catchments. The refinement of this into more specific targets which link directly to ecological impact is a difficult task. This is primarily because the requirements of biota are poorly quantified and the relationship between sediment yield and biota is mediated by the site-specific characteristics of the morphology and hydrology of the river and other receiving aquatic habitats (such as lakes).

4.2 Ecological requirements were collated for a number of species and communities of European importance within the EU-funded LIFE in UK rivers project. The critical sediment preferences identified were associated with suspended sediment concentrations and siltation (Table 2.1 in Smith and others 2002). Examples of quantified impacts of sediment on aquatic species, collated by Walling and others 2007, also quote suspended sediment concentrations, sediment deposition and siltation as well as dissolved oxygen flow-through. An annual mean suspended sediment concentration may be readily related to sediment yield. However, the timing and duration of high levels of suspended sediment may be of more importance than the annual mean (Newcombe and Jensen, 1996; Reiser, 1998).

4.3 In terms of substrate, it is the interaction of the sediment load with the hydraulics of the habitat that is responsible for both diverse habitat on the one hand and damaging levels of deposition or siltation on the other. Sediment accumulation has been strongly correlated with the availability of fine sediment in the water column (Carling, 1984; Sear, 1993) but at what level this becomes deleterious is dependent on channel morphology which is itself subject to anthropogenic modification. Some general statements regarding siltation levels may be based on stream power (a function of slope, flow and channel width) as a measure of channel flushing - see for example Milan and others (2000) quoted. in Walling and others 2007 - but channel morphology is highly variable and a local understanding of the functioning of the specific river system may be required in order to understand the linkage between sediment concentrations, siltation and ecological requirements.

4.4 In attempting to refine the ecological requirement, we have consulted with the Environment Agency to determine what further knowledge exists relating to the sensitivity of ecology to suspended sediment. Although several UK projects are currently being undertaken in relation to sediments and ecology, eg on the River Kennet and on the River Cherwell (Houston, Environment Agency, 2006; pers.comm.), no linkages have yet been made. This contrasts with relationships that have been identified between water chemistry and ecology. In the WFD, sediment issues have so far not been progressed. However, understanding the impacts of sediment on freshwater ecosystems is regarded as crucial (pers. comm.. Nigel Milner, Head of Fisheries Science, Environment Agency). Milner also emphasises that the quality as well as the quantity of the sediment is important. In this respect, there is ongoing work in relation to salmonids on the evaluation of the Sediment Intrusion and Dissolved Oxygen (SIDO) model (Alonso and others 1996) for use in UK rivers (Defra-funded project SF0225; Grieg and others 2005 - current work on the River Lugg catchment of the River Wye and on the River Itchen). This model was developed by the USDA and simulates the movement of water, sediment and dissolved oxygen through the stream-redd system. Daily mean flow and suspended solid concentrations (separated out into sand, silt and clay, and organic fractions) are required as driving variables for the model. It, therefore, has the potential to quantify an explicit link between catchment sediment yields and impact on salmonids. Some initial simulation experiments have been run for both the River Ithon and the River Test (URL://www.geog.soton.ac.uk/staff/das/profile/Documents/DEFRA_Final.pdf). In these the amount of clay and silt-sized material, the size fractions most responsible for sediment infiltration, were progressively reduced. Results showed that reductions in silt and clay of 30% and 75%, respectively, were required to raise the dissolved oxygen levels to above the 5 mgl-1 critical level and significantly improve the redd environment. However, relating these findings to annual catchment sediment yield is not straight forward, since it requires information on flow regime, the partitioning of sediment size fractions in suspended sediment and the proportion of sediment yield contributed during the period of incubation.

4.5 With regard to the wider ecology, the investigation of possible relationships between national ecological datasets (invertebrates and aquatic plant species) and sediment yield data/estimates may be valuable. However, this is likely to be a challenging task given the likely compounding influences of water quality, hydrology and sediment on ecology. It would also depend on access to the suspended solids data held by the Environment Agency, despite their low temporal resolution, to provide good regional coverage. For rivers, the aspects of channel dimensions and morphological modification might be approached through data held within the River Habitat Survey database.

4.6 Looking more broadly, the assessment of watercourses at risk due to sediment delivery pressures developed by the Environment Agency does include an element related to the vulnerability of the ecosystem. Here, this is determined by overlay with Salmon Action Plan areas, native trout waters and chalk catchments. The chalk river type is already specifically catered for in our typology and is reflected in the low sediment yield target for this type. However, the other ecological sensitivities are not specifically recognised in the typology and substantial work is needed to develop the link between targets and ecological sensitivity. Furthermore, the range of ecological sensitivities covered by the Environment Agency mapping is limited in its scope and a first step towards extending this has been provided in the set of ecological narratives supplied by Natural England (Chris Mainstone, pers. comm.) and presented in Appendix 2.

4.7 The UK Technical Advisory Group on the WFD also provides type-specific reference-condition descriptions. For rivers, these descriptions include information about substrate conditions which sits alongside ecological narratives relating to macrophytes and phytobenthos, fish and macroinvertebrates (UKTAG, 2004). An example of the substrate descriptions (slightly abbreviated) is given in Table 6 for the four most common WFD classes. It is apparent that all these descriptions are at a very broad scale and each of the WFD types includes a wide range of sediment environments. The description of the ecology is at a similar level and no specific linkage between the substrate and the ecology and no indication of ecological sensitivity to sedimentation is provided.

Table 6 Examples of substrate descriptions for WFD categories

WFD Class	WFD River Type	% typed length	Substrate description
1	small low altitude calcareous	26	in upper reaches fast flowing with stony beds while gravels, sands and silts tend to be found in the less steep sections.
10	small medium altitude siliceous	22	ubiquitous in upland areas; typically supporting eroding habitats in the upper reaches and depositing habitats in the lower reaches; substrates may range from silt, sand and gravel to cobbles, boulders and bedrock
5	medium low altitude calcareous	12	shallow slopes; variable width; predominantly depositional environment; gravels and silts most common
1	small low altitude siliceous	11	a range of slopes, resulting in a diversity of substrate types; pebbles and cobbles tend to dominate in faster flowing reaches, but more depositional environments with gravel, sand and silt may occur in more downstream reaches

4.8 For our typology, ecological narratives have been provided by Natural England (Mainstone, pers.comm.) to give some ecological/biological context to the proposed typology, in terms of the biological characteristics of the habitats occurring within each type, the mechanisms of impact by which they might be affected, and the vulnerability of these habitats to excessive fine sediment deposition. This qualitative approach is as far as it is possible to go given our current levels of knowledge of both ecological sensitivity and linkage between sediment yield and other sediment parameters which may be of more relevance to aquatic ecology. These narratives are included as Appendix 2.

5 Assessment of observed values of sediment yield and other characteristics of sediment delivery against target values

5.1 Having defined the typology and proposed target levels relating to sediment yield, we now need a means of comparing the performance of a catchment against this target. There are three issues to be considered:

- monitoring requirements;
- yield estimation techniques; and
- temporal variability.

5.2 In exploring these issues, we focus on the "low permeable other" catchment type. The target yield for this class is well-calibrated from available sediment yield data. Rating curves are not overly complicated by a groundwater flow response and we have access to continuous data from turbidity measurements and automatic sampler data from the LOIS monitoring programme as well as Environment Agency monitoring data for a number of catchments. This allows us to explore the issues raised in some detail.

5.3 A recognised formal test of measured values of environmental variables against targets uses a statistically verifiable ideal standard (SVIS), defined by Barnett and O'Hagan (1997). In their approach, developed in the context of compliance testing, natural variability in a population sampled is acknowledged, and they suggest that some individual samples might fail to achieve a standard, while the average behaviour of the population is compliant. They suggest that a small failure rate, perhaps 5% might be allowable while still judging a population compliant. The purpose of sampling is then to determine whether the observed failure rate in the sample is significantly higher than the specified acceptable failure rate. The combination of a statistically defined standard and a statistical verification of the standard constitutes an SVIS. Compliance testing for the EU UWWT and Bathing Water Directives is of this form. This highly formalised approach is appropriate where a population can be sampled, the measurement does not introduce further significant error, and successive samples can be assumed independent. The setting of the standard may be based on safe levels, prudent reduction, the precautionary principle, "best available technology not entailing excessive cost" (BATNEEC) or other criterion.

5.4 In the context of using SVIS with annual sediment yields, the population would comprise the annual yields of a water body. The sample would be the annual yield in random years. There are some difficulties with this approach in this context. First, the annual yield of a water body cannot be measured accurately without a major investment of resources, and secondly, the time scale implied by SVIS is unreasonable. We should therefore seek some more practical alternative to the use of an SVIS based on annual sediment yields.

Principles of catchment sediment yield estimation

5.5 The sediment variable of primary interest has been defined as the annual yield, with the action level also expressed as an annual yield. A requirement for testing is therefore that annual yield be measured, or estimated.

5.6 Many catchments will have no gauging or monitoring site. Accurate measurement of annual yield depends on continuous monitoring, which requires considerable expertise and resources in terms of installation, maintenance and calibration of sensors and samplers. Flow may be estimated by installing an ultrasonic Doppler sensor and a pressure transducer. These instruments measure velocity and depth respectively. A relationship between depth and cross sectional area of flow is then used to compute discharge as the product of velocity and cross-sectional area. Continuous suspended sediment concentration can be estimated using a turbidity sensor, calibrated against samples collected manually or using an automatic sampler. Once installed, these instruments require frequent maintenance, and calibration using manual sampling. There is also a requirement for considerable investment of time and expertise in the post-processing of turbidity data.

5.7 Even if continuous measurement is possible, the final yield computed relates only to the monitoring period. While this can readily be compared with reference values, the monitoring period may not be representative of long-term average catchment conditions. Some adjustment of the measured yield would be needed to allow for this. This would require the use of a simulation model. The model would need to include some measure of deviance from normality of the monitoring period, such as discharge in relation to the long-term mean. It would also require a measure of the influence of that deviance on yields. Any such model would introduce uncertainties into yield estimation even if the measurements over the monitoring period gave a perfect yield estimate.

5.8 The evident difficulties in using continuous data to assess the sediment yield status of a catchment suggest alternatives might be considered.

Practical statistical estimation of yield

5.9 Continuous recording can give measures of yield which are close to exact over the measurement period. If continuous data are not used, then estimates of the unmeasured values are required, and we should consider the error this introduces into yield estimation. Using a simple additive model, catchment sediment yield may be expressed as:

Equation 1

True yield = typology mean + local spatial effect + effect of monitoring period chosen = estimated yield + estimation error

In equation 1 the local spatial effect plus the typology mean is of primary interest in assessing the status of a catchment. This may be written, using equation 1 as:

Equation 2

Local spatial effect + typology mean = estimated yield – effect of monitoring period chosen + estimation error

5.10 Large values of the spatial effect are of greatest interest, since they imply a local sediment yield problem. The effect of the monitoring period chosen is assumed to have a long term mean of zero, and to be a nuisance variable at shorter time intervals, where it may be confounded with the spatial effect. The estimation error is treated as effectively zero when continuous measurements are made (although there are error sources even under continuous monitoring, since sensors do not give a fully accurate integrated flux through a river cross-section). If the estimation error is small in relation to typical local spatial effects, then neglecting it may be acceptable. If the time effect could be eliminated, a realistic approach would be to follow a sampling and estimation procedure which gave an upper limit on the estimation error that was small in relation to within-type variation in the local spatial effect. This would ensure that any high estimated yields could with confidence be attributed to local spatial effects.

5.11 The treatment of the time interval effect is problematic. The main temporal factor influencing yield at an annual time scale is likely to be the rainfall distribution and the resulting variability in the flow distribution. Even in an ungauged catchment, there are likely to be nearby rain- and flow-gauges which will give a good estimate of whether the measurement year was average. We then need a model relating annual yield at the site of interest to annual rainfall or flow at the measurement sites in order to make an adjustment. In addition to a lumped model considering annual values, a relationship may be sought at a finer time scale. This might include other weather characteristics such as storm intensity or length of time since the previous event. It is likely that such relationships exist, but might be difficult to find with existing data, particularly for use at national scale.

5.12 A commonly used simple approach to dealing with temporal effects is through flow adjustment. The mean concentration over the monitoring period is computed, and this is then multiplied by the mean annual flow to estimate the mean annual load (from which the yield may be derived through division by the catchment area). This approach, known as the “ratio method” (Cooper & Watts, 2002), assumes concentration is independent of flow, which is rarely the case for suspended sediment, and the estimate is therefore biased. There are various corrections for this bias, based in the simplest case on a linear relation through the origin relating concentration to discharge. This remains a crude approximation to the true relationship between discharge and concentration. It also depends on the availability of a mean annual flow.

5.13 If any temporal effect can be accounted for, where there is estimation error present, the measurement of yield does not define the local spatial effect. The estimated yield may be higher than the target for the spatial effect alone simply because of a large positive estimation error. This requires some modification of any test of yield against a reference value. Estimates of yield derived using statistical techniques have an associated standard error, which may be used to generate approximate confidence intervals for the true yield. A statistical test can then in principle be based on the probability that the true yield is above or below the reference value. For each catchment an exceedence probability based on approximate confidence intervals could then be quoted. This has some analogy with an SVIS, except that the probabilities are based on a model rather than direct observations. For estimates with high standard errors, such a test might give high probability of the yield exceeding a reference value even when the mean of the distribution was below the reference value. Rather than identify a problem in such cases, it might be preferable to require that an estimate of yield achieve a certain level of precision before taking action. The degree of precision is a function of the statistical properties of the underlying sequence and the method of estimation. Concern then focuses on determining the statistical properties of yield estimates, and in trying to improve the accuracy and precision of the estimates.

5.14 If we sample concentration and flow at discrete time intervals rather than use a continuous record to estimate yield, one of the key difficulties in estimation is that most of the annual yield is typically generated in a very few events. Continuous sampling is thought necessary in order to capture these events, since less frequent monitoring risks missing them and generating estimates which are either biased or have high and possibly poorly estimated variance. In order to reduce the overall sampling rate and not miss key events, a common practice is therefore to monitor less intensively during lower flows, and more intensively during higher flow events. It is assumed that by sampling high flow events intensively, one will obtain good estimates of the load transmitted during those periods which contribute most to the total load. By combining the data from these two sampling regimes in an appropriate way, and using an appropriate statistical analysis, an estimate of the total load can be derived, from which a yield estimate is readily calculated. Less intensive monitoring may be manual, with intensive sampling using stage-triggered automatic samplers. Measurements of discharge are also required, and there must be some means of estimating total discharge during both more and less intensive sampling periods.

5.15 The instrumentation required to trigger an automatic sampler is typically a pressure transducer. If this has to be installed, it might as well be attached to a logger and run continuously to give a continuous record of water depth. These measurements may be converted into a continuous flow measurement, provided it is sited at a suitable point for flow measurement, and a flow-depth rating curve is determined. Manual estimation of water depth and hence flow through a storm, and manual sampling would preclude a need for electronic instrumentation, at the cost of possibly missing significant events. Another alternative is triggering an automatic sampler remotely, but manually, depending on expected rainfall or flow conditions.

5.16 In defining schemes which do not measure the components of load (flow and concentration) continuously, it is useful to compare the true load (yield x area) with possible alternatives.

5.17 The true load passing a location on a river per unit time is:

Equation 3

$$True\ load = \int_t C(t)Q(t)\,dt \Big/ \int_t dt$$

where $C(t)$ and $Q(t)$ are concentration and discharge at time t. For any sampling regime, a natural estimate of load per unit of time is simply:

Equation 4

$$Estimated\ load = \frac{\sum_i C_i Q_i \Delta t_i}{\sum_i \Delta t_i}$$

5.18 In equation 4 C_i and Q_i are concentration and discharge at time t_i and Δt_i is the length of the time interval $\left((t_{i-1}+t_i)/2,(t_i+t_{i+1})/2\right)$, subject to suitable treatment at each end of the series. The numerator in equation 4 is simply a discrete version of the numerator integral in equation 3. The denominator of equation 4 is the length of the time interval. Under continuous monitoring Δt_i is very small and the difference between equations 3 and 4 is considered negligible. In other schemes some estimation error is introduced.

5.19 The simplest special case of equation 4 has fixed time interval, in which case the estimated load reduces to the mean of the sample values:

Equation 5

$$Estimated\ load = \frac{1}{n}\sum_i C_i Q_i$$

5.20 Other special cases of equation 4 include mixed sampling regimes, for example at either a fixed low frequency (n_l points, interval Δt_l) or a fixed high frequency (n_h points, interval Δt_h). In this case equation 4 becomes:

Equation 6

$$Estimated\ load = \frac{\Delta t_l \sum_{i=1}^{n_l} C_i Q_i + \Delta t_h \sum_{i=1}^{n_h} C_i Q_i}{n_l \Delta t_l + n_h \Delta t_h}$$

$$= \frac{\sum_{i=1}^{n_l} C_i Q_i + w \times \sum_{i=1}^{n_h} C_i Q_i}{n_l + w \times n_h}; \quad w = \Delta t_h / \Delta t_l$$

5.21 For the general case, the difference between equations (3) and (4) is the sum of a sequence of components, each of the form:

Equation 7

$$error_{t_i} = \int_{(t_{i-1}+t_i)/2}^{(t_i+t_{i+1})/2} C(t)Q(t)\,dt - \frac{(t_{i+1} - t_{i-1})}{2} C_i Q_i$$

5.22 The mean value of the error terms in equation 7 is assumed to be zero. However, the estimation of the variance of each term depends on the underlying smoothness of the concentrations and discharges. The purpose of more frequent sampling during high flows is to reduce the variance in equations 5 or 6. A full treatment of the estimation of the variance is complex (Cooper & Watts, 2002), but a number of approximations are available.

5.23 If automatic sampling is used at high flows and routine monitoring at low flows, then the situation approximates equation 6. A typical sampling interval for automatic samplers is of the order of two hours, during which time concentration and flow changes are likely to be smooth (good linear approximation) in many medium-sized UK rivers. More responsive catchments may need a shorter sampling interval although use of this would need to be balanced against the potential loss of samples during long duration events as automatic samplers generally only contain 24 bottles. Any error in the use of a linear interpolator is likely to be due to a lack of higher order terms in a smooth curve, rather than random noise. Such error is difficult to characterise statistically, and may be ignored to a first approximation. Where monitoring is less frequent, errors are due to unmeasured flow responses to rainfall which are more statistical in nature. The accuracy of yield estimation over these periods relies on having a large number of data points. If sampling were random, then the variance of the estimate could be found from standard sampling theory. Lack of randomness means the correlation of successive measurements should be accounted for in any variance calculations. As a first approximation, however, the assumption of randomness may be used to estimate variances.

5.24 Note that the purpose of automatic samplers is to estimate during periods of particularly high and rapidly fluctuating load. This generally occurs at high flows. However, some caution may be required in streams where concentration and discharge do not have a simple relationship. This occurs, for example in Chalk streams, where the highest flows may be associated with groundwater flow with little suspended sediment, while more modest flows in response to storms give higher concentrations.

5.25 It appears that even with reduced sampling it is necessary to install flow measuring equipment to estimate the sediment yield of a water body. It is unrealistic to measure discharge manually during automatic sampling. Once flow gauging equipment has been installed, it is likely to be run continuously, to provide trigger values for the automatic sampler. This will generate many more measurements of discharge than there are water quality measurements. Since discharge and suspended sediment concentration are commonly related, these additional flow measurements may at some sites be used to improve the estimation of concentrations, and ultimately the estimated yield. This is a less direct approach than the simple methods based on equation 4.

Model-based estimation – rating curves

5.26 In equation 4, the estimation of load at unmeasured points is done by simply assuming the fixed measured value over a defined time period around that value. We take $C(t) = C_i$ and $Q(t) = Q_i$ over the time interval $\left((t_{i-1} + t_i)/2, (t_i + t_{i+1})/2\right)$, which by symmetry is equivalent to linear interpolation.

5.27 Other modelled values of $C(t)$ or $Q(t)$ may be considered for substitution in equation 3 to give yield estimates. Weather and catchment characteristics may be used to estimate both concentration and flow; for example rainfall measurements may be used to generate flow estimates through a rainfall-runoff model. But perhaps the commonest model is to express concentration as a function of flow, through the rating curve. This model is particularly useful if a continuous record of flow is available, with much less frequent measurements of concentration.

5.28 The model typically fitted is:

Equation 8

$$\log(C_i) = a + b\log(Q_i)$$

where a and b are parameters and log is the natural logarithm (base e). Assuming a normal distribution for the logarithms of concentration, the estimated concentration is:

Equation 9

$$\hat{C}_j = Q_j^{\hat{b}} \exp\left(\hat{a} + \hat{\sigma}^2/2\right)$$

where hats denote estimates after fitting equation 8, σ^2 being the residual variance.

5.29 A mixture of automatic and routine sampling may be used to generate a rating curve. Automatic sampling ensures there are sufficient measurements to characterise the relationship at high flows. Evidence suggests that in some catchments there is a threshold discharge at which suspended sediment concentrations start to increase significantly. This threshold is often at a flow of around 0.5 to 1 mm day^{-1} equivalent in UK rivers. Discharge of this magnitude is perhaps sufficient to start to mobilise sediment, the threshold depending on the sediment available and the morphology of the river. In catchments where sediment is always available, there may be no evidence of a threshold. If a threshold is present, a “broken stick” is preferable to the single line of equation 8. Data are divided into those with flow below and above the threshold. A horizontal line following the mean (logged) concentration is used for the first group of (logged) data points, and a straight line regression (equation 8) is fitted through the second group. In practice, the location of the threshold may be located by eye, or estimated along with the other parameters using numerical optimisation. Once a rating curve has been fitted, it provides a point estimate of concentration at any flow value (equation 9). The rating curve estimate may be written:

Equation 10

$$Rating\ curve\ load\ estimate = \frac{1}{n}\sum_j \hat{C}_j Q_j$$

where n is the number of flow measurements, and $\hat{C}_j$ are concentration estimates derived from the rating curve. Fitting the rating curve provides an error variance associated with each point simulation of concentration (Cooper & Watts, 2002). This may be used to provide an estimated variance for yields computed using the simulated concentrations.

Simple and rating curve yield estimates for selected catchments

5.30 We have established that continuous monitoring to estimate yields is resource-intensive. There are also limited existing continuous data from which to make inferences about relationships between sediment yield and catchment characteristics. The suggested alternatives are to estimate sediment yields by less intensive sampling, using the weighted mean or rating curve methods described. These approaches not only allow less resource-intensive estimation, but also open up the possibility that less high quality data sets may be able to provide useful information on sediment yields, despite not having continuous records of flow and concentration.

5.31 Apart from the high quality data used to define our typology, there are other data sets, notably those held by the EA, which, while not giving a continuous record are very extensive and might be used to locate possible sediment yield problems. The EA routinely measures concentrations of numerous chemical constituents at several hundred or more monitoring sites in England and Wales. At a proportion of these, suspended solids concentration is also measured. Monitoring at a typical site is every two weeks, and at many sites data have been collected for many years. If yields are to be estimated, a measure of discharge as well as suspended solids concentration is required, and EA monitoring sites do not generally coincide with flow gauging sites. However, there is often a nearby site where flow is gauged every 15 minutes, which may be used for the purpose of load estimation.

5.32 Data collected as infrequently as once every two weeks are not generally considered adequate to measure suspended sediment yield, and there is a belief that yield estimates based on sample means are biased. This is on the grounds that infrequent sampling may fail to capture storm events. This in itself would not cause bias under a random sampling scheme. Under a systematic scheme, bias would be introduced if there were periodicity in the data which was in phase with the sampling interval. This might be possible if there were diurnal variation in load. A more likely source of bias is failure to sample during flood events, for logistical reasons. Under random sampling, the effect of infrequent sampling is to increase the variance of the yield estimate. Most yield estimates will fall below the mean, but this is not necessarily an indication of bias in a highly skewed distribution. But, for small samples, sample estimates of the mean and variance will usually be too low.

5.33 For yield estimation purposes the high variance of estimates may be insufficient reason for discarding the quite major historic data records held by the EA. These lower frequency monitoring data which have been collected over long periods, or at a very large number of sites, are likely to have monitored numerous large storms. These should provide a large enough sample to give some estimates of yield, either at individual sites or for catchment types. Data from these sites may be useful in improving the definition of typologies, and providing information on the relationship between discharge and suspended sediment concentration.

5.34 The major focus of our analysis is on those catchments where there is a continuous record, EA monitoring data and automatic sampler data. The catchments considered are all of the same designated catchment type (“low permeable other”) and are located in Yorkshire and the Trent catchment, including seven of the LOIS sites listed in Table 5 (Section 3 above), and one of the Bradford sites. The period of the continuous record and automatic sampling are from 1995 to 1997. The EA data run over a longer preceding period. This means that temporal effects may account for any differences in yield estimates at the same site. If there is little difference in yield estimates then EA data elsewhere may be used with some confidence to estimate yields, though this is subject to a number of assumptions. More realistically, we might hope to put bounds on the difference between estimates of yield based on continuous and less frequent measurement.

5.35 The results of analysing these data are shown in Table 7. The raw data from which these results are derived are those shown in the first five panels of Figure E. In Table 7, the first three numeric columns give estimated mean flow at the sites concerned. The first of these is the mean daily flow for the days of the EA monitoring period on which measurements were taken. The second shows mean daily flow over the whole of the EA monitoring period. The third column gives the mean daily flow over the continuous monitoring period. The exact yield is that calculated from continuous turbidity data. Succeeding columns give estimated yields computed by various methods, with approximate standard errors. The first three refer to EA data only, estimated as the daily flow weighted mean, the same statistic adjusted by the annual mean daily flow (the ratio estimate), and finally an estimate found by using a rating curve (the red lines in Figure E) to estimate unmeasured concentrations, these being assumed daily values. The remaining three yield estimates, with their approximate standard errors, use automatic sampler data in some way. The first uses both EA and automatic sampler data to give a rating curve (the green lines in Figure E), which is then applied to the EA monitoring period. Next are the yields for the continuous monitoring (EPIC) period, using the EA-only rating curve (red line), followed by yields for the continuous monitoring (EPIC) period using the combined EA and automatic sampler data (green line). The estimates to compare with the exact values of yield are those made over the continuous monitoring (EPIC) period.

5.36 Inspection of Table 7 suggests that yield estimates are highly dependent on the rating curve fitted. In every case the combined automatic sampler and EA rating curve is steeper beyond the critical threshold than the curve derived from EA data alone. This results in uniformly higher estimates of yield using the combined rating curve. The automatic sampler data give greater resolution of the high flow portion of the rating curve, but values may not be strictly comparable with data from manual sampling. Automatic sampler measurements at the same sites suggest these are higher than manual sampling concentrations under the same flow conditions. One possibility is that an automatic sampler draws water at a fixed distance from the river bed, while manual samples are collected from the top of the flow. If this is a real effect, then the combined rating curves are too steep. If we look at estimated yields over the continuous period using the two different rating curves, we see that in six out of the eight cases the true yield falls between the two estimates. In two cases, the Don and the Aire at Beal Weir, the exact yield is lower than both rating curve estimates. The difference between the two rating curve estimates is around a factor of 2, which is large. However, the results do not support the notion that any estimate of yield from limited data is bound to be lower than the exact yield. Estimates shown for the EA period indicate the degree of internal consistency and the extent of temporal variability. Results are all within a factor of 2.

5.37 The approximate standard errors for the mean and ratio estimates refer to the mean yield using n samples. This takes no account of the finiteness of the population. For the rating curve, the measurement variance σ^2 for concentrations is derived from the fitting, assuming a lognormal distribution of concentration about the predicted value. The variance of the yield is then computed as $\sigma^2 \sum Q_i^2 / N$. It is notable that confidence intervals derived from these standard errors do not necessarily include the true value. This may be for a number of reasons. First, the approximations used in computing the standard errors may be poor, due to serial correlation in the data, and, in the case of rating curves, because uncertainty in the parameter estimates themselves is not included. There may also be temporal effects in comparing EA period yields with continuous monitoring period yields. It is also possible that continuous monitoring, automatic samplers and manual sampling are not measuring the same thing. There is some consistency between all the EA data estimates, but the two rating curve estimates over the continuous monitoring period are not consistent in the sense that their confidence intervals do not overlap. The consistently steeper rating curve using both EA and automatic sampler data, rather than just automatic samplers, suggests the two methods do not measure the same thing, and this results in bias. However, it appears from our limited data that using EA data alone may tend to underestimate, while the combination of data overestimates.

Table 7 Yield estimates at LOIS core sites† using EPIC (automatic sampler) and EA monitoring data

	Flows m^3 s^{-1}			**Yield estimates t km^{-2}yr^{-1}**							**No of data points**	
Site	EA daily flow on days with sediment measurement	EA daily flow on all days over measurement period	EA daily flow over EPIC monitoring period	Exact yield	EA yield by daily flow weighted mean	EA yield adjusted for full daily flow record (ratio method) se 3	Rating curve estimate of yield using EA data. EA period se 0.3	RC estimate of yield using EA and LOIS data. EA period se<5	Rating curve estimate of yield using EA data. EPIC period	RC estimate of yield using EA and EPIC data. EPIC period	EA	EPIC
Bradford Beck at Shipley	0.62	0.66	0.8	40.1	15.6	16.59	23.64	42.88	30.68 (7.7)	54.05 (16.8)	314	652
Don at Doncaster	14.47	16.21	13.36	12.6	19.7	22.06	20.52	31.79	18.29 (1.4)	30.06 (3.0)	433	87
Ure at Westwick Lock	21.79	20.74	19.06	35.4	17	16.16	17.31	51.13	18.27 (2.5)	59.1 (11.5)	115	205
Wharfe at Flint Mill Weir	16.93	16.94	12.96	15.3	14.1	14.07	11.48	31.86	8.50 (0.7)	23.39 (3.3)	113	86
Swale at Crakehill	19.32	19.39	17.31	33.5	17.7	17.78	17.23	32.94	18.63 (1.6)	36.85 (3.5)	114	384
Trent at North Muskham	87.48	80.15	69.29	10.2	14	12.85	9.72	13.47	8.24 (0.5)	11.38 (0.8)	296	127
Ouse at Skelton	47.4	48.47	40.39	23	19.1	19.49	16.93	43.05	14.12 (0.9)	36.26 (3.6)	303	205
Aire at Beal Weir	33.67	35.23	33.12	21.6	23.5	24.61	23.31	36.09	24.13 (1.1)	38.34 (2.3)	353	112

†EPIC data are LOIS (1994-1997), except for Bradford Beck (2000-2001)

5.38 Table 8 shows estimates with approximate standard errors for other EA catchments where no continuous data are available. These are all predominantly classified as well-drained lowland other than Chalk ("low permeable other"), with an estimated target of 20 and an investigation threshold of 50 t km^{-2} yr^{-1}. Approximate confidence limits for the estimated yields for a large proportion of them fall below the estimated target level.

5.39 One possibility is that the yields are underestimates. Alternative explanations are that the estimated lower quartile for this catchment type is too low, that a new typology is required, or that a temporal effect is responsible for the difference. It may also be that the typology is substantially correct, but that there is a regional pattern of low yields. If we return to the data from which the typology was defined, we find a preponderance of catchments in the south-west being used to classify well-drained lowland other than chalk. These south-western catchments have higher sediment yields than the EA catchments of the same typology. This may be due to morphological differences which might be used as a basis for refining the typology. Recently available yield estimates from continuous monitoring on the River Tern tend to confirm this interpretation. The Tern is of the same catchment type in central England and has shown yields of 5-6 t km^{-2} yr^{-1}.

5.40 If we take the rating curve yield estimates, then only the Wiske has an approximate confidence region whose upper bound exceeds the action limit 50 t km^{-2} yr^{-1}. Some caution is needed in interpreting this, since the Wiske has uncertain high flow measurements due to drowning of the gauging weir. It is also the case that the interquartile range has been defined from exact measurements of yield. The yield quoted for the Wiske is modelled, and the test against the interquartile range rests on the adequacy of the model, and may also include temporal effects.

Table 8 Yield estimates using EA monitoring and daily flow data. Selected sites, Yorkshire and the Trent catchment

Site	**EA mean daily flow on days with sediment measurement m^{3}s^{-1}**	**EA mean daily flow on all days over measurement period m^{3}s^{-1}**	**EA yield by daily flow weight-ed mean t km^{-2} yr^{-1}**	**EA yield adjusted for full daily flow record (Ratio method) with SE t km^{-2} yr^{-1}**		**Rating curve estimate of yield with SE t km^{-2} yr^{-1}**		**Number of data pts**
Holme at Queen's Mill[†]	1.89	2.16	18	20.6	7.38	12.3	0.44	300
Aire at Lemonroyd	17.44	17.48	24.8	24.9	2.1	24.26	0.56	452
Dearne at Barnsley Weir	1.23	1.39	38.2	43.3	21.68	23.33	0.91	102
Doe Lea at Staveley	0.61	0.67	28.3	31.3	3.56	39.47	1.43	296
Bedale Beck at Leeming[‡]	2.08	2.09	7.9	7.89	1.24	15.84	1.02	115
Wiske at Kirby Wiske[‡]	3.09	3.4	40.4	44.6	9.71	44.85	2.84	117
Dove at Kirkby Mills	0.99	1.06	33.5	36.1	23.9	13.57	0.7	120
Seven at Normanby	1.51	1.8	9.4	11.3	1.39	26.21	1.96	119
Derwent at Buttercrambe	11.81	15.67	5.3	7.04	1.82	9.39	0.14	72
Soar at Pillings Lock	9.29	9.56	11.3	11.7	1.72	11.03	0.31	299
Sence at South Wigston	0.99	1	21.8	22.2	8.34	22.87	1.04	110
Rothley Brook at Rothley	0.81	0.79	22.3	21.9	7.26	12.92	0.53	84
Derwent at Church Wilne[‡]	17.21	18.56	11	11.8	1.71	10.84	0.21	295
Trent at Yoxall	11.19	12.73	6.7	7.68	0.56	8.48	0.12	316
Meece Brook at Shallowford	0.44	0.56	3.2	4.2	1.06	3.95	0.12	81
Went at Walden Stubbs	0.41	0.57	5.4	7.61	2.12	8.6	0.51	65
Dover Beck at Lowdham	0.12	0.14	1.8	2.3	0.59	1.99	0.04	83
Erewash at Sandiacre	1.58	2.04	10.9	14.11	3.17	10.86	0.25	64
Tame at Lea Marston[‡]	13.61	13.65	26.8	26.9	1.5	24.85	0.29	1378
Rea at Calthorpe Park	0.57	0.81	3.3	4.71	0.55	9.38	0.39	87
Cole at Coleshill	0.91	0.96	8.7	9.14	1.54	7.53	0.26	568
Trent at Shardlow	47.09	48.39	10.9	11.3	1.87	13.17	0.45	105

Table continued…

Site	EA mean daily flow on days with sediment measurement $m^3 s^{-1}$	EA mean daily flow on all days over measurement period $m^3 s^{-1}$	EA yield by daily flow weight-ed mean t $km^{-2} yr^{-1}$	EA yield adjusted for full daily flow record (Ratio method) with SE t $km^{-2} yr^{-1}$		Rating curve estimate of yield with SE t $km^{-2} yr^{-1}$		Number of data pts
Manifold at Ilam	3.04	3.49	17.2	19.9	7.33	14.01	0.3	83
Churnet at Basford Bridge†	1.3	1.93	5.7	8.53	1.34	8.95	0.21	187
Dove at Marston	11.48	13.71	5.6	6.67	1.2	12.71	0.32	55
Skell at Alma Weir	1.51	1.45	4.8	4.65	1	5.42	0.3	111
Poulter at Cuckney	0.33	0.3	2.5	2.27	0.16	2.17	0.03	60
Idle at Mattersley	2.32	2.59	4.1	4.58	0.9	4.76	0.09	89

† upstream reservoir may influence concentrations, ‡ possible backwater effects means that flow measurements are poor

5.41 There is also some variability between simple and rating curve yield estimates. In most cases where there is a large discrepancy, the standard error of the ratio estimate is high, giving an approximate confidence interval which covers the rating curve estimate. Where this is not the case (for example on the Seven), the raw data might be investigated.

5.42 The catchments considered are all of the same designated catchment type. Ideally a similar analysis would be carried out for other types. There are no continuous data from upland peat sites in the Pennines where yield has been estimated from lake bathymetry, and annual estimation of yields other than as a long-term mean is also problematic for other lake sediment records. Continuous measurements are also not presently available from most of the remaining sites used in typology definition. We do have records from the Plynlimon sites, and these could potentially be further investigated. However, this is a very limited selection. Chalk catchments need special treatment in view of the poor association between discharge and suspended sediment concentration.

5.43 While not using exact measurements, analyses such as these can provide statistical inferences on yields. Subject to the limitations of the estimated standard errors, these can be compared with target values and can also suggest possible modifications to typologies. The approach adopted here might usefully be applied to the whole of the EA routine monitoring database.

Temporal variability

5.44 Yield at a site will normally be estimated using measurements from a limited monitoring period. This may not be representative of the long term mean because of particular features of the weather and catchment conditions during the monitoring period. To examine the influence of this factor, we explore a number of series for each of which there are several years' data. These are EA sites where sampling has been either weekly or once every two weeks over several years. Allowing for within-year variation in frequency this provides 25 to 50 points from which to estimate an annual yield. This is a small number, and in some individual years there will be failure to capture large events.

5.45 For each year, a ratio estimate and a rating curve estimate of yield are computed, along with approximate standard errors. The sites selected are three in Yorkshire and four in the Midlands. The longest series is from the Tame at Lea Marston, with a data record from 1974 to 1995. The shortest series run from 1986 to 1995.

5.46 If there is a temporal effect on yields at an annual scale due to weather conditions one might expect this to have regional influence. So yield estimates at different sites would be correlated.

5.47 Data from the Tame in isolation are first considered. The Tame drains parts of southern Birmingham, and in addition to having a large proportion of urban drainage it is also heavily influenced by water treatment works discharges. These factors may influence its sediment and hydrological regime. Data were collected weekly or every two weeks from mid 1975, with daily sampling prior to that. Figure 14 shows the ratio and rating curve estimates of yield for each year, with standard errors. Two rating curve estimates are shown.

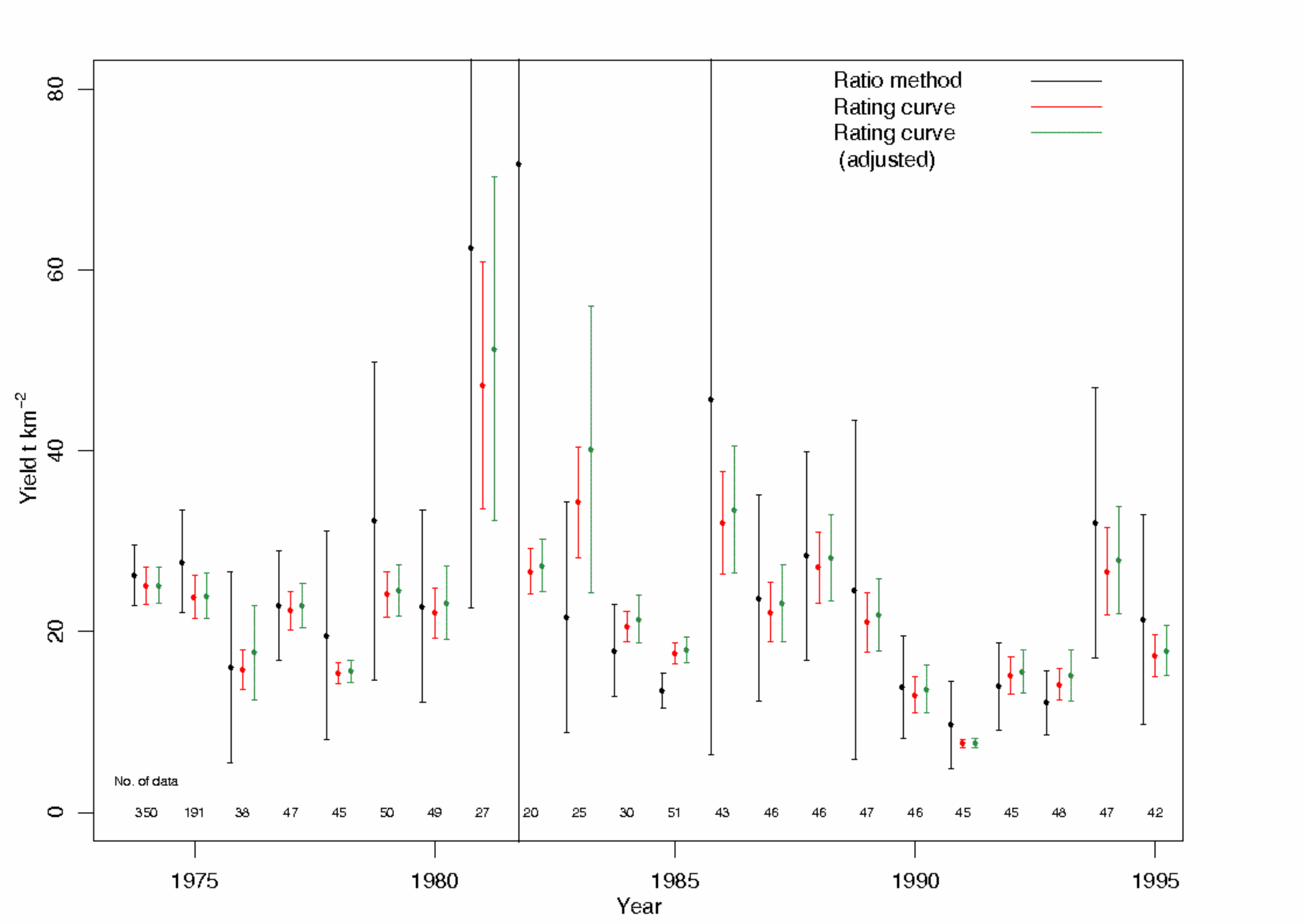


Figure 14 Annual yield estimates (+/- 2xSE) for the Tame at Lea Marston

5.48 The first does not account for parameter variability in computing estimates and their confidence intervals, while the second does, using the approach of Cooper & Watts (2002). Nevertheless the estimate still includes other unaccounted sources of approximation associated with serial autocorrelation in the concentration series. The difference between the two estimation methods is generally small compared to differences between both procedures and the ratio method, and in comparison with between-year variability.

5.49 The standard errors for the ratio method are always higher than for the rating curve, often substantially. However, the rating curve estimates are generally within the confidence limits for the ratio method, so that there is some consistency between the two approaches. Figure 15 shows the relationship between estimated annual yield and annual discharge. This is in general a poor relationship, though with a significant trend (p=.015, r2=.26). The lowest two mean annual flows were in the drought years 1975 and 1976, but these years were not associated with the lowest estimated yields, presumably because of the distribution of high flow magnitudes when they occurred.

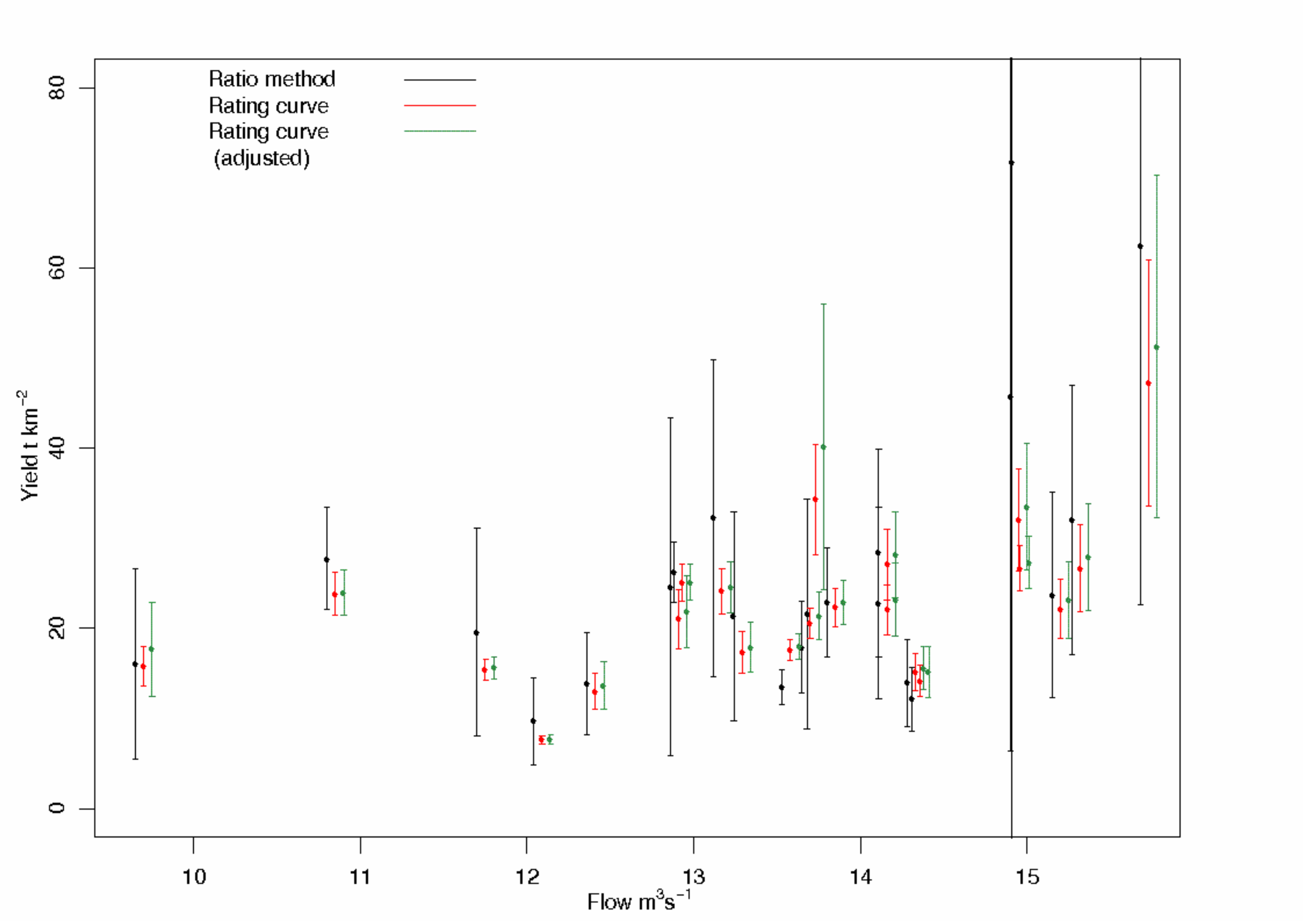


Figure 15 Relationship between annual yield and annual mean flow, Tame at Lea Marston

5.50 If we monitor a new site weekly for a year, including continuous flow monitoring, then we expect to correct for conditions during that year. A measure of the location of the year's annual flow in the distribution of annual flows can be obtained by analogy with a nearby gauged catchment of similar characteristics (and same typology). The expected difference in concentration must then be estimated. One option is to find the ratio of the long term flow to the flow in the present year, call it λ. Then an immediate first estimate of the yield in a typical year is to multiply by λ each discharge in the monitored year, and compute the associated yield. If a "broken stick" relationship has been fitted, this means multiplying the computed yield by λ for those (generated) flows less than the threshold value, and by λ^{1+b} (where b is the slope of the relationship between suspended sediment concentration and flow) for flows above the threshold. To take an example, if there is no threshold, the slope is 1, and λ is 2, then the multiplier is 4. That is, a doubling of flow gives four times the sediment yield. If this approach is used for the Tame with the year of lowest estimated yield (7.7 tonnes in 1991) with annual mean flow of 12.09, then the adjustment for an average year is $(13.5/12.1)^{1+.69} = 1.20$, giving a yield of 9.27 tonnes. This value is well below the estimated yield for those years with flow close to the mean, suggesting the proposed natural estimator of an adjusted yield may be a poor one.

5.51 A further temporal effect on the Tame is a significant decline (t=-7.7; p=0) in the estimated intercept of the rating curve. The standard error of each individual intercept estimate is of the order of 0.1 (except 1974, 1975) with a decline from 3.38 (se 0.03) in 1974 to 2.60 (se 0.10) in 1995. A likely cause of this is improvements to discharges from point sources. However, the decline in estimated yield over the period is not significant (p=0.2). This example is a reminder that any estimate of temporal effect due to weather variables may be confounded by longer term temporal trends.

5.52 The two groups of catchments in Yorkshire (3) and the Midlands (4) are all of the “low permeable other” catchment type. Their annual yield has been computed for each year of data for each site using the rating curve method with EA routine monitoring data at one to two week intervals. Rating curves have been fitted using point concentration measurements and daily mean flows, in the absence of point flow measurements. The annual mean flow has been scaled to mm day^{-1} equivalent, and the yield/discharge relationship shown in Figure 16.

5.53 The figure shows straight line fits for each catchment, and a combined fit. There is no clear distinction between the individual lines, but the combined fit gives r^2=.62. The fitted line suggests that an increase in annual mean flow of 1mm day^{-1} will generate an increase in yield of 16 tonnes km^{-2}. The quality of the combined fit suggests the fitted line and its prediction interval might be used as a “target area” for new catchments. However, the seven catchments selected do not represent the full range of sediment yields for this typology. All are located in Eastern England and have yields at the low end of the range of 20-50 t km^{-2} yr^{-1} identified in the typology definition. Adjustments for temporal variability might be based on regional coherence in the behaviour of catchments within a typology.

5.54 With one year’s data available for a new site, a rating curve would be used to generate an estimate of sediment yield and its standard error. If in the first instance a new site fell outside the main target value and investigation threshold (20 and 50 t km^{-2} yr^{-1} respectively for ‘low permeable other’ type), its behaviour in relation to local catchments using a local prediction interval such as shown in Figure 16 might be investigated. In addition to a direct comparison at the measured flow, an estimated long-term flow could be made by a proportionality argument with local streams having both a long-term value and a flow record for the monitoring year. A predicted yield in a typical year would then be found by moving along the regional regression line to the location of the simulated long-term flow at the new monitored location. This is shown schematically in Figure 17.

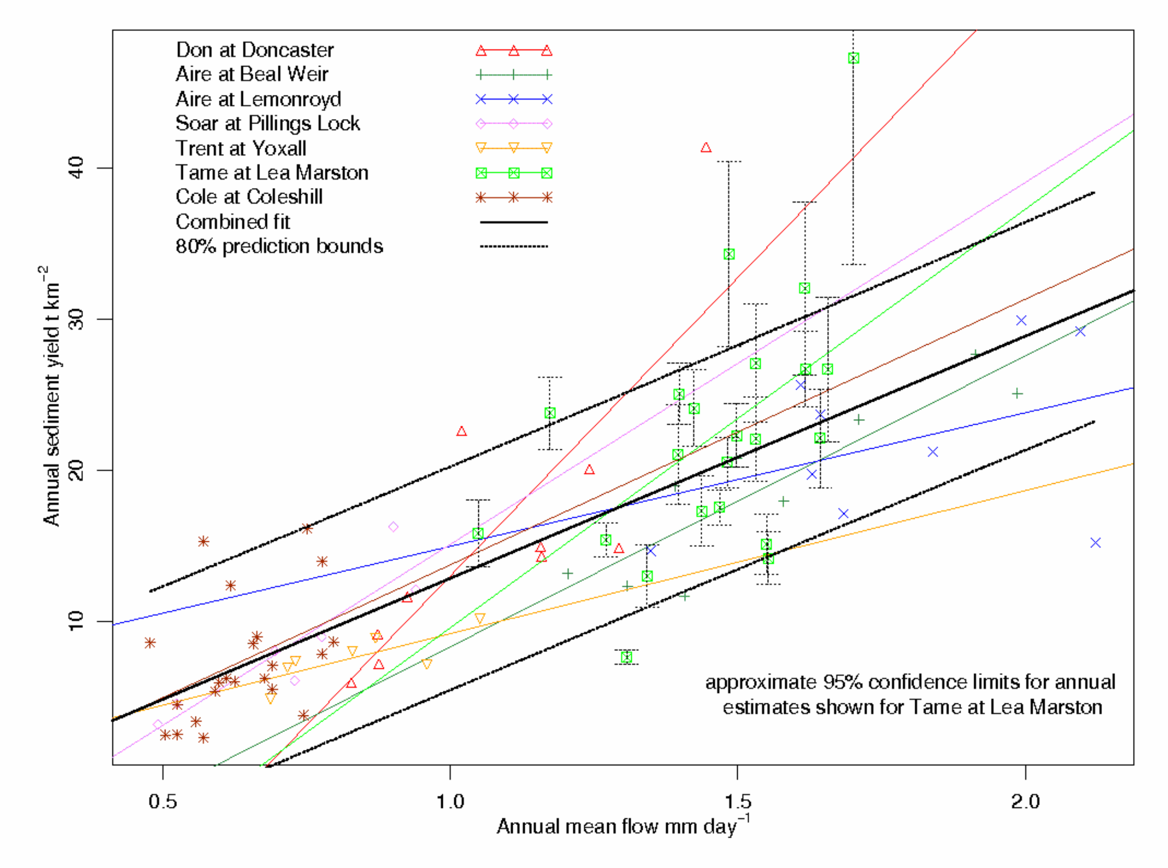


Figure 16 Annual rating curve estimates of yield against flow, selected catchments

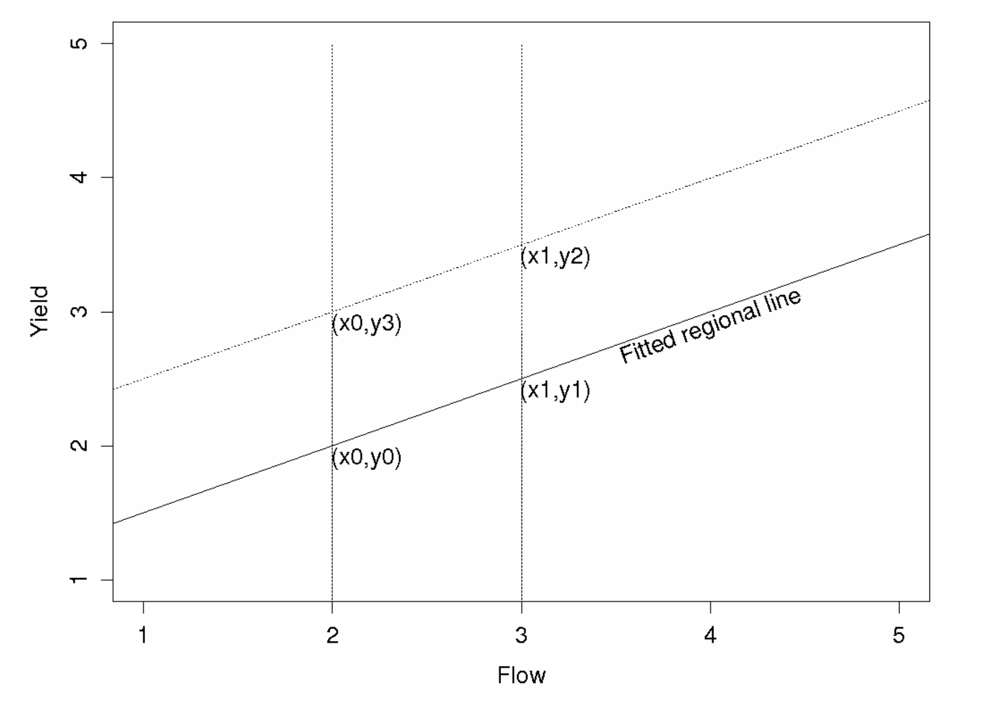


Figure 17 Schematic diagram for temporal yield adjustment

5.55 In Figure 17, x1 represents the flow over the monitoring period at the new site within a regional group. It is assumed that data from other sites in the region give the regional proportion p by which the flow during the monitoring period differed from the long-term mean flow. The value x0 is then set to x1/p, an estimate of the long-term mean flow at the new site. In Figure 17, p is 1.5. The (simulated) yields y0 and y1 are estimated from x0, x1 and the fitted regional line. The yield y2 is estimated over the monitoring period at the new site, and the mean annual yield at the new site to be estimated is y3. The upper dashed line parallel to the fitted regional line may not be the best representation of the rating curve at the new site, but if annual estimates are sparse there is no reasonable alternative based on data from the new site alone. Evidently under the assumed model y3=y0+(y2-y1), it may be preferable to use both a regional regression line and a new site estimated rating curve which go through the origin, in which case the alternative value of y3 can readily be computed. Both these approaches are alternatives to the ratio method described earlier. The estimate y2 will have an associated standard error, and a standard error for y3 should also be sought. The choice of a suitable value requires further statistical investigation, but as a first approximation the standard error of y2 may be used.

5.56 Procedures such as rating curve methods, which use modelled values of yield rather than measured values, are dependent on the adequacy of the model as applied to the available data. The results presented here also use point concentrations with daily flow values to estimate rating curves, a procedure which will introduce further error. Point flow measurements are potentially available and should be used in preference. Since the EA data we have used are collected weekly or fortnightly, and do not include automatic sampler data through high flow events, poor estimation of yields might be expected, and this should be reflected in large computed standard errors. The inclusion of data from automatic samplers should provide better estimates, although the LOIS example data have shown that caution should be exercised in mixing manual and automatic sampling, and the extrapolation of a rating curve computed over one period for use in another period may also be unreliable.

5.57 The example shown refers only to a single catchment type (“low permeable other”) for which suitable data were available. It is likely that a similar approach could be used for remaining catchment types having an approximately monotonic relationship between discharge and sediment concentration. This is in line with recommendations from the PSYCHIC project which are that routine sampling and continuous flow records to generate a flow/concentration relationship are probably sufficient for load estimation in high baseflow catchments. Where there is not a strong relationship between suspended sediment concentrations and discharge, a rating curve estimate of sediment yield will be inappropriate and the ratio method will be more suitable for sediment yield estimation. In the special case of chalk catchments, it is clear from Figure 12 (Section 3) that while routine sampling and continuous flow records may be suitable, using the ratio method, for estimating sediment yield in these catchments, short-lived high sediment concentrations in response to runoff events (rather than groundwater which dominates the seasonal hydrograph response) may be more critical for ecological sensitivity. To capture these events requires continuous turbidity measurements.

Other characteristics of sediment delivery

5.58 Following Walling and others' initial investigation of typologies for sediment in rivers and the need for linkage to catchment management, the focus of our work has been on annual sediment yield. This variable has been used both for defining typologies and in the context of compliance testing. We have also examined rating curves for a number of catchments and explored their use in the practical estimation of sediment yields. However, the suspended sediment/discharge relationship also provides detailed information on catchment response which is lost if the data are used only for yield estimation.

5.59 The suspended sediment/discharge relationship reflects the mobilisation and availability of suspended sediment in different catchments, and shows detail of concentrations in different flow ranges which is lost in aggregating data for yield estimation. This variation with discharge is likely to be of great ecological importance. It is possible for catchments having the same area-adjusted sediment yield to have quite different patterns of sediment transfer, with distinct ecological consequences.

5.60 Section 3 and Appendix 1 give examples of the relationship between suspended sediment and discharge. A number of regularities are seen. One common feature is a threshold discharge below which concentration is fairly constant, and above which there is a notable increase in concentration with discharge. The location of the threshold is assumed to be related to the availability of material. Rivers which carry sediment at low discharge generally have readily available sources of sediment - possibly including allochthonous material and point source discharges. More active rivers have little fine bed material and fine sediment only reaches the river from soil erosion from the land or from active bank erosion. Dependent on the coincidence of the water and sediment waves, this may be rapidly moved through the catchment without significant within-river deposition. Once flows decline or sediment sources are exhausted, concentrations return to very low values. Hysteresis patterns can provide valuable information on such behaviour and the propensity for sediment deposition in individual events.

5.61 Rivers which carry sediment even at very low flows are likely to have muddy bed habitat which is particularly suitable for some river ecologies rather than others. From an ecological perspective, such information might be important in defining typologies, but this information is not contained in yield estimates alone and, indeed, it may be only weakly related to sediment delivery processes.

5.62 For some rivers carrying sediment at low flows there may be no threshold discharge, but a steady increase in concentration as discharge increases. For other rivers which do show a threshold, this may indicate the discharge at which delivery from soil erosion commences, or the discharge which is sufficiently energetic to mobilise bed/bank materials or tap into fine materials deposited within riverine dead zones. At discharges well above the threshold, suspended sediment concentrations reflect the stream power at the specified discharge, and the availability of sediment of mobilisable size. Mountain streams with very coarse stream sediment will generally show high suspended sediment concentrations only under the highest discharge conditions when the gravel bed is mobilised. The ecology of such streams is again likely to be distinctive.

5.63 The incorporation of concentration/discharge information into typology definition is therefore likely to be of great value ecologically, since more subtle effects than annual yields can be accommodated. This requires some selection of standardised statistics for inclusion in procedures for typology definition. A typology is then defined in terms not only of sediment yield, but also various characteristics of the concentration/discharge relationship. This is then a multi-criterion definition, which traditionally would be approached using some form of canonical correlation analysis to relate typology classification to catchment characteristics. Such an approach is taken in the RIVPACS procedure (Wright and others 1998). A multi-criterion version of the tree algorithm we have used is provided by De'ath (2002). However, compliance assessment with several criteria requires assignment of weights, and the definition of targets becomes more complex. Measurement at a new location may indicate compliance for some criteria, but not for others. In these circumstances, some overall measure of compliance may be required.

5.64 An alternative to using suspended sediment/discharge parameters in typology definition is to use parameter variability within types. High yields within a type may be associated with particular characteristics of the suspended sediment/discharge relationship. In such cases, examination of a scatter plot is likely to provide greater insight than the yield alone. For example, high yield might be due to persistent sediment transport even at low flows, or to a few high-yielding events. Such alternatives might suggest different approaches to catchment management to control sediment transport. Characteristics of the relationship need not necessarily form part of target-setting but will form a valuable part of the assessment of an individual catchment and its response to changes in catchment management.

5.65 There are clearly some catchments (chalk, for example) where there is no relationship between concentration and discharge apparent from a simple scatter plot. Nevertheless, the sediment-generating mechanism is not an entirely random process, and the scatter plots represent a mixture of processes. In these cases, it is necessary to distinguish between high flows generated by groundwater and those associated with catchment runoff processes. The form of parameterisation this might take is likely to require modelling, using data from a number of individual catchments.

5.66 Good concentration/discharge data are at present limited to a small number of projects such as LOIS, LOCAR and PSYCHIC. While these data are excellent, they do not provide sufficient national cover to generate typologies or targets. Other data has been gathered in a large number of PhD studies but access to these data is limited. There is a large volume of data held by the EA which are suitable for a study of discharge/suspended sediment relationships. While EA data tend to be biased towards locations on larger rivers and downstream of STWs, a fuller investigation of this data set might be fruitful.

6 Discussion on operational application of findings

6.1 In this project we have analysed existing data in an attempt to improve upon currently proposed catchment typologies to make them more appropriate to setting targets for sediment yield. We have then sought to determine sediment yield targets for each catchment type and compare them with other evidence on historic sediment yields which may be more representative of reference conditions. The use of rating curves in target-setting, the extent of existing information on the sensitivity of biota to sediment and the various issues associated with assessing whether targets are being met have also been explored. Our findings are summarised below and a number of unresolved issues are raised.

Typology

6.2 The WFD and Walling and others catchment typologies provide a possible basis for classifying catchments for the purpose of identifying sediment yield characteristics. Statistical analysis based on the high quality sediment yield data collated by Walling and others (2008) suggests sediment yields from many of the catchment types are indistinguishable. In some cases this is because they are poorly populated by catchments with available data. In other cases, even though there are adequate data, the distribution of sediment yields is indistinguishable between types.

6.3 We have, therefore, sought a rational statistical procedure for defining a new typology using available catchment characteristic data. Regression and recursive partition analysis provide a reduced set of catchment types using soil, altitude and catchment permeability characteristics. These have a clear scientific interpretation. The ratio of between- to within-type variability is much higher for this new typology than for the WFD and Walling and others typologies, enabling more realistic targets to be set for each catchment type. While the new types are readily computed for England and Wales catchments, a disadvantage is that they introduce new classifiers based on permeability and HOST class, and also an altitude split which is not consistent with the WFD reporting typology being used for river water bodies. The classes identified are described in Table 9 below. In deriving the typology, we have had to use available data rather than data from sites in reference condition. This means that we have not been able to exclude the influence of catchment management. In general, we hope that catchment management issues are more limited to within-type rather than between-type variation, and this seems to be borne out to a certain extent by examination of sediment core data.

6.4 Comparison of the typologies suggests that there is little statistical basis for using catchment area in defining typology, but that it is insufficient to class all low altitude agricultural land as the same type. There is a clear, and understandable, distinction between chalk catchments and others. The present data also do not provide any statistical basis for defining a separate urban type.

Identification of target yields

6.5 We have taken a pragmatic view of target setting and suggest making use of the lower and upper quartiles of the available data. The values of these quartiles are shown for each of the catchment classes in Table 9. It should be noted that we have no example catchments for the classes “low impermeable peat” and “high permeable other” shown in brackets in Table 9. In the UK, “chalk” catchments do not occur at high altitude.

Table 9 Summary of catchment types and associated sediment yields

Type description	Catchment properties	Lower quartile sediment yield t km^{-2} yr^{-1}	Upper quartile sediment yield t km^{-2} yr^{-1}
High impermeable peat (and low impermeable peat)	HOST 29 > 25%	(50) (no data)	(150) (no data)
Low permeable Chalk	HOST 1 > 25%	2	5
High impermeable other (and high permeable other)	HOST 29 < 25% HOST 1 < 25% Altitude > 330m	10 (no data)	20 (no data)
Low impermeable other	HOST 29 < 25% HOST 1 < 25% Altitude < 330m SPR > 40%	40	70
Low permeable other	HOST 29 < 25% HOST 1 < 25% Altitude < 330m SPR < 40%	20	50

Figures shown in brackets are suspected of being inappropriately high due to anthropogenic impact

6.6 In a pragmatic approach to target setting, we have assumed that the lower quartile can be considered as guideline target values for management purposes, while we propose that the upper quartile be used to trigger further investigation. Clearly, the available data cover catchments with different levels of anthropogenic impact. We have, therefore, assessed the proposed target values in two ways.

6.7 First, assuming that land cover provides an adequate descriptor of anthropogenic impact, we have investigated how sediment yield varies with the proportion of cropped and urban/suburban land cover within those catchment types for which there are sufficient data. As shown in Figure 10, there is no separation of high and low sediment yield according to land cover. This may be because catchment percentages of land cover are only crude approximation of anthropogenic impact. It does not take into account land management practices, proximity of sediment sources to the river system nor the effect of other activities on sediment yield. A more detailed assessment of anthropogenic impact would use field data for individual catchments.

6.8 Secondly, we have assessed the suggested target values against historical sediment yields and other estimated yields available in the literature. Sediment yields for both historical and recent periods derived from reservoir/lake cores are presented in Table 4. Increases in sediment yield have been attributed to agricultural expansion, increased livestock numbers and land drainage. The last two of these would not be picked up in our analysis of land cover as a descriptor of anthropogenic impact. Of the data relating to the historical period, many of the catchments are woodland and suggest much lower sediment yields than the proposed values given in Table 9. They are in the range of 5-12 t km^{-2} yr^{-1}. For non-woodland catchments, yields tend to confirm or be slightly lower than the values given in Table 9, for example 15 t km^{-2} yr^{-1} compared to 20 t km^{-2} yr^{-1} for the "low permeable other" category and 32 t km^{-2} yr^{-1} compared to 40 t km^{-2} yr^{-1} for the "low impermeable other" category. This discrepancy probably arises because of slight differences, such as in predominant location, between the reservoir/lake core sub-population and the catchment sub-population used for typology definition. In the longer term, these new data might be used to refine the typology. However, given uncertainty in measurements and the unknown influence of climate, we suggest retaining the target values given in Table 9 for these categories.

6.9 The “high impermeable peat” category gives us greatest concern regarding the use of the quartiles as a proposed target value. For this reason the figures are shown in brackets in Table 9. The catchments from which this is derived are all located within the southern Pennines, an area which is known to be highly eroded due to both over-grazing and footpath erosion, severely affected by loss of Sphagnum due to industrialisation, and subject to moorland gripping and heather-burning (Tallis, 1998). Furthermore, the estimates are derived from repeated bathymetry, a technique which can have a questionable accuracy (Foster and Lees, 1999). A published estimate of sediment yield in 1980 for Great Eggleshope Beck in the more northern Pennines which also falls into this category is 12 t km^{-2} yr^{-1} (Carling, 1983). This may represent estimates more related to reference conditions. Further measurements of sediment yield for less anthropogenically-impacted peat catchments are needed to refine this target.

6.10 Other evidence that the typology and target values need further refinement comes from our analysis of EA data for many catchments in Yorkshire and the Midlands. While not of the highest quality for yield estimation, the estimated values for these “low permeable other” catchments are lower than expected. This is supported by recent high-resolution data for the Tern catchment collected within the LOCAR project and suggests that a refinement of the typology should be considered. Data from a large number of other EA monitoring sites in England and Wales might be analysed to give a more comprehensive assessment of the typology.

Application of typology and use of target/threshold values

6.11 In the course of this project, a number of issues relating to the application of the typology and the use of sediment yield targets have arisen. These are discussed below.

Typology

6.12 The derived typology has been defined on a catchment basis. It can, therefore, be applied to any point from which a catchment can be defined eg any water course or standing water body. It was originally intended that mapping would be undertaken using the WFD-defined water body ‘catchments’ in England and Wales. However, each mapped water body ‘catchment’ is not a true hydrological catchment, but rather a local drainage region. The catchment type of the water body must be based on the whole upstream drainage area, but application of the typology to the WFD waterbody ‘catchment’ map would result in typing based on only a small subset of that drainage area, resulting in widespread mis-classification.

6.13 Sediment yield targets need to be set on the basis of both the nature of the catchment generating the sediment, and the nature of the receiving water. In large catchments, we need to be able to preserve information relating to the upper catchment, in terms of both its sediment yield characteristics and its ecology. This requires nesting of catchments progressing down the drainage network, something that is difficult to depict on a 2-dimensional map. Consequently, a more appropriate means of mapping would relate to points on the river network - each point would be labelled with its catchment type (and implied target yield). Due to this nesting, the ecological narratives in Appendix 2 relate to the habitats that tend to be found around the foot of each catchment type, excluding any habitats that may occur in the upper catchment.

6.14 When evaluating or managing a catchment, this implies that a number of strategic points on the surface water network could be selected and the catchments draining to these points delineated using an appropriate resolution digital elevation model. Classification of each catchment according to the proposed typology requires determination of the average altitude (which can be derived from the DEM) and access to the HOST spatial database. The SPR used in the classification was derived from the HOST database (Boorman and others 1995). HOST class is available at a 1km grid resolution, either as proportions or as the dominant value over the grid square. A 1km grid resolution may be coarse in relation to the size of some catchments, and it is desirable in classifying catchments to ensure that any partial grid squares are suitably accounted for. The coarseness of the grid will be one of the sources of uncertainty in estimating the typology of some catchments. The necessary GIS operations are essentially straightforward and may be carried out using, for example, ArcGIS macros.

6.15 Generic information on ecological sensitivities, derived from the narratives in Appendix 2 would then be related to each of the strategically-defined points, and, depending on the specific habitats found around these points, a more or less precautionary view of sediment yield targets could be taken.

Use of targets

6.16 In our pragmatic approach to target-setting, we assumed that the lower quartile of the sediment yield distribution provided us with an estimate of target sediment yields which may be close enough to reference conditions to protect aquatic ecosystems. With the exception of peat catchments, some independent confirmation of this was provided by historical sediment yield data. The lower quartile value therefore provides an ideal management target in cases where there is good evidence for high ecological sensitivity to sediment. However, estimates of sediment yield even from high quality data have a degree of uncertainty and considerable variation (generally more than a factor of two) from year to year (eg Figure 14). This means that, even for target conditions, there will be a fairly wide distribution of sediment yield values. Given this, we proposed that the upper quartile of the distribution of sediment yields within each catchment type be used as a threshold to trigger investigation into the causes of the high yield as these pose the greatest potential risk and are therefore a priority in terms of investigation.

6.17 Given the variability in sediment yield and the lack of a well-defined quantitative link between sediment yield and ecological status, this may be thought of as a realistic approach to determining the need for investigation. However, the implementation of the lower and upper quartiles is obviously open to refinement, other interpretation and use in other ways. For example, for water bodies where there is known to be high ecological sensitivity to sediment, it may be more appropriate to initiate an investigation into the causes of sediment delivery and possible mitigation measures for much lower observed sediment yields. Indeed, in cases where there are silt-related concerns, a preferred approach is through a full catchment appraisal, including fluvial audit and analysis of suspended sediment and flow data. These can then be used alongside the typology and targets presented here to come to a local decision about what might be a sensible target or targets and the possible management scenarios likely to achieve that target. Considering the proposed strategy for applying sediment yield targets to a specific catchment described in Walling and others (2008), the generic sediment targets described in this report simply contribute to one element of the process (see Figure 18).

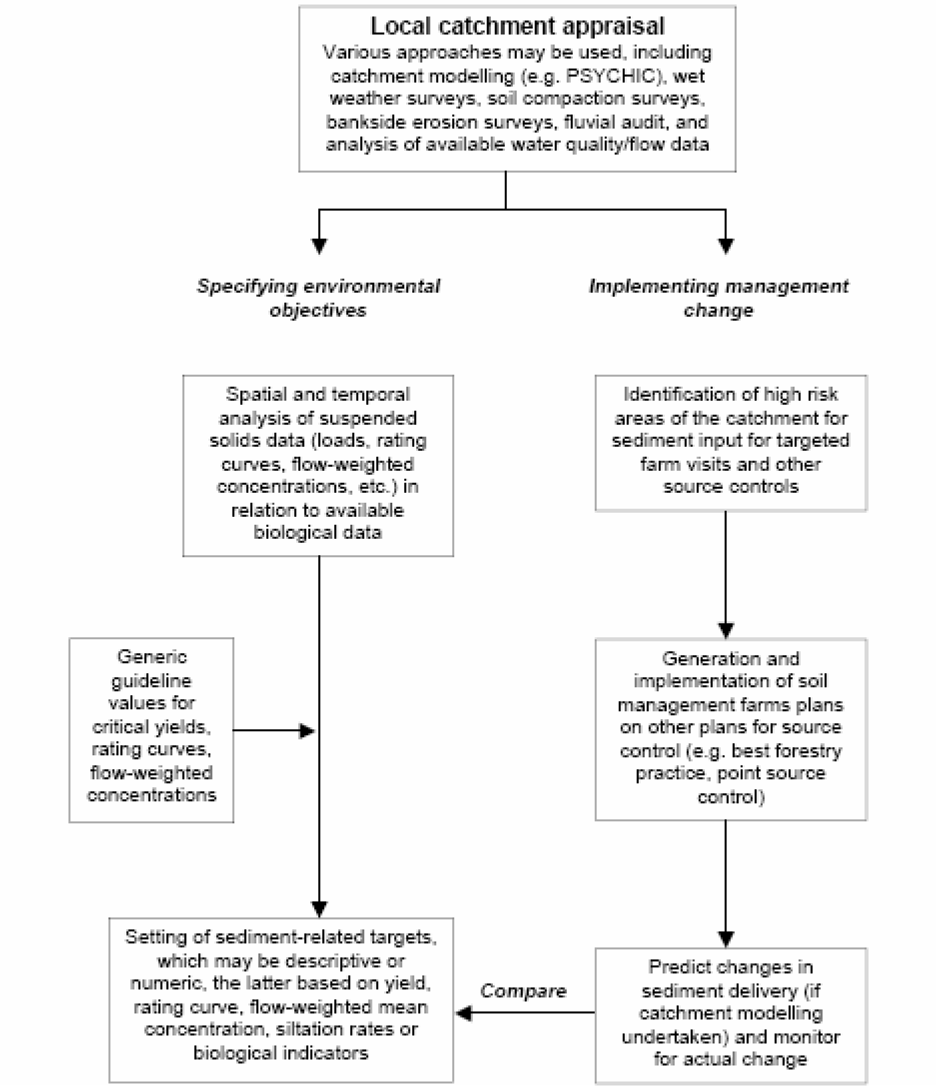


Figure 18 Contribution of this work to the proposed strategy for the application of sediment yield targets (after Figure 4.3 of Walling and others (2008))

Exploration of rating curves

6.18 Walling and others (2008) suggested that rating curves, relating suspended sediment concentration to flow, might be used to provide a better link between sediment yield data and ecological sensitivity. Published rating curves have limited value in that they often give no indication of the degree of fit or the standard error of rating curve parameters. We have, therefore, explored rating relationships for those catchments for which we have access to the raw data. Twenty-four of these are shown in Appendix 1. It is clear from these plots that the use of rating curves in relation to sediment targets is not straight forward. No clear straight line relationships hold, hysteretic behaviour is highly variable and, for chalk streams, high sediment concentrations are often unrelated to high flows. Nevertheless, information in the discharge/suspended sediment relationship, when quantified, is of potential value either in defining typologies or investigating the within-type behaviour of individual catchments. Particular associations of discharge and concentration are likely to have distinct interpretations in terms of ecological effects, providing greater insight than provided by a yield estimate alone. The study of hysteresis within an individual catchment can also provide valuable insight into the type of events which may lead to deposition of fine sediment. Rating curves, in the broadest sense of the term, should therefore be investigated in all cases where further understanding of the impact of sediment and a need to manage sediment inputs is required.

Assessment of observed values of sediment yield against target values

6.19 By whatever means the proposed target values are implemented, we require estimates of sediment yield for each catchment of interest which can be compared to these targets. True measured yields for use in testing of catchments against target or threshold values can in principle be determined using continuous monitoring, but this requires substantial resources of expertise and instrumentation. This is likely to be impractical.

6.20 Yield estimation using less intensive sampling requires fewer resources and is a more practical means of assessing sediment yields, particularly if a mixture of routine monitoring measurements and automatic samplers is used. At the least this requires continuous flow measurement and large numbers of suspended sediment samples from both baseflow and a range of flow events. Methods of estimating sediment yield from such data were described in Section 5. For all catchments, the so-called “ratio method” may be used. In some catchments, rating curve methods may prove more useful. The estimated sediment yields will generally have high variance, and may lack robustness if they are model-based (rating curves). However, they do provide a practical alternative to continuous monitoring. The inclusion of estimated standard errors then allows a statistical comparison with the relevant target value. An analysis of sediment yields based on continuous, automatically sampled, and Environment Agency data for a range of catchments within the “low permeable other” category has been presented. It shows how estimated values may under or over-estimate the true sediment yield quite widely. This argues for a ‘soft’ management approach to applying the suggested targets and investigation thresholds, to ensure that significant management action is not undertaken unnecessarily.

6.21 The other issue that we have addressed is how to deal with temporal variability. The high quality sediment yield data collated by Walling and others (2008) generally only relate to three or fewer years of measurement or are a long-term average from reservoir/lake records. Evidence from, for example, the LOIS and Plynlimon datasets, and from the Tame suggests that yields are highly variable from year to year and that the wettest years do not necessarily correspond to the highest yields. However, with the exception of the Tame, these findings only relate to a small number of years of measurement and so the question was approached through regional analysis of routine EA monitoring data for catchments in the “low permeable other” category in Yorkshire and the Midlands. This analysis suggests that there may be simple relationships between rating curve estimates of annual yields and flow within a catchment type, at least regionally. These may provide a realistic means of assessing sediment yield for catchments which account for between-year variability in flows and overcomes some of the difficulties associated with estimating temporal effects. The corollary of this analysis is that, within a catchment type, the annual flow for the catchment may be a cause of some of the observed distribution of sediment yields and is a factor which should be taken into account when assessing observed values against targets.

Some final comments

6.22 Sediment yield has been chosen as a test variable on the assumption that it can be related back to catchment management through models such as PSYCHIC and, in this way, make a connection between the desired target and appropriate action to reduce sediment yields. However, the link through to the ecology is tentative and there are clear difficulties in the use of this variable – first, in measuring yield accurately and, secondly, in accounting for bias associated with the measurement period. We have suggested how to approach these issues, while retaining the notion of annual sediment yield as a defining variable for both typology and testing catchments against target values.

6.23 Other options include the use of other variables in typology definition and as generators of target values. Many of these relate to the variation of suspended sediment with discharge, often expressed in terms of a rating curve, and further investigation of the potential use of different characteristics derived from plots of suspended sediment against discharge should be undertaken. Readily measurable variables known to have ecological impact would be natural candidates. In the case of spawning gravels, such variables might be inferred from experience with the SIDO model in the UK and might include suspended sediment concentrations, specifically silt and clay particle size fractions, at particular times of the year. Reference tests based on easily collected samples are also appealing. In view of the commonly observed importance of high flows in sediment mobilisation, one might for example sample during high flow events. If the suspended sediment concentration exceeded a reference value for k out of a pre-specified n samples taken under a suitably designed sampling regime, this might be taken as evidence that action was needed.

6.24 A scheme such as this would constitute a statistically verifiable ideal standard, and be analogous to the Bathing Water and UWWT Directives. Such an approach is both practically and theoretically more appealing than the use of the annual yield although, for the purposes of catchment management and linkage with tools such as PSYCHIC, the relationship between yield and characteristics derived from the “rating curve” will need to be established for each catchment type. Other candidate variables might be related to seasonal measures which relate more closely to life cycle stages of the biota. In the special case of chalk streams, where high sediment concentrations may not be related to discharge, it is particularly important to determine the sediment characteristic which has the greatest ecological impact. This may also involve further sediment characterisation in terms of both particle size and sediment oxygen demand.

7 Conclusions

1) An evidence-based typology for sediment delivery has been derived from available high quality sediment yield data. This maximises the between-type variation and is shown to perform better for sediment yield than other typologies.

2) In the absence of sediment yield data for reference sites, lower and upper quartiles are proposed as target and investigation thresholds for practical catchment management. The use of the lower quartile as a target is, in most cases, supported by historical data from sediment cores. We believe that the high values found in upland peat catchments are largely due to anthropogenic influence and further data are required to define a realistic target for this type of catchment.

3) Some exploration of sediment rating curves in relation to typology and target-setting has been undertaken. There is potential to take this work further in terms of understanding catchment behaviour and definition of parameters which relate to both sediment yield and ecological sensitivity.

4) There is limited on-going work on the linkage between biota and sediment yield. The need to quantify this linkage in order to define values of sediment yield, or other parameters likely to protect against sediment impacts, needs substantial strategic R&D.

5) The statistical rationale and process for comparing observed values with target values has been explored and practical suggestions for estimating yield and for dealing with temporal variability have been made. Further work is needed on detection of change.

8 Recommendations for future work

1) The typology of catchments and associated targets developed for sediment yield is based on existing high quality data. The data available were not specifically designed for this purpose and there is concern over both the spatial coverage and the level of anthropogenic impact in some catchment types eg upland peat. This affects both the scope of the typology and the proposed target values. To address this issue, we believe that better spatial coverage can be achieved through use of widespread suspended solids data held by the Environment Agency. While we accept that this is lower quality data in terms of sampling frequency, we believe that the data, with suitable screening and analysis, would help to address the problem of spatial coverage, This could then aid in identifying where the need for further high quality suspended sediment data or palaeolimnological studies to define sediment yields for reference conditions might best be focused.

2) More work is needed to explore the use of suspended sediment/discharge relationships, ie rating curves in the broadest sense of the term, in both target setting and understanding sediment behaviour in different catchment types. This should include the development of characteristics which are useful in the context of ecological sensitivity and which can also be related to sediment yield and hence to catchment management.

3) In terms of assessing compliance with targets, the issue of detection of change needs to be addressed - particularly in terms of specific characteristics, eg suspended sediment concentrations in specific flow ranges, where management action is most likely to generate reductions. This would involve definition of such characteristics, the devising of suitable sampling schemes and development of statistical methods to detect change.

4) The practical application of this work within individual catchments remains to be fully explored. This can only be done through working with staff from the relevant agencies in the field.

5) Fundamental to the sediment issue is the need to develop a quantitative link between sediment and its ecological consequences and to develop the ability to relate this to catchment management. To this end, we would stress the importance of adequately funded strategic R&D on the relationship between sediment delivery, depositional behaviour within habitats and biological consequence with and without geomorphological constraints imposed by river engineering. The greatest need for this is in the riverine context but consideration also needs to be given to other habitats including standing waters. It will require a multi-disciplinary approach considering the full range of biota vulnerable to excessive fine sediment delivery, and is likely to require three-dimensional modelling and new insights into methods for linkage across both temporal and spatial scales. It may also involve the development of existing models, such as SIDO in the context of salmonids. Given the complexity and scope of the work, the need will be for substantial collaborative funding from NERC, the Environment Agency, Natural England and Defra.

6) Work so far has only looked at suspended sediment (ie solids) in a broad sense. In relation to biological impact, characterisation in terms of particle size and oxygen demand is crucial and there is a basic need to address the lack of data relating to these variables.

9 References

ALONSO, C.V., THEURER, F.D. & ZACHMANN, D.W. 1996. *Sediment intrusion and dissolved oxygen transport model – SIDO.* Technical Report No. 5, USDA-ARS National Sedimentation Laboratory, Oxford, Mississippi. 269pp.

ANDERSON, J.M., DUNBAR, M. & FRIBERG, N. 2004. *Report on existing methods and relationships linking pressures, chemistry and biology in rivers.* REBECCA Deliverable D6, Contract No.: SSPI-CT-2003-502158, 137 pp. Available from: URL://www.rbm-toolbox.net/docstore/docs/3.1713.D6-uusi.pdf

BARNETT, V. & O'HAGAN, A. 1997. *Setting environmental standards*. London: Chapman & Hall.

BOORMAN, D.B., HOLLIS, J.M. & LILLEY, A. 1995. *Hydrology of soil types: a hydrologically-based classification of the soils of the United Kingdom*. Report No. 126, Institute of Hydrology, NERC.

BRONSDON, R.K. & NADEN, P.S. 2000. Suspended sediment in the rivers Tweed and Teviot. *Sci. Total. Environ*., 251/252, 95-113.

BUTCHER, D.P., and others. 1993. *Reservoir sedimentation rates in the Southern Pennines region, UK. In:* J. MCMANUS & R.W. DUCK, eds. *Geomorphology and sedimentology of lakes and reservoirs,* 73-93. Chichester: Wiley.

CARLING, P.A. 1983. Particulate dynamics, dissolved and total load, in two small basins, northern Pennines, UK. *Hydrological Sciences Journal*, 28, 355-375.

CARLING, P.A. 1984. Deposition of fine and coarse sand in an open-work gravel bed. *Canadian Journal of Fisheries and Aquatic Sciences*, 41, 263-270.

COOPER, D.M. & WATTS, C.D. 2002. A comparison of river load estimation techniques: application to dissolved organic carbon. *Environmetrics*, 13, 733-750.

DAVISON, P.S., WITHERS, P.J.A., LORD, E.I., BETSON, M.J. & STROMQVIST, J. (In Press). PSYCHIC – *a process-based model of phosphorus and sediment mobilisation and delivery within agricultural catchments in England and Wales*. Part 1 - Model description and parameterisation. J. Hydrol.

DE'ATH, G. 2002. Multivariate regression trees: a new technique for modelling species-environment relationships*. Ecology* 83(4), 1105-1117.

DEARING, J.A. 1992. Sediment yields and sources in a Welsh Upland lake-catchment during the past 800 years. *Earth Surface Processes and Landforms*, 17, 1-22.

ENVIRONMENT AGENCY. 2004. *River water bodies at risk of not achieving Water Framework Directive objectives due to diffuse sediment delivery pressures*. URL://www.environment-agency.gov.uk/commondata/acrobat/r_diff_seds_v1_1008189.pdf

FOSTER, I.D.L. 1995. Lake and reservoir bottom sediments as a source of soil erosion and sediment transport data in the UK. *In*: I.D.L. FOSTER, A.M. GURNELL & B.W. WEBB. *Sediment and water quality in river catchments.* John Wiley & Sons Ltd.

FOSTER, I.D.L. and others. 2003. Changing suspended sediment and particulate phosphorus loads and pathways in underdrained lowland agricultural catchments; Herefordshire and Worcestershire, UK. *Hydrobiologia*, 494, 119-126.

FOSTER, I.D.L. and others. 1985. *Earth Surface Processes and Landforms*, 10, 45-68.

FOSTER, I.D.L., GREW, R. & DEARING, J.A. 1990. Magnitude and frequency of sediment transport in agricultural catchments. *In*: J. BOARDMAN, I.D.L. FOSTER & J.A. DEARING, eds. *Soil erosion on agricultural land*, 153-171. Chichester: John Wiley and Sons.

FOSTER, I.D.L. & WALLING, D.E. 1994. Using reservoir deposits to reconstruct changing sediment yields and sources in the catchment of the Old Mill Reservoir, South Devon, UK, over the past 50 years. *Hydrological Sciences Journal*, 39, 347-368.

FOSTER, I.D.L. & LEES, J.A. 1999. Changing headwater suspended sediment yields in the LOIS catchments over the last century: a paleolimnological approach. *Hydrological Processes*, 13, 1137-1153.

FRASER, A.I., HARROD, T.R. & WALLING, D.E. 2000. *Sediment delivery from arable land and delivery to surface waters. Phase I: A pilot GIS feasibility study*. Final report to the Environment Agency.

GREIG, S.M., SEAR, D.A. & CARLING, P.A. 2005. The impact of fine sediment accumulation on the survival of incubating salmon progreny: Implications for sediment management. *Science of the Total Environment*, 344, 241-258.

HAINES-YOUNG, R.H. and others. 2000. *Accounting for nature assessing habitats in the UK countryside.* DETR.

HALL, D. 1967. The pattern of sediment movement in the River Tyne. *Int. Assoc. Hydrological Sc. Publ.,* 75, 117-140.

HARROD, T.R. 1998. *A systematic approach to national budgets of Phosphorus loss through soil erosion and surface runoff at National Soil Inventory (NSI) nodes.* Final Report to MAFF. MAFF project NT1014, SSLRC Project JF3818.

HARROD, T.R. and others. 2000. *Research on the quantification and causes of upland erosion.* Final report to MAFF (Project SP0402).

HEYWOOD, M.J.T. 2002. *Sedimentation of salmonid spawning gravels: an investigation of associated sediment dynamics in the Hampshire Avon catchment*. Unpublished PhD thesis, University of Exeter.

IMESON, A.C. 1970. *Erosion in three East Yorkshire catchments and variations in the dissolved, suspended and bedloads*. Unpublished PhD thesis, University of Hull.

KINNIBURGH, D.G. & NEWELL, A.J. 2003. *Water Framework Directive: Lake typology based on the BGS 1:625,000 and 1:250,000 digital solid geological maps*. ESRI Arcview legend prepared for the Environment Agency.

LAMBERT, C.P. & WALLING, D.E. 1987. Floodplain sedimentation: a preliminary investigation of contemporary disposition within the lower reaches of the River Culm, Devon, UK. *Geografiska Annaler*, 69A(1), 393-404.

MCHUGH M, and others. 2002a. *Prediction of sediment delivery to watercourses from land. Phase II*. R&D Technical Report No P2-209, Environment Agency, UK.

McHUGH, M., HARROD, T. & MORGA, R. 2002b. The extent of soil erosion in upland England and Wales. *Earth Surface Processes and Landforms*, 27, 99-107.

MILAN, D.J., PETTS, G.E. & SAMBROOK, G. 2000. Regional variations in the sediment structure of trout streams in southern England: benchmark data for siltation assessment and restoration. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 10, 407-420.

MORRIS, D.G. & FLAVIN, R.W. 1990. A digital terrain model for hydrology. *Proceedings 4th International Symposium on Spatial Data Handling, Zurich*. Vol. 1, 250-262.

NEAL, C. 1997. Introduction to the Special Issue of Hydrology and Earth Systems Sciences, the water quality of the Plynlimon catchments. *Hydrol. Earth. Sys. Sci.*, 1(3), 385-388.

NEWCOMBE, C.P. & JENSEN, J.O.T. 1996. Channel suspended sediment and fisheries: a synthesis for quantitative assessment of risk and impact. *North American Journal of Fisheries Management*, 16, 693-727.

NICHOLLS, D.J. 2001. *The source and behaviour of fine sediment in the River Torridge Devon and their implications for salmon spawning*. Unpublished PhD thesis, University of Exeter.

O'SULLIVAN, P.E. and others (eds). 1989. *Southwest England and the Shropshire-Cheshire Meres Excursion Guide A*. Vth International Symposium on Palaeolimnology, Cumbria UK. September 1989.

REED, D.W. and others. 1999. *Flood Estimation Handbook*. Centre for Ecology and Hydrology.

REISER, D.W. 1998. Sediment in gravel-bed rivers: ecological and biological considerations. *In*: P.C. KLINGEMAN, R.L. BESCHTA, P.D. KOMAR & J.B. BRADLEY, eds. *Gravel-bed rivers in the Environment*, 199-228. Colorado: Water Resource Publications.

SEAR, D.A. 1993. Fine sediment infiltration into gravel spawning within a regulated river experiencinf floods: ecological implications for salmonids. *Regulated Rivers Research and Management*, 8, 373-390.

SMITH, B.P.G., NADEN, P.S. & COOPER, D.M. 2002. Methods for the assessment and monitoring of siltation in SAC rivers. Part 3: Integrated assessment procedure. *Life in UK Rivers.* Report to Natural England. 46pp.

SMITH, B.P.G. and others. 2003. Characterising the fine sediment budget of the River Swale, Yorkshire, UK during the 1994 to 1995 winter season. *Hydrobiologia,* 494, 135-143.

TALLIS, J.H. 1998. Growth and degradation of British and Irish blanket mires. *Environmental Reviews,* 6(2), 81-122.

UKTAG. 2003. *Guidance on Typology for Rivers for Scotland, England and Wales.* URL://www.wfduk.org/tag_guidance/Article_05/Folder.2004-02-16.5312/TAG2003%20WP%202a%20%2803%29

UKTAG. 2004. *Type specific reference condition descriptors for rivers in Great Britain.* UK Technical Advisory Group on the Water Framework Directive. URL://www.wfduk.org/tag_guidance/Article_05/Type%20specific%20reference%20conditions/WP8a%20%2802%29%20Type%20Specific%20Reference%20Conditions%20for%20Rivers%20%28v1.%20PR1%2029.06.04%29

VENABLES, W.N. & RIPLEY, B.D. 1994. *Modern applied statistics with S-Plus*. Springer-Verlag.

WALLING, D.E. & AMOS, C.M. 1999. Source, storage and mobilisation of fine sedidment in a chalk stream system. *Hydrological Processes*, 13, 323-340.

WALLING, D.E. and others. 2003. Changes in the fine sediment dynamics of the Ouse and Tweed basins in the UK over the last 100-150 years. *Hydrological Processes*, 17, 3245-3269.

WALLING, D.E. and others. 2002. Establishing sediment budgets for two small lowland agricultural catchments in the UK. *Catena*, 47, 323-353.

WALLING, D.E. & WEBB, B.W. 1987. Suspended load in gravel-bed rivers: UK experience. *In:* C.R. THORNE, J.C. BATHURST & R.D. HEY, eds. *Sediment transport in gravel-bed rivers*., 691-723. Chichester: Wiley.

WALLING, D.E., WEBB, B.W. & SHANAHAN, J. 2008. Investigations into the use of critical catchment sediment yields for assessing and managing fine sediment inputs into aquatic ecosystems. *Natural England Research Report*, No. 007.

WARBURTON, J., EVANS, M.G. & JOHNSON, R.M. 2003. Discussion on 'The extent of soil erosion in upland England and Wales'. *Earth Surface Processes and Landforms*, 28, 219-223.

WASS, P.D. & LEEKS, G.J.L. 1999. Suspended sediment fluxes in the Humber catchment. *Hydrol. Proc.,* 13, 935-953.

WASSON, J-G., GARCIA, A . & VILLENEUVE, B. 2004. Regional models: Large scale evaluation of pressures / impact relationships across European Hydro-ecoregions. Examples from River Invertebrates. Ongoing work on regionalization. URL://www.rbm-toolbox.net/docstore/docs/3.936.J-GWasson_Regional%20models.pdf

WOOD, G. and others. 2003*. Erosion risk of catchments in England and Wales Environment Policy.* Risk and Forecasting report no. 45.

WOOD, P.J. & ARMITAGE, P.D. 1997. Biological effects of fine sediment in the lotic environment. *Environmental Management*, 21, 203-217.

WRIGHT, J.F., FURSE, M.T. & MOSS, D. 1998. River classification using invertebrates: RIVPACS applications. *Aquatic conservation – marine and freshwater ecosystems*, 8, 617-631.

Appendix 1 Sites used in analysis and example rating curves

Table A Catchment list, yield and 3 typologies

Index	Easting	Northing	Name	Yield	Typology		
					Walling	WFD	New
4	406150	428800	Mixenden	11.00	1	38	lio
5	413600	404050	Snailsden	289.46	1	44	hip
8	403850	415300	Deanhead	37.90	1	38	hip
9	283550	130500	Blackball stream at Lyshwell, Devon	4.00	1	38	hio
10	414050	405700	Holme Styles	2.90	1	38	hpo
11	391150	423000	Gorpley	143.34	1	44	hip
12	414750	442850	Reva	286.14	1	38	lio
13	403500	401900	Chew	212.69	1	44	hip
14	399900	454400	Embsay	165.39	1	38	hip
15	399100	416500	Green Withens	21.73	1	44	hip
16	392550	431500	Gorple Upper	64.24	1	44	hip
17	411850	441950	Graincliffe	69.40	1	38	lio
19	401450	457650	Barden Upper	125.05	1	38	hip
20	446250	498550	Cod Beck	74.36	1	41	lio
21	421700	406100	Ingirchworth	88.25	1	41	lpo
22	404450	447650	Silsden	221.61	1	38	lpo
23	409800	412100	Blackmoor-foot	89.81	1	38	lpo
24	393650	432800	Widdop	101.30	1	38	hip
25	405550	388200	Kinder	135.14	1	38	hip
26	423200	390350	Strines	113.40	2	10	hip
28	421400	400150	Langsett	169.30	2	10	hip
29	426950	396100	Broomhead	51.00	2	10	hip
30	354950	662200	N Tyne	25.00	3	38	hpo
31	315500	657850	N Esk	26.00	3	38	hio

Table continued…

					Typology		
32	422550	390650	Loxley	49.70	3	44	hip
33	396050	353250	Churnet	6.70	3	11	lpo
34	454950	311150	Bradgate	45.60	4	2	lio
35	374650	602900	Rede	43.10	4	11	hip
36	355650	453800	Wyre	34.80	4	10	lip
38	430100	297150	Merevale Lake, North Warwickshire	9.00	6	40	lpo
44	314000	94800	East Devon catchment 3	50.00	7	41	lpo
49	356000	248000	Belmont (Rosemaund catchment), Herefordshire	81.90	7	40	lio
50	281750	42750	Stokely Barton, Slapton, Devon	31.26	7	37	lpo
52	285100	52150	Old Mill, Dartmouth Devon	54.00	7	37	lpo
54	432350	290700	Seeswood Pool, North Warwickshire	68.90	7	40	lio
55	432900	290450	Seeswood Pool, North Warwickshire	36.00	7	40	lio
56	435350	318200	Lower Smisby (Smisby catchment), Derbyshire	80.30	7	40	lpo
58	316200	99000	East Devon catchment 4	46.00	7	41	lpo
60	314100	93250	East Devon catchment 5	56.00	7	40	lpo
64	290250	98850	Jackmoor Brook at Pynes Cottage, Devon	30.00	7	2	lpo
65	281300	44550	Start, Slapton, Devon	9.67	8	1	lpo
67	397050	140000	Chitterne (Avon basin)	2.40	8	2	lpc
70	392000	127300	Sem (Avon basin)	9.20	8	2	lic
71	440150	279800	Coombe Pool, Warwickshire	36.00	8	2	lpo
72	282500	47650	Gara, Slapton, Devon	9.25	8	1	lpo
74	312850	87300	Sid	47.00	8	2	lpo
76	293600	107600	River Dart at Bickleigh, Devon	58.00	8	1	lpo
77	295850	112600	River Lowman at Tiverton, Devon	52.00	8	1	lpo
78	344100	255250	Stretford Brook (Wye basin)	13.20	8	2	lpo
79	377550	94100	River Piddle	11.00	8	2	lpc
80	295450	120900	River Batherm at Bampton, Devon	35.00	8	10	lpo
81	340100	228450	Worm Brook (Wye basin)	27.70	8	2	lpo
83	366650	248850	Frome (Wye basin)	40.50	8	2	lpo
84	413300	155900	West Avon (Avon basin)	4.70	8	2	lpc
85	413360	155970	East Avon (Avon basin)	4.95	8	2	lpc
86	356000	219300	Garron Brook (Wye basin)	20.10	8	2	lpo
88	298650	93650	River Clyst at Clyst Honiton, Devon	26.00	8	2	lpo

Table continued…

					Typology		
90	416100	126200	Ebble (Avon basin)	4.40	9	5	lpc
91	409750	130800	Nadder (Avon basin)	9.90	9	5	lpc
92	292700	125850	River Barle at Brushford, Devon	16.00	9	13	hio
98	293500	126000	Upper Exe at Pixton, Devon	19.00	9	13	lpo
102	409500	130950	River Nadder at Wilton	12.50	9	5	lpc
103	302200	106100	River Culm at Woodmill, Devon	32.00	9	5	lpo
104	248700	663500	White Cart	122.00	9	5	lpo
106	249600	106700	River Torridge, Devon	89.00	9	4	lio
108	290700	96100	River Creedy at Cowley, Devon	39.00	9	4	lpo
109	275650	651600	Avon	174.00	9	14	lip
110	295350	99800	River Culm at Rewe, Devon	20.00	9	5	lpo
112	415400	141950	River Avon at Amesbury	4.50	9	5	lpc
113	255850	666200	Kelvin	33.00	9	5	lio
114	294250	117850	River Exe at Stoodleigh, Devon	20.00	9	13	lpo
115	408300	134550	River Wylye at South Newton	1.40	9	5	lpc
116	389900	647700	River Tweed at Norham	11.60	9	16	lpo
117	442850	453050	River Nidd at Cowthorpe	17.10	9	4	lpo
118	422750	499400	River Swale at Catterick Bridge	58.40	9	13	hip
122	293600	101650	River Exe at Thorverton, Devon	40.37	9	13	lpo
124	239550	680500	Leven	36.00	9	13	lio
125	447750	444150	River Wharfe at Tadcaster	15.30	9	13	lio
127	439150	426600	River Calder at Methley Bridge	25.90	9	14	lpo
129	435500	467050	River Ure at Westwick Lock	35.40	9	14	lio
130	370200	628050	River Teviot	59.20	10	16	lio
131	456800	404000	River Don at Doncaster	12.60	10	8	lpo
132	441500	474850	River Swale at Leckby Grange	33.50	10	8	lpo
134	415800	114550	River Avon at East Mills	4.20	10	8	lpc
136	270400	657950	Clyde at Blairston	62.00	10	16	lio
137	267200	661600	Clyde at Daldowie	60.00	10	17	lio
138	453400	425550	River Aire at Beale Weir	21.60	10	8	lpo
140	456750	455350	River Ouse, Northeast England	23.00	10	8	lpo
144	479150	360150	River Trent at North Muskham	10.20	10	8	lpo
145	436250	283500	Wyken Slough, Warwickshire	10.00	11	40	lpo

Table continued…

					Typology		
146	370850	305850	Holmer Lake (Urban/mining)	20.10	12	40	lpo
147	447000	168200	Lambourn at Shaw	0.90	9	5	lpc
148	463600	174800	Pang at Tidmarsh	0.88	9	5	lpc
149	453750	173050	Pang at Frilsham	0.13	8	2	lpc
150	371850	96450	Piddle at Little Puddle	1.86	8	2	lpc
151	370850	90350	Frome at Loudsmill	4.74	9	5	lpc
152	386750	86800	Frome at East Stoke	6.61	9	5	lpc
153	412900	432950	Clayton Beck at Middlebrook	80.21	12	11	lpo
154	415150	437550	Bradford Beck at Shipley Weir	40.08	12	2	lpo
155	284300	287600	Tanllwyth	34.65	1	38	hio
156	282400	284150	Cyff	5.52	1	38	hio

Table B Catchment references

Index	Method	Reference
4	reservoir sedimentation	Butcher and others (1993)
5	reservoir sedimentation	Butcher and others (1993)
8	reservoir sedimentation	Butcher and others (1993)
9	continuous turbidity for 17-year study period	Walling and Webb (1987)
10	reservoir sedimentation	Butcher and others (1993)
11	reservoir sedimentation	Butcher and others (1993)
12	reservoir sedimentation	Butcher and others (1993)
13	reservoir sedimentation	Butcher and others (1993)
14	reservoir sedimentation	Butcher and others (1993)
15	reservoir sedimentation	Butcher and others (1993)
16	reservoir sedimentation	Butcher and others (1993)
17	reservoir sedimentation	Butcher and others (1993)
19	reservoir sedimentation	Butcher and others (1993)
20	reservoir sedimentation	Butcher and others (1993)
21	reservoir sedimentation	Butcher and others (1993)
22	reservoir sedimentation	Butcher and others (1993)
23	reservoir sedimentation	Butcher and others (1993)
24	reservoir sedimentation	Butcher and others (1993)
25	reservoir sedimentation	Butcher and others (1993)

Table continued…

Index	Method	Reference
26	reservoir sedimentation	Butcher and others (1993)
28	reservoir sedimentation	Butcher and others (1993)
29	reservoir sedimentation	Butcher and others (1993)
30	reservoir sedimentation	Ledger and others (1974) in Walling and Webb (1981)
31	reservoir sedimentation	Ledger and others (1974) in Walling and Webb (1981)
32	reservoir sedimentation	Young (1958) in Walling and Webb (1981)
33	reservoir sedimentation	Rodda and others (1976) in Walling and Webb (1981)
34	reservoir sedimentation	Cummins and Potter (1972) in Walling and Webb (1981)
35	reservoir sedimentation	Hall (1967)
36	reservoir sedimentation	Rodda and others (1976) in Walling and Webb (1981)
38	lake sediment cores	Foster and others (1990)
44	automatic sampling 1967-8	Walling (1971)
49	continuous turbidity plus automatic sampling 1997-99	Walling and others (2002)
50	1987-88	O'Sullivan and others (1989)
52	reservoir sediment cores 1942-1991	Foster and Walling (1994)
54	2-hourly turbidity meter records	Foster (1995)
55	reservoir sediment cores 1954-1995	Foster (1995)
56	continuous turbidity plus automatic sampling 1997-99	Walling and others (2002)
58	automatic sampling 1967-8	Walling (1971) in Walling and Webb (1981)
60	automatic sampling 1967-8	Walling (1971) in Walling and Webb (1981)
64	continuous turbidity for 17-year study period	Walling and Webb (1987)
65	1987-88	O'Sullivan and others (1989)
67	continuous turbidity plusautomatic samplers	PSYCHIC (pers. comm.)
70	continuous turbidity plusautomatic samplers	PSYCHIC (pers. comm.)
71	reservoir sediment cores 1946-1995	Foster (1995)
72	1987-88	O'Sullivan and others (1989)
74	automatic sampling 1967-8	Walling (1971) in Walling and Webb (1981)

Table continued…

Index	Method	Reference
76	continuous turbidity for 17-year study period	Walling and Webb (1987)
77	continuous turbidity for 17-year study period	Walling and Webb (1987)
78	continuous turbidity plus automatic samplers	PSYCHIC (pers. comm.)
79	continuous turbidity	Walling and Amos (1999)
80	continuous turbidity for 17-year study period	Walling and Webb (1987)
81	continuous turbidity plusautomatic samplers	PSYCHIC (pers. comm.)
83	continuous turbidity plusautomatic samplers	PSYCHIC (pers. comm.)
84	continuous turbidity plusautomatic samplers	PSYCHIC (pers. comm.)
85	continuous turbidity plusautomatic samplers	PSYCHIC (pers. comm.)
86	continuous turbidity plusautomatic samplers	PSYCHIC (pers. comm.)
88	continuous turbidity for 17-year study period	Walling and Webb (1987)
90	continuous turbidity plusautomatic samplers	PSYCHIC (pers. comm.)
91	continuous turbidity plusautomatic samplers	PSYCHIC (pers. comm.)
92	continuous turbidity for 17-year study period	Walling and Webb (1987)
98	continuous turbidity for 17-year study period	Walling and Webb (1987)
102	continuous turbidityFebruary 1999 to August 2000	Heywood (2002)
103	continuous turbidity for 17-year study period	Walling and Webb (1987)
104	continuous turbidity measurement1964-7	Fleming (1970) in Walling and Webb (1981)
106	continuous turbidity	Nicholls (2000)
108	continuous turbidity, 17 yrs	Walling and Webb (1987)
109	continuous turbidity 1964-7	Fleming (1970)
110	continuous turbidity, 17 yrs	Walling and Webb (1987)
112	continuous turbidity Feb 1999 to Aug 2000	Heywood (2002)
113	continuous turbidity 1967-8	Fleming (1970) in Walling and Webb (1981)
114	continuous turbidity, 17 yrs	Walling and Webb (1987)
115	continuous turbidity Feb 1999 to Aug 2000	Heywood (2002)
116	continuous turbidity	Bronsdon and Naden (2000)
117	continuous turbidity Nov 1994 to Oct 1997 plus automatic and manual sampling	Wass and Leeks (1999)
118	continuous turbidity Nov 1994 to Oct 1997 plus automatic and manual sampling	Wass and Leeks (1999)
122	continuous turbidity Jan to Dec 1983	Lambert and Walling (1987)

Table continued…

Index	Method	Reference
124	continuous turbidity 1966-7	Fleming (1970) in Walling and Webb (1981)
125	continuous turbidity Nov 1994 to Oct 1997 plus automatic and manual sampling	Wass and Leeks (1999)
127	continuous turbidity Nov 1994 to Oct 1997 plus automatic and manual sampling	Wass and Leeks (1999)
129	continuous turbidity Nov 1994 to Oct 1997 plus automatic and manual sampling	Wass and Leeks (1999)
130	continuous turbidity	Bronsdon and Naden (2000)
131	continuous turbidity Nov 1994 to Oct 1997 plus automatic and manual sampling	Wass and Leeks (1999)
132	continuous turbidity Nov 1994 to Oct 1997 plus automatic and manual sampling	Wass and Leeks (1999)
134	continuous turbidity Feb 1999 to Aug 2000	Heywood (2002)
136	continuous turbidity 1967-8	Fleming (1970) in Walling and Webb (1981)
137	continuous turbidity 1964-7	Fleming (1970) in Walling and Webb (1981)
138	continuous turbidity Nov 1994 to Oct 1997 plus automatic and manual sampling	Wass and Leeks (1999)
140	15 minute discharge and SS records, Jan 1995 to Dec 1996	Walling and others (1997)
144	continuous turbidity Nov 1994 to Oct 1997 plus automatic and manual sampling	Wass and Leeks (1999)
145	reservoir sediment cores 1954-95	Foster (1995)
146	reservoir sediment cores 1954-95	Walling and Webb (1987)
147	continuous turbidity plus automatic and manual sampling	LOCAR, Old (2006)
148	continuous turbidity plus automatic and manual sampling	LOCAR, Old (2006)
149	continuous turbidity plus automatic and manual sampling	LOCAR, Old (2006)
150	continuous turbidity plus automatic and manual sampling	LOCAR, Old (2006)
151	continuous turbidity plus automatic and manual sampling	LOCAR, Old (2006)
152	continuous turbidity plus automatic and manual sampling	LOCAR, Old (2006)
153	continuous turbidity plus automatic and manual sampling	Bradford Beck study, Old (2006)
154	continuous turbidity plus automatic and manual sampling	Bradford Beck study, Old (2006)
155	continuous turbidity plus automatic and manual sampling	Plynlimon: data for several years, Naden (2006)
156	continuous turbidity plus automatic and manual sampling	Plynlimon: data for several years, Naden (2006)

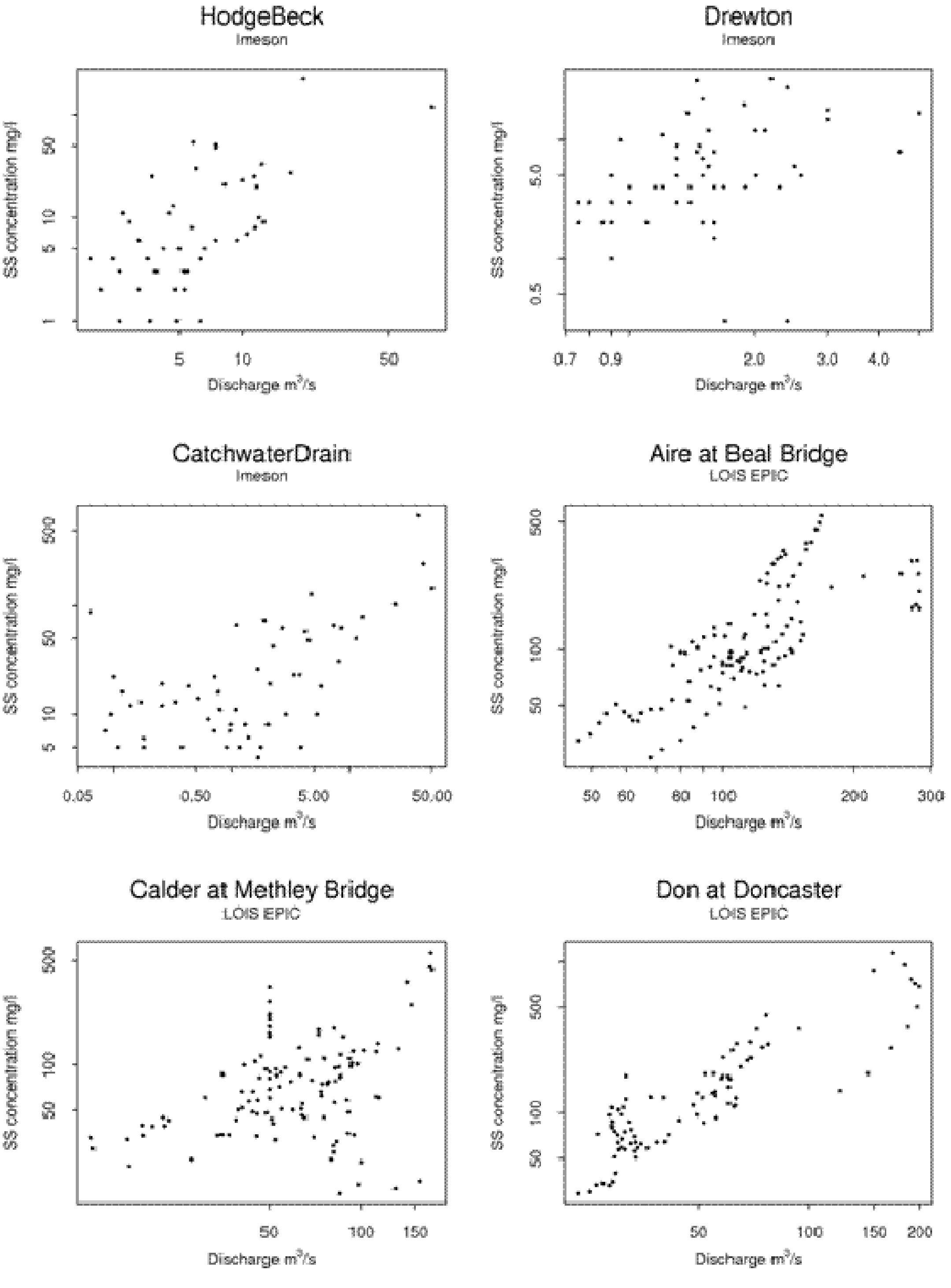


Figure A Rating curves for sites with raw data

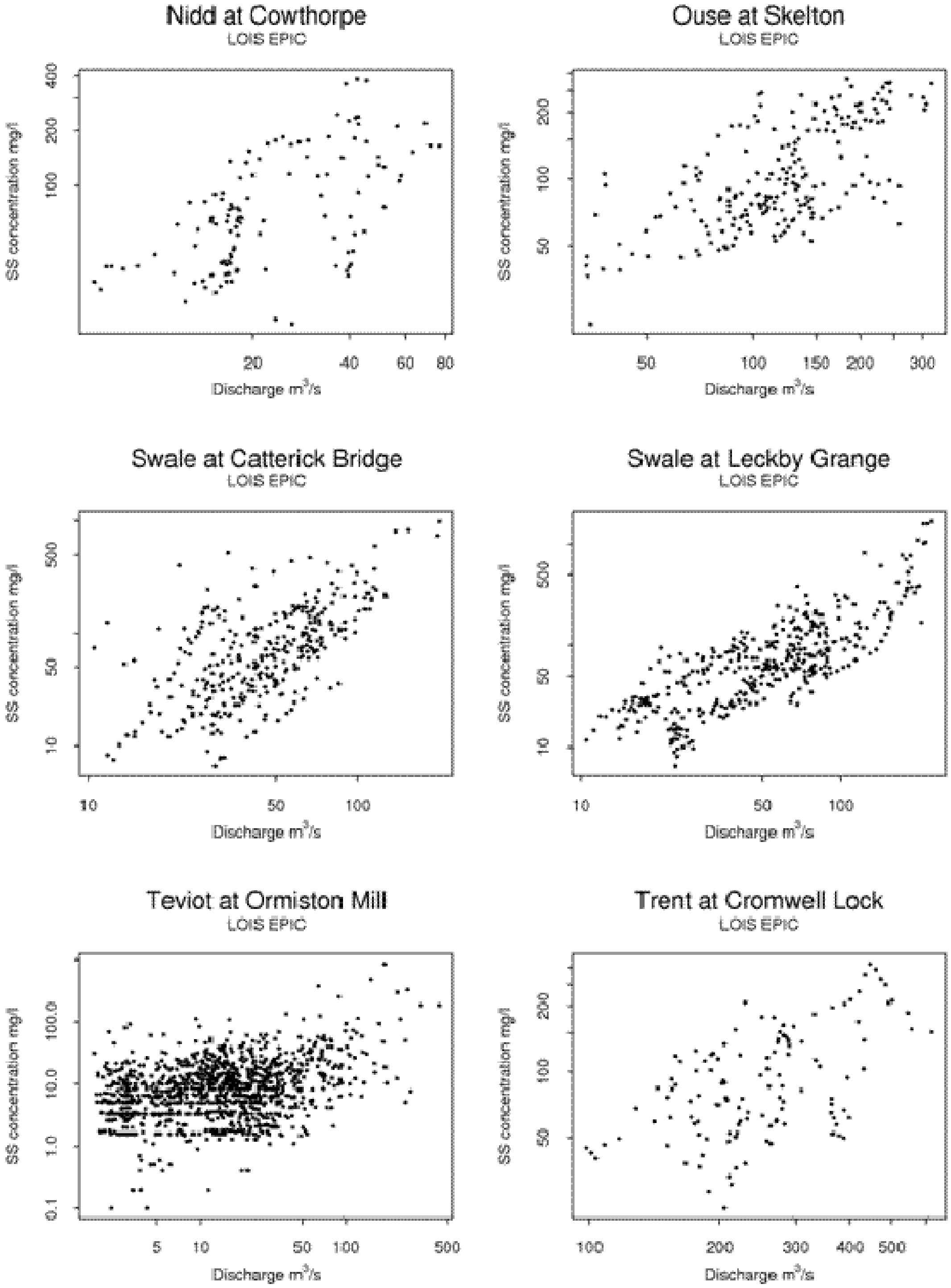


Figure B Rating curves for sites with raw data

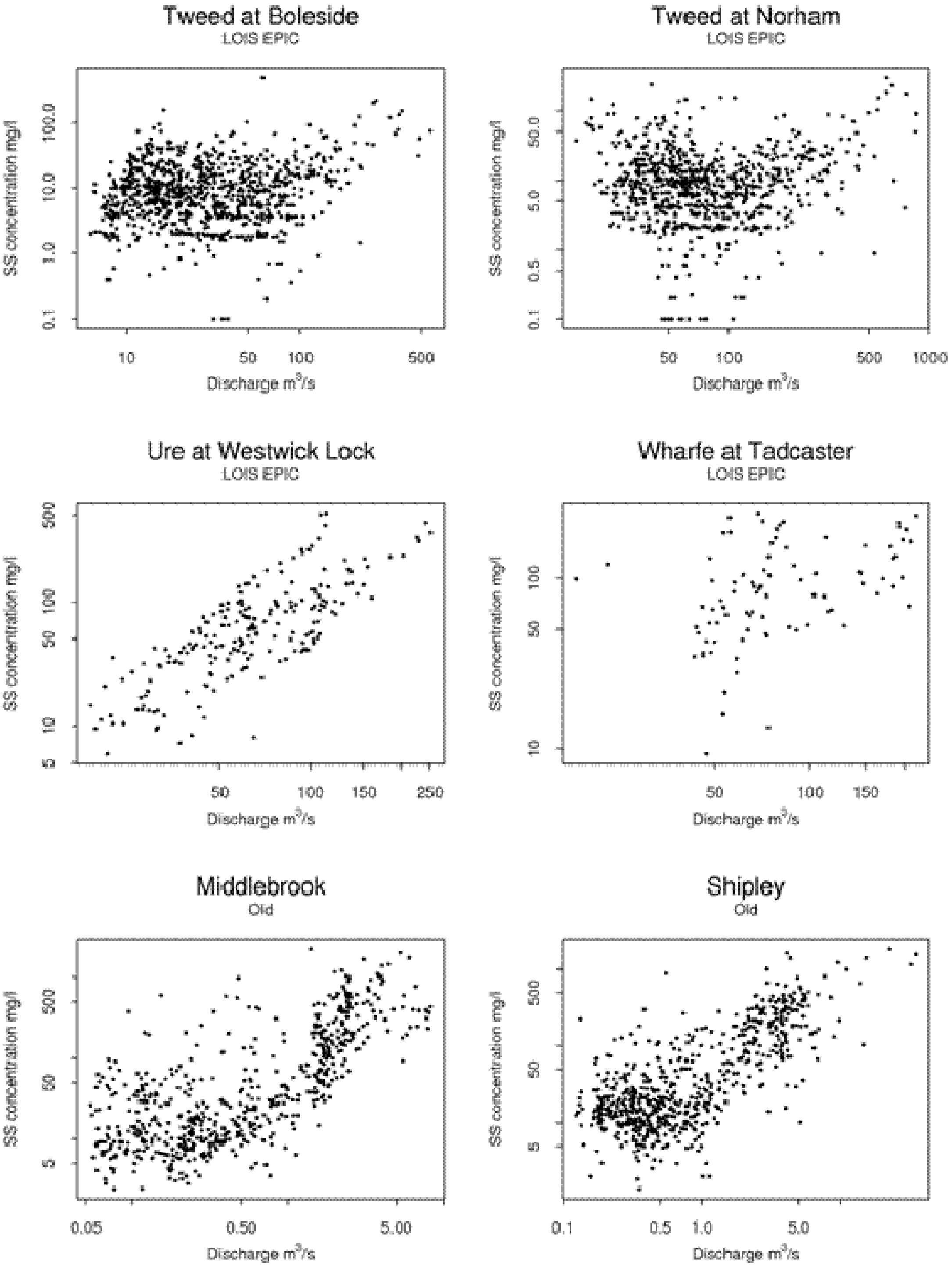


Figure C Rating curves for sites with raw data

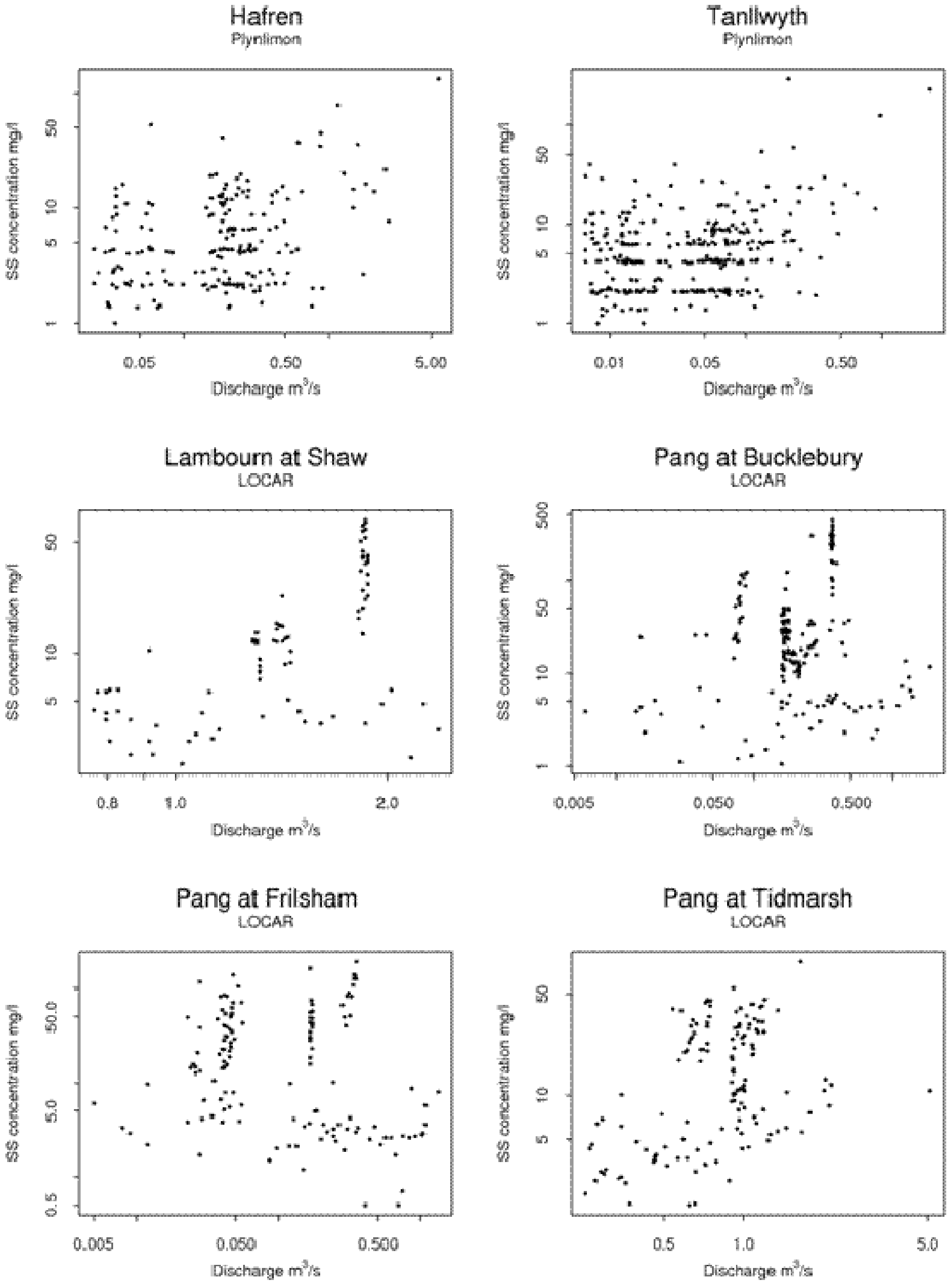
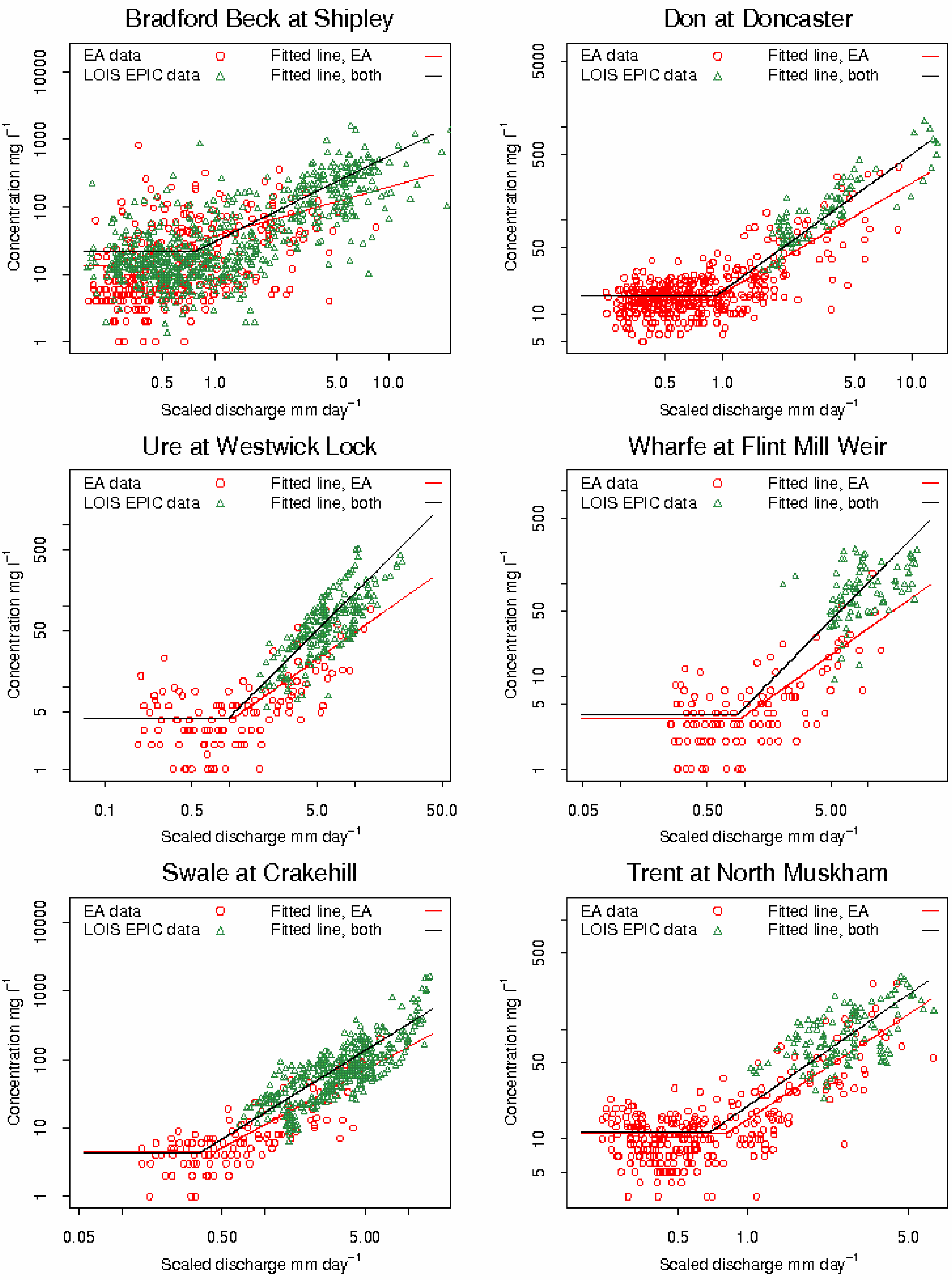


Figure D Rating curves for sites with raw data


Bradford Beck at Shipley

Don at Doncaster

Ure at Westwick Lock

Wharfe at Flint Mill Weir

Swale at Crakehill

Trent at North Muskham

Figure E Rating curves for selected catchments

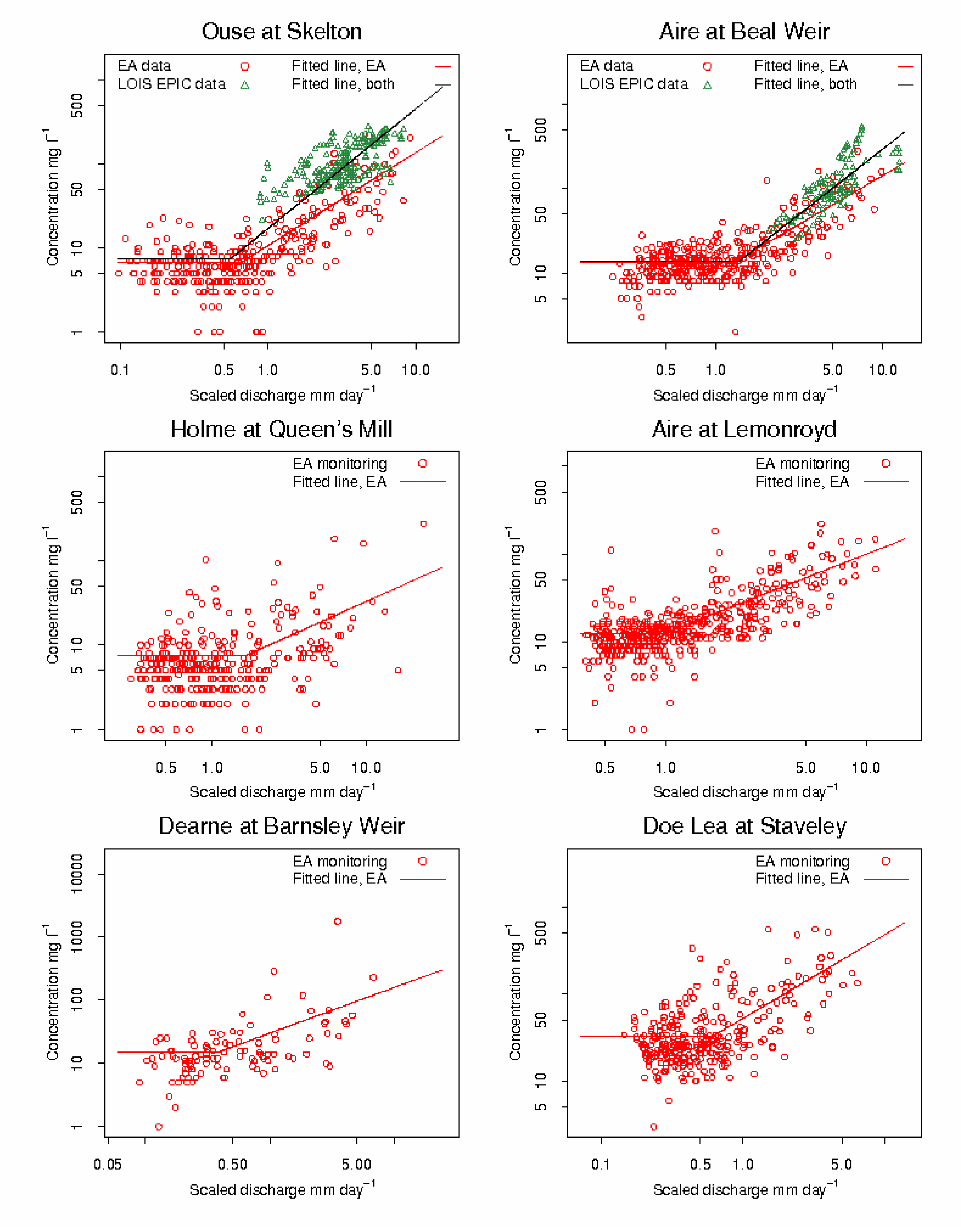


Figure F Rating curves for selected catchments

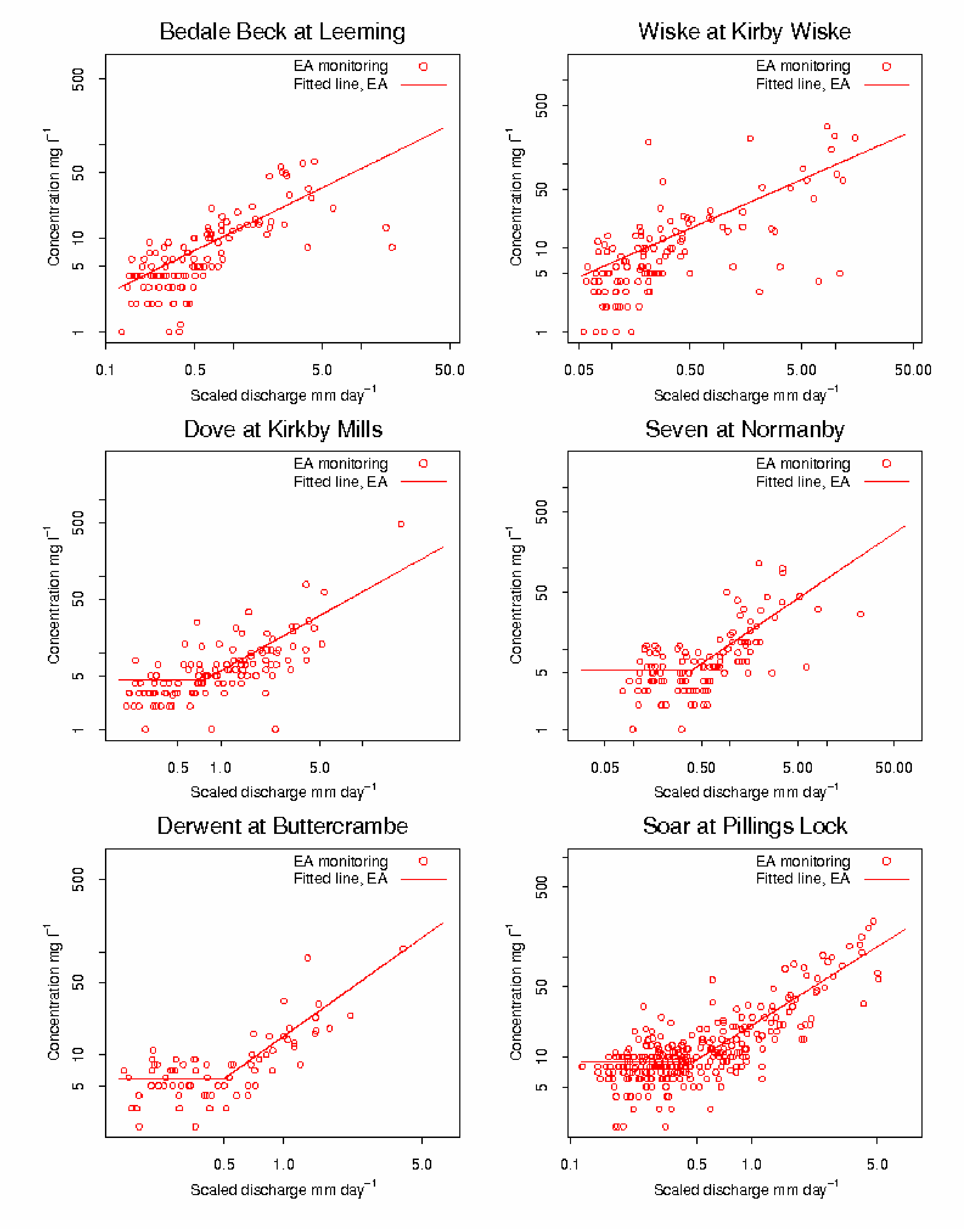


Figure G Rating curves for selected catchments

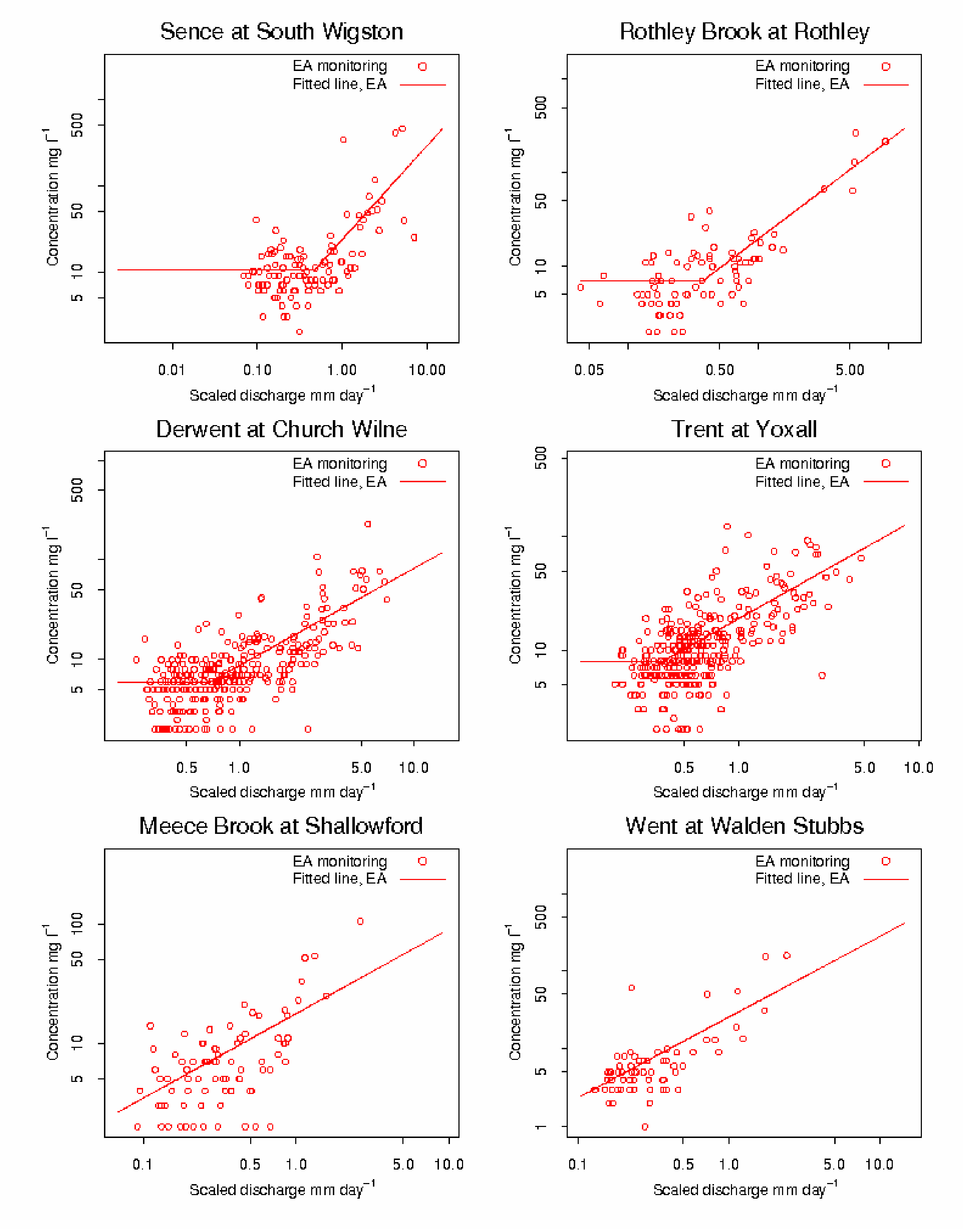


Figure H Rating curves for selected catchments

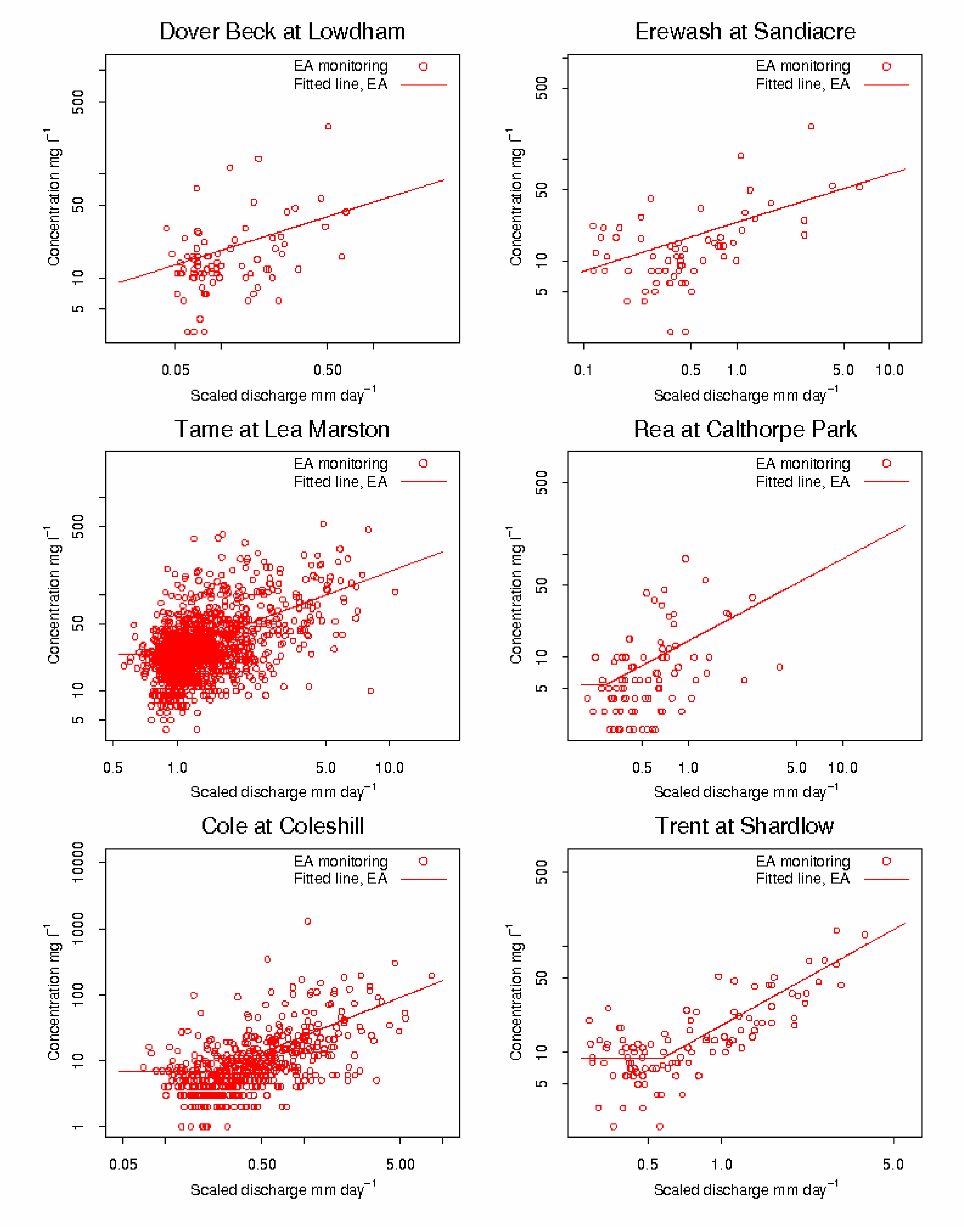


Figure I Rating curves for selected catchments

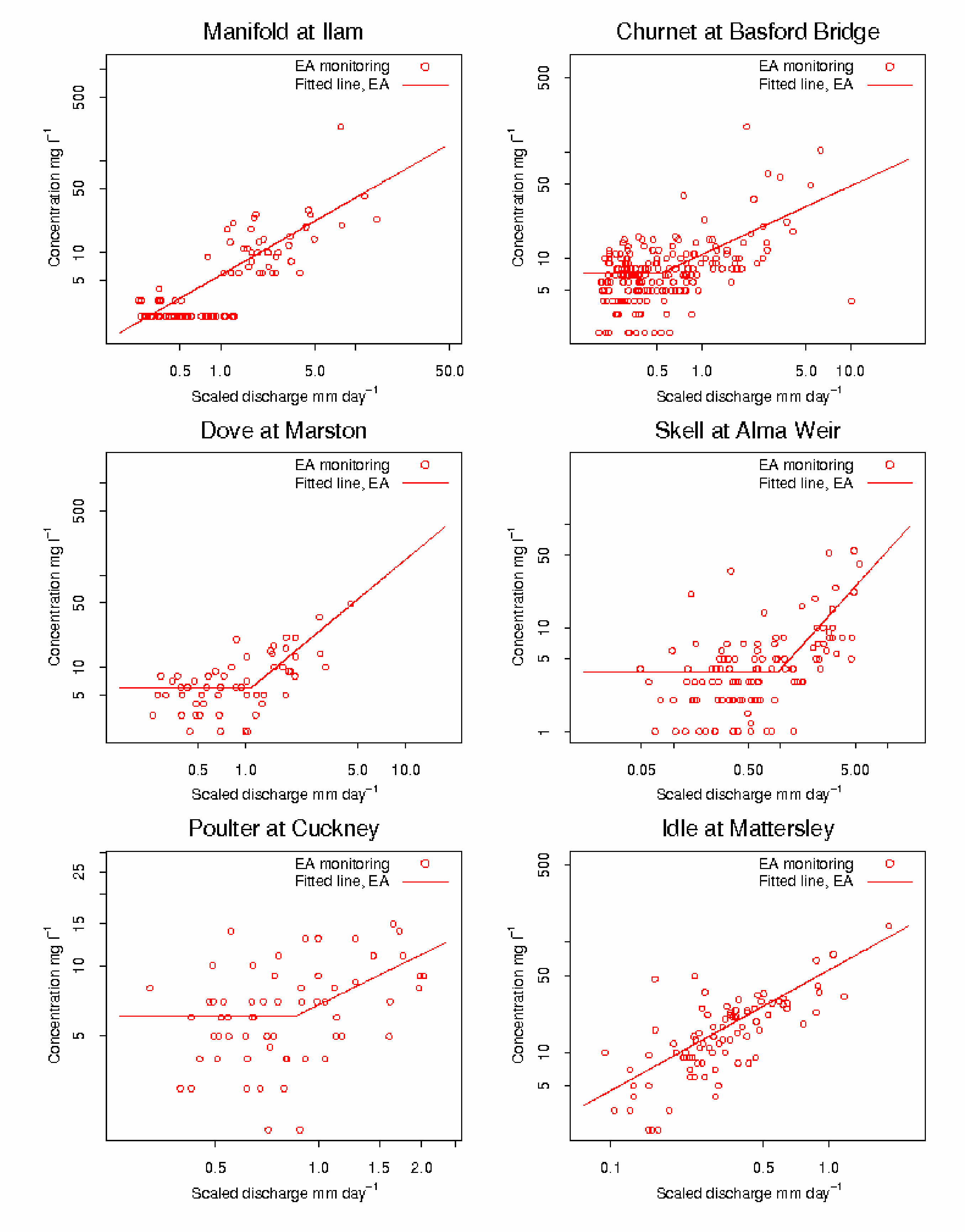


Figure J Rating curves for selected catchments

Appendix 2 Ecological characterisation of catchment typology for sediment yield

The following ecological narratives for each of the catchment types defined in the new typology have been supplied by Chris Mainstone of Natural England.

B1 High impermeable peat

Water courses

a) Biological characteristics

Natural watercourses in these catchments are predominantly high energy streams, with oligotrophic, cool waters running over coarse bed materials (mainly bedrock, boulders and cobbles). The flora is dominated by mosses and liverworts, whilst the fish fauna is dominated by salmonids. The macroinvertebrate community is characterised by stonefly, caddis-fly and mayfly species specialised adapted to living in or on coarse bed material with strong scouring flows.

b) Biological sensitivity to siltation

The coarse bed material of this type of watercourse is heavily relied upon by characteristic fish and invertebrate fauna, using the interstices for flow refuge and cover against predation. Salmonids bury their eggs deep in the substrate, and the eggs require a good flow-through of clean, well-oxygenated water. The young salmonid fry swim up to the surface and remain dependent on surface interstices for refuge through their early development. Characteristic invertebrates spend most of their time within substrate interstices, or on the underside of surficial stones.

c) Environmental vulnerability to siltation

The flora and fauna of this type of watercourse is sensitive to increased loads of fine sediment if material is deposited in sufficient quantities to clog up the interstices of coarse substrates. However, the strong scouring flows characteristic of the type mean that fine sediments are generally flushed through to reaches further down the river network.

Standing waters

a) Biological characteristics

Upland tarns occur in this catchment type, which may have a bed of peat or mineral substrate including coarse and fine material. These are typically fed by smaller feeder streams. The submerged flora is generally poor, with the fish fauna again salmonid-dominated. At the downstream end of catchments of this type, larger upland lakes may occur. These are typically deep and oligotrophic, and thermal stratification of the water column typically occurs. Bed materials along lake margins are typically coarse, consisting of boulders, cobbles and gravels, within sheltered areas of finer sediment supporting ‘lawns’ of shoreweed and associated plants. In the deeper, cooler waters, sub-arctic fish species (arctic char and whitefish such as vendace) may be present.

b) Biological sensitivity to siltation

As with their flowing water counterparts, the interstices of coarse bed materials in these standing waters are extensively used by characteristic fish and invertebrates for refuge. In addition to the widely known sensitivity of salmonids to siltation, whitefish species also utilise coarse substrates for spawning and are particularly sensitive to surficial siltation. Rosette-forming plant species such as shoreweed require a firm bed on which to establish – excessive deposition of fine sediment results in loss of competitiveness and invasion by larger rooted plants.

c) Environmental vulnerability to siltation

Coarse substrates generally occur on exposed lake shores where fine materials are more easily resuspended and distributed to other parts of the lake. However, the heavy loads of fine material yielded by this catchment type, and the erosive nature of the watercourses feeding such standing waters, means that the availability of fine material is generally very high, and most of the fine sediment yield entering the tarn or lake tends to be caught.

B2 High impermeable other

Watercourses

a) Biological characteristics

Natural watercourses in these catchments are predominantly high energy streams, with oligotrophic, cool waters running over coarse bed materials (mainly bedrock, boulders and cobbles). The flora is dominated by mosses and liverworts, whilst the fish fauna is dominated by salmonids. The macroinvertebrate community is characterised by stonefly, caddis-fly and mayfly species specialised adapted to living in or on coarse bed material with strong scouring flows.

b) Biological sensitivity to siltation

The coarse bed material of this type of watercourse is heavily relied upon by characteristic fish and invertebrate fauna, using the interstices for flow refuge and cover against predation. Salmonids bury their eggs deep in the substrate, and the eggs require a good flow-through of clean, well-oxygenated water. The young salmonid fry swim up to the surface and remain dependent on surface interstices for refuge through their early development. Characteristic invertebrates spend most of their time within substrate interstices, or on the underside of surficial stones.

c) Environmental vulnerability to siltation

The flora and fauna of this type of watercourse is sensitive to increased loads of fine sediment if material is deposited in sufficient quantities to clog up the interstices of coarse substrates. However, the strong scouring flows characteristic of the type mean that fine sediments are generally flushed through to reaches further down the river network.

Standing waters

a) Biological characteristics

Upland tarns occur in this catchment type and will generally have a bed of mineral substrate including coarse and fine material. These are typically fed by smaller feeder streams. The submerged flora is generally poor, with the fish fauna again salmonid-dominated. At the downstream end of catchments of this type, larger upland lakes may occur. These are typically deep and oligotrophic, and thermal stratification of the water column typically occurs. Bed materials along lake margins are typically coarse, consisting of boulders, cobbles and gravels, and support ‘lawns’ of shoreweed and associated plants. In the deeper, cooler waters, sub-arctic fish species (arctic char and whitefish such as vendace) may be present.

b) Biological sensitivity to siltation

As with their flowing water counterparts, the interstices of coarse bed materials in these standing waters are extensively used by characteristic fish and invertebrates for refuge. In addition to the widely known sensitivity of salmonids to siltation, whitefish species also utilise coarse substrates for spawning and are particularly sensitive to surficial siltation. Rosette-forming plant species such as shoreweed require a firm bed on which to establish – excessive deposition of fine sediment results in loss of competitiveness and invasion by larger rooted plants.

c) Environmental vulnerability to siltation

Coarse substrates generally occur on exposed lake shores where fine materials are more easily resuspended and distributed to other parts of the lake. However, the heavy loads of fine material yielded by this catchment type, and the erosive nature of the watercourses feeding such standing waters, means that the availability of fine material is generally very high, and most of the fine sediment yield entering the tarn or lake tends to be caught.

B3 Low impermeable other

Water courses

a) Biological characteristics

Natural watercourses in these catchments have high flow variabilities generated by the impermeability of the catchment soils - river flows are flashy in response to rainfall, and baseflows tend to be correspondingly low. Coarse bed substrates can be in short supply, but this is often due to heavy engineering works to improve land drainage and flood defence. Where it occurs, coarse bed material is critical to the survival of riffle-dwelling benthic macroinvertebrates. Salmonids and rheophilic cyprinids (such as dace and chub) occur in river sections that support sufficient gravel and current velocities, using the substrate for spawning and nursery habitat.

Where coarse materials are naturally absent, these watercourses would often naturally have a firm bed supporting a range of submerged macrophytes.

b) Biological sensitivity to siltation

Coarse bed material in these watercourses is critical due to its typical scarcity. Where it occurs, the interstices are used for flow refuge and cover against predation. Salmonids bury their eggs deep in the substrate, and the eggs require a good flow-through of clean, well-oxygenated water. The young salmonid fry swim up to the surface and remain dependent on surface interstices for refuge through their early development. Rheophilic cyprinids utilise the top layer of gravel for spawning, so are most susceptible to surface siltation. Characteristic invertebrates spend most of their time within substrate interstices, or on the underside of surficial stones.

In sections naturally devoid of coarse substrate, the river bed can get severely choked with unconsolidated fine material. This generates poor rooting conditions for submerged plants.

c) Environmental vulnerability to siltation

The flora and fauna of this type of watercourse is sensitive to increased loads of fine sediment, if material is deposited in sufficient quantities to clog up the interstices of coarse substrates or to generate unstable fine substrates unsuitable for macrophyte rooting. Although these catchments are flashy, scouring forces are not necessarily high due to low stream gradients. Flushing is also impaired by the extensive overwidening and overdeepening of channels.

Standing waters

a) Biological characteristics

Where they occur, lakes are shallow and base-rich, naturally containing a luxurious submerged plant community characterised by a range of pondweed (Potamogeton) species. Substrates are frequently unconsolidated and organic. Ditch systems created in this landscape have similar botanical characteristics. The submerged plant community gives rise to diverse macroinvertebrate and fish communities, which are often highly interconnected to the communities of adjacent rivers and streams.

b) Biological sensitivity to siltation

Standing waters of this type have relatively low sensitivity to siltation, at least in physical terms. However, where firm substrates are present it is important that these are protected against the rapid accumulation of unconsolidated sediment.

c) Environmental vulnerability to siltation

Owing to the dominance of surface run-off as a hydrological pathway, these standing waters are vulnerable to receiving enhanced levels of siltation from their catchments.

B4 Low permeable chalk

Water courses

a) Biological characteristics

Natural watercourses in these catchments are predominantly low energy rivers and streams, referred to as chalkstreams. Baseflows are fed from the chalk aquifer, delivering a relatively stable flow regime, water chemistry, water temperature and exceptional water clarity. These rivers typically have high levels of gravel substrates derived from the flint in the catchment. The interstices of these gravels give rise to a rich benthic macroinvertebrate community characterised by a diverse array of caddis-fly, mayfly and riffle beetle species. They also provide critical habitat for spawning and juvenile development of salmonid species and current-loving (rheophilic) cyprinid fish such as dace and chub.

The high natural infiltration rates within the catchment mean that hydraulic scouring forces are low, favouring the development of a rich submerged macrophyte community characterised by water-crowfoot and starwort species. The plant community provides further habitat for a range of invertebrate species such as gastropod molluscs and blackfly larvae, and refuge for juvenile and adult fish.

b) Biological sensitivity to siltation

The coarse bed material of this type of watercourse is heavily relied upon by characteristic fish and invertebrate fauna, using the interstices for flow refuge and cover against predation. Salmonids bury their eggs deep in the substrate, and the eggs require a good flow-through of clean, well-oxygenated water. The young salmonid fry swim up to the surface and remain dependent on surface interstices for refuge through their early development. Rheophilic cyprinids utilise the top layer of gravel for spawning, so are most susceptible to surface siltation. Characteristic invertebrates spend most of their time within substrate interstices, or on the underside of surficial stones. Whilst the submerged plants characteristic of these rivers attract silt around their root mass as they grow, open gravels are required for initial establishment so that shoot fragments or seeds can gain a foothold in the substrate.

c) Environmental vulnerability to siltation

The flora and fauna of this type of watercourse is therefore sensitive to increased loads of fine sediment, if material is deposited in sufficient quantities to clog up the interstices of coarse substrates. The weak scouring flows characteristic of the type mean that fine sediments are poorly flushed, making these rivers highly sensitive to increased sediment loads. Localised groundwater upwelling through the gravel substrate can occur and help maintain oxygen through-flow in the face of high silt levels.

Standing waters

a) Biological characteristics

Where they occur, lakes are shallow and highly calcareous and naturally contain a luxurious submerged plant community characterised by stonewort (particularly Chara) species. Water clarity is very high and substrates are naturally coarse and firm. Ditch systems created in this landscape have similar biological characteristics. The submerged plant community gives rise to diverse macroinvertebrate and fish communities, which are often highly interconnected to the communities of adjacent rivers and streams.

b) Biological sensitivity to siltation

As with their flowing water counterparts, the interstices of coarse bed materials in these standing waters are extensively used by characteristic fish and invertebrates for refuge. Rooted submerged plants characteristic of these standing waters require a firm, aerated substrate to establishment and growth.

c) Environmental vulnerability to siltation

Vulnerability depends on the nature of water delivery to these habitats. Some will be fed largely by groundwater, permitting a high degree of filtration and a low vulnerability to siltation. Habitats fed by the river system under high flow conditions will be most vulnerable.

B5 Low permeable other

Water courses

a) Ecological characteristics

Natural watercourses in these catchments are medium to low energy rivers and streams, draining catchments dominated by permeable but non-calcareous soils. Flow regimes tend to be intermediate between the stable flows of the ‘low permeable chalk’ type and the flashy flows of the ‘low impermeable other’ type. Those watercourses of highest gradients within the type will have considerable coarse bed material, whilst those of lowest gradients will be strongly depositional in character with a predominance of silt and sand on the bed. River engineering often reduces the occurrence of coarse materials that would otherwise accumulate at intervals along the watercourse in riffle-pool sequences.

Where it occurs, coarse bed material is critical to the survival of riffle-dwelling benthic macroinvertebrates. Salmonids and rheophilic cyprinids (such as dace and chub) occur in river sections that support sufficient gravel and current velocities, using the substrate for spawning and nursery habitat. Such sections also provide habitat opportunities for current-loving plants species such as water-crowfoots and starworts. The plant community provides further habitat for a range of invertebrate species such as gastropod molluscs and blackfly larvae, and refuge for juvenile and adult fish.

Where coarse materials are naturally absent, these watercourses would often have a firm bed supporting a range of submerged macrophytes.

b) Biological sensitivity to siltation

Where coarse bed material naturally occurs, the interstices are used for flow refuge and cover against predation. Salmonids bury their eggs deep in the substrate, and the eggs require a good flow-through of clean, well-oxygenated water. The young salmonid fry swim up to the surface and remain dependent on surface interstices for refuge through their early development. Rheophilic cyprinids utilise the top layer of gravel for spawning, so are most susceptible to surface siltation. Characteristic invertebrates spend most of their time within substrate interstices, or on the underside of surficial stones.

In sections naturally devoid of coarse substrate, the river bed can get severely choked with unconsolidated fine material, often arising from a combination of artificially enhanced sediment delivery and artificially enhanced sediment retention. This generates poor rooting conditions for submerged plants and can create sediment anoxia with consequences for burrowing invertebrates.

c) Environmental vulnerability to siltation

The flora and fauna of this type of watercourse is therefore sensitive to increased loads of fine sediment, if material is deposited in sufficient quantities to clog up the interstices of coarse substrates. The weak scouring flows characteristic of the type mean that fine sediments are generally poorly flushed, making these rivers sensitive to increased fine sediment accumulation from enhanced sediment loads. The effect of increased accumulation will be most keenly felt in areas with coarse bed sediments, although the flora and fauna in depositional sections may suffer from reduced bed stability.

Standing waters

a) Biological characteristics

Where they occur, lakes are generally shallow, naturally containing a luxurious submerged plant community typically characterised by a range of pondweed (Potamogeton) species. Substrates are generally dominated by fine sediments, which may be firm and aerated or unconsolidated and anoxic. Ditch systems created in this landscape that are fed from the river network tend to have similar botanical characteristics. The submerged plant community gives rise to diverse macroinvertebrate and fish communities, which are often highly interconnected to the communities of adjacent rivers and streams.

b) Biological sensitivity to siltation

As with their flowing water counterparts, the interstices of any coarse bed materials in these standing waters are extensively used by characteristic fish and invertebrates for refuge. Many rooted submerged plants characteristic of these standing waters require a firm, aerated substrate for root establishment and growth.

c) Environmental vulnerability to siltation

Vulnerability depends on the nature of water delivery to these habitats. Some will be fed largely by groundwater, permitting a high degree of filtration and a low vulnerability to siltation. Habitats fed by the river system under high flow conditions will be most vulnerable. Standing waters with naturally firm and aerated substrates are at risk of losing their characteristic plant and invertebrate assemblages through the excessive deposition of unconsolidated fine material.

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