Assessing "modern background sediment delivery to rivers" across England and Wales and its use for catchment management

ADRIAN L. COLLINS[1,3], IAN FOSTER[2,6], YUSHENG ZHANG[1], RICHARD GOODAY[1], DAVID LEE[1], DAVID SEAR[3], PAMELA NADEN[4] & IWAN JONES[5]

1 ADAS, Pendeford House, Wobaston Road, Wolverhampton WV9 5 AP, UK
adrian.collins@adas.co.uk
2 University of Northampton, School of Science and Technology, St George's Avenue, Northampton NN2 6JD, UK
3 University of Southampton, Geography and Environment, Highfield, Southampton SO17 1BJ, UK
4 Centre for Ecology and Hydrology, Crowmarsh Gifford, Wallingford OX10 8BB, UK
5 Queen Mary University of London, School of Biological and Chemical Sciences, Mile End Road, London E1 4NS, UK
6 Department of Geography, Rhodes University, Grahamstown 6140, Eastern Cape, South Africa

Abstract Catchment sediment management across England and Wales continues to require alternative criteria to the existing guideline standard (an annual mean suspended sediment concentration of 25 mg L^{-1}) provided by the European Union Freshwater Fish Directive. In response, a recent collaborative science project has investigated the scope for developing alternative catchment-specific sediment targets using an integrated modelling toolkit coupling sediment pressures from agriculture and impacts on aquatic biota, including fish and macroinvertebrates. Part of this work involved using palaeolimnological reconstruction to quantify "modern background sediment delivery to rivers" (MBSDR) across England and Wales, prior to recent agricultural intensification. It is proposed that the estimates of MBSDR can be used to assess the maximum ceiling of mitigation because no management strategy should aim to control background sediment loss arising from natural physiographic and hydrological drivers, and to correct the gap between past, present or future projected sediment pressures on watercourses and "good ecological status" for sediment.

Keywords sediment delivery; palaeolimnology; modelling; management; policy

INTRODUCTION

The pivotal role of fine sediment in catchment diffuse pollution problems has been increasingly acknowledged. Excessive loadings of fine sediment have a number of negative impacts, including reductions in light penetration and concomitant changes in primary production (Wood & Armitage, 1997) and the alteration of river morphology, which can reduce the amount and quality of aquatic habitat available for fauna and flora (Clarke & Wharton, 2001) as evidenced by the degradation of fish spawning gravels resulting from elevated ingress rates (Greig *et al*., 2005). Fine sediment is also a key vector for the transport and dispersal of nutrients, organic and inorganic contaminants and heavy metals (e.g. Collins *et al*., 2005; Kay *et al*., 2007).

Although elevated sediment loads are perceived to be responsible for the degradation of water quality across England and Wales, catchment-scale management targets for fluvial sediment transport are not well developed in Europe (Collins & Anthony, 2008) and there remains a reliance on the annual average guideline suspended sediment concentration of 25 mg L^{-1} cited in the European Freshwater Fish Directive (EU, 2006). The problems and uncertainties associated with using a single sediment target across England and Wales have been summarized by Collins & Anthony (2008), whilst the recent review of international approaches to setting sediment management thresholds by Collins *et al*. (2011) has suggested that the use of sediment regimes, such as sediment yields, offers some potential for overcoming some, but not all, of these limitations.

In the above context, the recent work by Foster *et al*. (2011), as part of a major collaborative research project, has illustrated how palaeoenvironmental reconstruction can provide a key data source from which to establish sediment yield under "modern background" conditions across England and Wales. Palaeoenvironmental reconstruction provides a basis for establishing those sediment pressures that would occur given the natural physiographic and hydrological characteristics of catchments and associated modern anthropogenic impacts. The latter must be taken into account since the scope for returning sediment pressures to truly “instrinsic” levels is limited by the need to maximize agricultural production in the context of food security and related issues. “Background” sediment pressures based on palaeoenvironmental data thereby provide a basis for quantifying the maximum likely impact of catchment sediment mitigation strategies and for correcting the gap between current or future projected reductions required to meet “good ecological status”. Even a perfect mitigation programme should not endeavour to eliminate all fine sediment from rivers since healthy aquatic habitats are dependent upon some fine sediment inputs to avoid the development of homogenized river channel substrates (Yarnell *et al.*, 2006). Accordingly, and in the simplest sense, estimates of modern background sediment pressures could also be taken to represent ecological demand for sediment, given the drive for simplistic approaches to setting sediment water quality targets for informing catchment management.

Estimation of background sediment pressures for the modern day requires identification of a time threshold in the sediment yield record that pre-dates the most significant recent phase of agricultural intensification impacting on sediment transport in catchment systems. An implicit assumption in using background sediment pressures in target setting is that the hydrological conditions and delivery efficiency of the river network to the lake or reservoir yielding the palaeoenvironmental data are unchanged. Published Holocene lake sediment investigations for the UK show several phases of increased sediment accumulation during the Bronze Age to Romano-British periods, as well as subsequent Medieval and Post-Medieval phases that are strongly linked to agriculture (e.g. Chiverell *et al.*, 2008). Similarly, Holocene floodplain accumulation rates in UK rivers have been shown to be related to periods of rapid environmental change, including the agricultural revolution of the Middle Ages and the widespread uptake of the plough (Macklin *et al.*, 2009). Although Holocene sediment accumulation rates have been reconstructed using natural lakes in the UK, these long-term sedimentary basins are generally restricted to the uplands. Lowland areas have a general paucity of natural lakes, although reservoirs have been used for palaeoenvironmental reconstructions encompassing the last approx. 100–150 years (e.g. Foster, 2010). On this basis, the recent work by Foster *et al.* (2011) proposed that since the most dramatic increase in recent sediment yields occurred after 1945, the last approx. 100–150 years should be used to establish provisional modern background sediment pressures for catchments across England and Wales.

RECONSTRUCTING “MODERN BACKGROUND SEDIMENT DELIVERY TO RIVERS”

Sediment yield reconstruction based on historical lake sediments normally focuses on the finer sediment that reaches the deep water zone, and published studies in the UK show that these sediments are usually <63μm in diameter and therefore closely match the particle size distribution of suspended sediments transported by UK rivers. Using lake sediments to reconstruct sediment yields involves:

1 Dating the sediment sequence.
2 Correlating time-synchronous layers from cores taken across the lake with the dated sequence in order to estimate sediment volume (and mass) deposited across the receptor through time.
3 Correction of the sediment mass for autochthonous contributions (e.g. organic matter content, diatom silica and lake shoreline erosion contributions) and atmospheric inputs.
4 Correcting for lake trap efficiency.

A detailed explanation of these procedures can be found in Foster (2010).

Only 19 lake-based sediment yield reconstructions, excluding sites heavily impacted by 20th century mining operations and covering the last ~100–150 years, have been published for England and Wales. Although several studies have used the total mass of sediment accumulating in reservoirs since their construction to estimate long-term average sediment yields, most of these have focused on upland storage reservoirs and the estimates of total sediment mass provide information on spatial variations in average sediment yield, as opposed to temporal changes in sediment yield. On this basis, the latter studies were not included in the synthesis of palaeoenvironmental data for establishing preliminary modern background sediment pressures for rivers across England and Wales. Only two reconstructions have been reported for Wales (Dearing *et al*., 1981; Dearing, 1992). The reconstructed data, appropriate for the purposes of this study, were reviewed in the context of dominant land cover class with a view to identifying corresponding modern background sediment yields. It is well-documented that specific sediment yields commonly decrease with catchment area because of increasing opportunities for longer-term sediment retention including that on flood-plains (de Vente *et al*., 2007). The estimates of modern background sediment yields based on small lake catchments should therefore be further refined as a function of catchment area to aid extrapolation beyond the small systems from which they are derived. Since insufficient data on long-term sediment storage and budgets (cf. Walling & Collins, 2008) exist for multiple basins of contrasting size across England and Wales, these refinements were not possible as part of this work to date. On this basis, it was proposed that the estimates of modern background sediment yield should be taken as indicative of "modern background sediment delivery" (MBSDR) to watercourses for spatial extrapolation and upscaling purposes, as opposed to being representative of net downstream yields in larger drainage basins.

Table 1 presents the estimates of MBSDR for England and Wales produced on the basis of the data review and synthesis. On the basis of the data synthesis, and bearing in mind the relatively high uncertainty for large areas of the UK where no reconstructed data are available, two categories of MBSDR were defined:

1 The *target modern background sediment delivery to rivers* (TMBSDR) is the recommended target based on best current scientific knowledge.
2 The *maximum modern background sediment delivery to rivers* (MMBSDR) has been introduced to recognize uncertainty in the sediment yield reconstructions and the extrapolation of these data to ungauged areas across England and Wales.

Table 1 Estimated "modern background sediment delivery to rivers" across England and Wales.

Land cover	Target (kg ha^{-1} year^{-1})	Maximum (kg ha^{-1} year^{-1})
Forested catchments	<50	100
Mixed forest / moorland / upland rough grazing	<50	100
Upland moorland / rough grazing	<50	100
Peat	<<500	650
Lowland agriculture (A)	<100	150
Lowland agriculture (B)	<200	350

SPATIAL EXTRAPOLATION OF THE ESTIMATES OF MBSDR

For the majority of the lake-based case studies reviewed, it was possible to estimate MBSDR on the basis of the dominant land cover in the upstream catchment. For spatial extrapolation of these values, the 1 km raster data summary of the Land Cover Map (LCM2000) (Fuller *et al*., 2002) was used to assess land cover in each 1 km^2 across England and Wales. The widespread broad habitat classes were grouped into five types compatible with the land cover criteria listed in Table 1. National extrapolation of the estimates of MBSDR was more problematic in the case of lowland agricultural catchments given the wide range in MBSDRs based on the sediment yield data reported by existing lake studies. A typology of soil susceptibility to water erosion for England and Wales based on soil associations proposed by Evans (1990) was used for extrapolating the lake-based MBSDR estimates for lowland agricultural catchments. Soil associations identified as being at very low, low or moderate erosion risk by water were used in the definition of lowland agricultural MBSDR category A, whereas soil associations identified as being at high or very high risk of accelerated soil erosion by water were used to define lowland agricultural MBSDR category B (Table 1). Soil associations were mapped using the NATMAP vector soil map (National Soil Resource Institute, Cranfield University). A slope of 3 degrees was used as the threshold separating categories A and B with the median slope for each 1 km^2 across England and Wales being assessed using a 50-m digital elevation model (DEM). Target and maximum MBSDR were calculated as a weighted-average, based on the proportion of each of the land cover categories in each 1 km^2 across England and Wales. These values for each 1 km^2 in each of 3380 individual waterbodies were averaged. Non-applicable areas (i.e. more than 90% classed as open waterbody or unclassified) and urban areas were removed from the spatial extrapolation using a corresponding GIS mask layer (cf. Shepherd & Bibby, 2004). The tentative maps of MBSDR produced on the basis of the above extrapolation scheme are presented in Fig. 1. These estimates should be interpreted with some caution since no historical sediment yield data are currently available for large areas of England and Wales.

Table 2 Summary data for the sediment "gap" analysis using the estimates of TMBSDR.

Qualitative screening	No. waterbodies	Area (km^2) of waterbodies	% of total area of waterbodies
1980			
Above TMBSDR	1049	48 950	32
Near TMBSDR	1761	77 618	51
Uncertain	570	24 205	16
Total	3380	150 774	100
2004			
Above TMBSDR	968	45 215	30
Near TMBSDR	1730	77 099	51
Uncertain	682	28 459	19
Total	3380	150 774	100

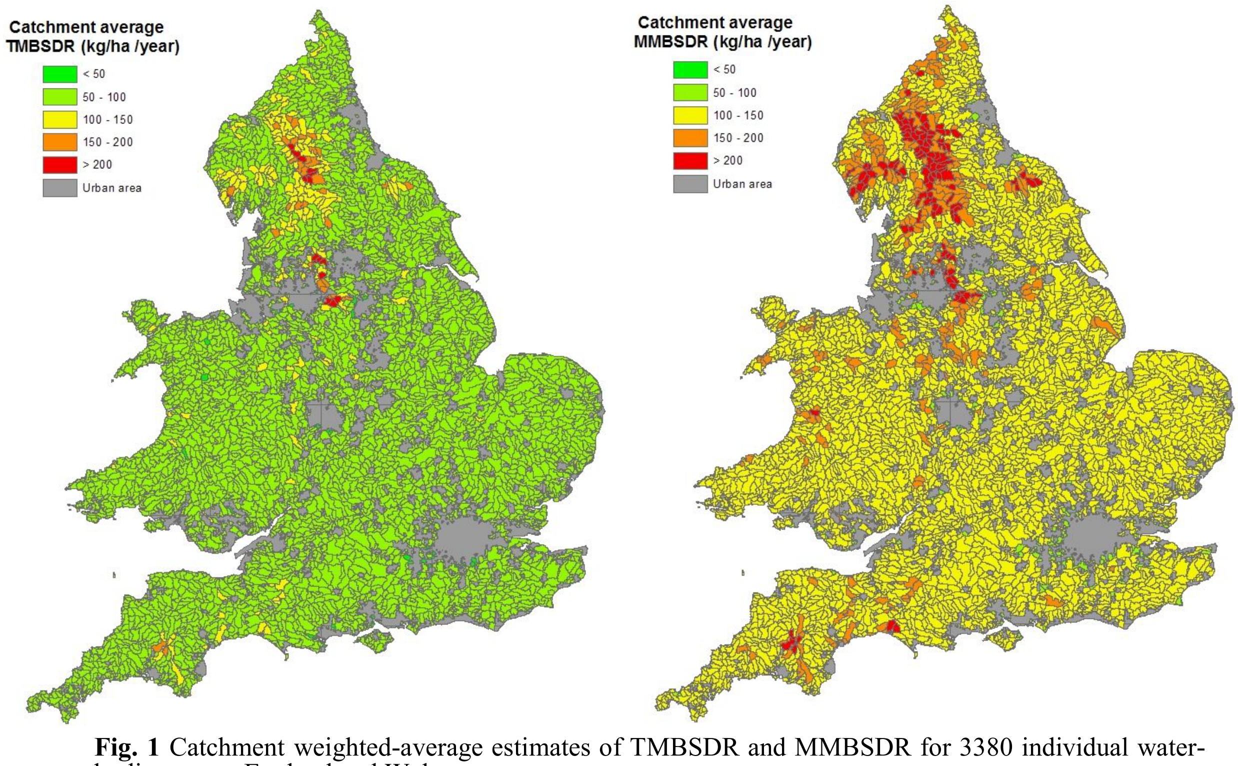

Fig. 1 Catchment weighted-average estimates of TMBSDR and MMBSDR for 3380 individual water-bodies across England and Wales.

"GAP" ANALYSIS USING THE ESTIMATES OF MBSDR

The use of the estimates of MBSDR for sediment policy support purposes is on-going. One example of their application is to estimate the "gap" between simulated sediment delivery to watercourses for the recent past (1980 and 2004) and the estimates of TMBSDR as a means of identifying the maximum ceiling of sediment reduction for mitigation strategies. This gap analysis has deployed a new national scale soil erosion and sediment delivery model, which sits within the ADAS Pollutant Transport (APT) framework for multiple pollutants (sediment, phosphorus and nitrogen). The sediment module of APT has been designed to be sensitive to daily weather input time series, soils and management practice data and information available from basic farm surveys. The hydrological core of the sediment module in APT partitions flow between surface runoff, rapid drain flow, slow or matric flow through soil and deep seepage from the base of the soil profile towards groundwater. Both surface runoff and drain flow are based on a curve number approach including modifications to this number resulting from the influence of bare soil surface conditions (defined as fine seed bed, standard seed bed, rough ploughed), soil moisture deficit, crop cover, trampling and poaching, capping and tramline wheelings. For the mobilization component of the sediment delivery continuum, soil erodibility is based upon the calculations in EPIC (Erosion-Productivity Impact Calculator; Williams *et al*., 1984). Post sediment mobilization at the plot scale, sediment sorting and retention in the landscape prior to delivery to watercourses is calculated at the edge-of-plot, edge-of-field, exit-from-field margin and from the field-to-river. The prediction of the absolute grain size of sediment delivered to watercourses has been evaluated using empirical data for 43 sites across England and Wales.

Simulated sediment delivery to watercourses for 1980 and 2004 used land-use data specific to those years extracted from the ADAS land-use database (Comber *et al*., 2008). This database integrates national land cover data (Fuller *et al*., 2002) with returns from the June Agricultural Census. The results from 20 years of simulation for each reference year, using the input weather data files for 1991–2010 were used to estimate median and ranges in annual loadings for the 3380 individual waterbodies across England and Wales. These simulated loadings were, in turn, compared with the estimates of TMBSDR for each individual waterbody to estimate the corresponding gap. On this basis, the analysis to date thereby examines the potential role of land use change in driving the gap between simulated sediment delivery to watercourses and TMBSDR. Qualitative screening of the gap analysis was undertaken on the basis of the ranges (10th and 90th percentiles) in simulated sediment delivery to watercourses using the 1991–2010 input weather data series. If the TMBSDR fell within the simulated range provided by the sediment module of APT, then it was assumed that the two values (simulated for either 1980 or 2004 and TMBSDR) are very close and thereby essentially the same, indicating no gap. If the TMBSDR was below the 10th percentile value of simulated sediment delivery to watercourses for either 1980 or 2004, this was taken to be indicative of a true or certain gap in sediment pressure. Conversely, if the TMBSDR was above the 90th percentile value of simulated sediment delivery to watercourses for either 1980 or 2004, this was taken to be indicative of an uncertain gap in sediment pressure. It should be noted that no explicit account is taken of the prior uptake of sediment mitigation measures in the simulations for either 1980 or 2004. Figures 2 and 3 and Table 2 summarize the gap analysis between simulated sediment delivery to watercourses for 1980 and 2004, and the estimated TMBSDR. This preliminary analysis suggests that on the basis of structural land-use change only in the farming sector, the proportion of the total area represented by the 3380 individual waterbodies with an actual sediment gap has remained essentially constant (32% in 1980 *versus* 30% in 2004). For both reference years, the sediment gap exceeds 300 kg ha^{-1} $year^{-1}$ (30 t km^{-2} $year^{-1}$) for certain areas in Wales and northern England.

PERSPECTIVE

This contribution summarizes the results of preliminary sediment "gap" analysis for England and Wales, designed to identify the maximum ceiling for sediment mitigation strategies. The MBSDR layers require improvement, using for example, new palaeoenvironmental reconstruction data for the south and southeastern areas of England. The analysis outlined above can be used to screen catchments by identifying those where a sediment gap exists and where remedial action is therefore required. On-going work is assessing what reductions in this gap might be technically feasible using the mitigation options supported by agri-environment funding schemes.

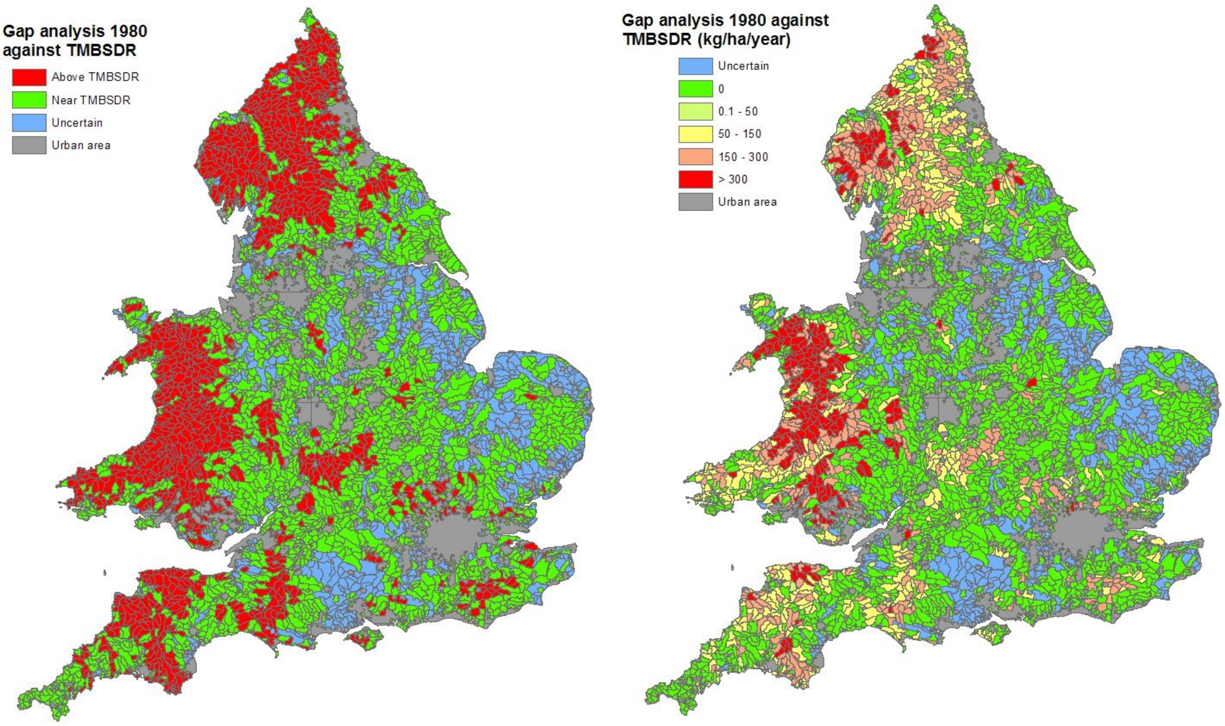

Fig. 2 The sediment “gap” for 1980.

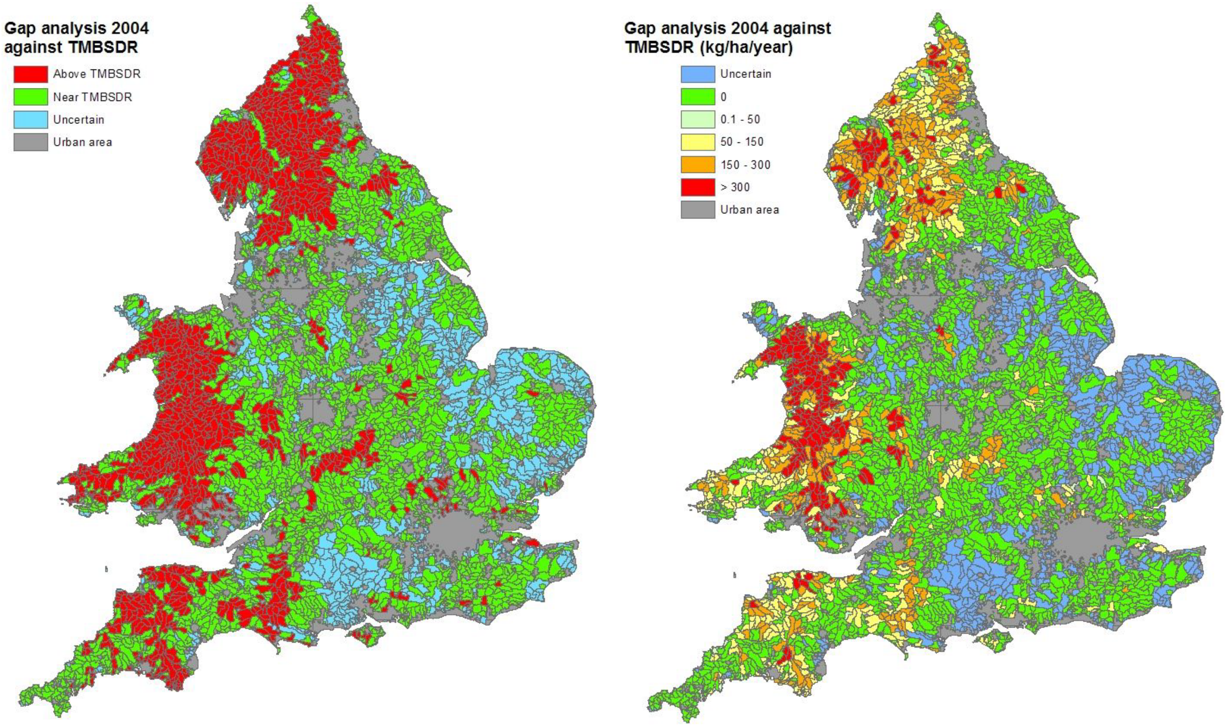

Fig. 3 The sediment “gap” for 2004.

Acknowledgements The authors gratefully acknowledge the funding provided by the Department for Environment, Food and Rural Affairs (Defra) project WQ0128 (Extending the evidence base on the ecological impacts of fine sediment and developing a framework for targeting mitigation of agricultural sediment losses).

REFERENCES

Chiverrell, R. C., Oldfield, F., Appleby, P. G., Barlow, D., Fisher, E., Thompson, R. & Wolff, G. (2008) Evidence for changes in Holocene sediment flux in Semer Water and Raydale, North Yorkshire, UK. *Geomorphology* 100, 70–82.

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

Collins, A. L. & Anthony, S. G. (2008) Assessing the likelihood of catchments across England and Wales meeting 'good ecological status' due to sediment contributions from agricultural sources. *Environmental Science and Policy* 11, 163–170.

Collins, A. L., Walling, D. E. & Leeks, G. J. L. (2005) Storage of fine grained sediment and associated contaminants within the channels of lowland permeable catchments in the UK. In: *Sediment Budgets*, vol. 1 (ed. by D. E. Walling & A. J. Horowitz), 259–268. IAHS Publ. 291. IAHS Press, Wallingford, UK.

Collins, A. L. Naden, P. S., Sear, D. A., Jones, J. I., Foster, I. D. L. & Morrow, K. (2011) Sediment targets for informing river catchment management: international experience and prospects. *Hydrol. Processes* 25, 2112–2129.

Comber, A., Anthony, S. & Proctor, C. (2008) The creation of a national agricultural land use dataset: combining pycnophylactic interpolation with dasymetric mapping techniques. *Transactions in GIS* 12, 775–791.

Dearing, J. A. (1992) Sediment yields and sources in a Welsh upland lake-catchment during the past 800 years. *Earth Surf. Processes Landf.* 17, 1–22.

Dearing, J. A., Elner, J. K. & Happey-Wood, C. M. (1981) Recent sediment flux and erosional processes in a Welsh Upland Lake Catchment based on magnetic susceptibility measurements. *Quaternary Research* 16, 356–372

de Vente, J., Poesen, J., Arabkhedri, M. & Verstraeten, G. (2007) The sediment delivery problem revisited. *Progress in Physical Geography* 31, 155–178.

European Union (2006) Directive 2006/44/EC the European Parliament and of the Council of 6 September 2006 on the quality of fresh waters needing protection or improvement in order to support fish life. *Official Journal of the European Union L264*, 20–31.

Evans, R. (1990) Soils at risk of accelerated erosion in England and Wales. *Soil Use and Management* 6, 125–31.

Foster, I. D. L. (2010) Lakes and reservoirs in the sediment cascade. In: *Sediment Cascades: An Integrated Approach* (ed. by T. P. & R. J. Allison). Wiley, Chichester. 345–376.

Foster, I. D. L., Collins, A. L., Naden, P. S., Sear, D. A., Jones, J. I. & Zhang, Y. (2011) The potential for palaeolimnology to determine historic sediment delivery to rivers. *J. Palaeolimnology* 45, 287–306.

Fuller, R. M., Smith, G. M., Sanderson, J. M., Hill, R. A. & Thomson, A. G. (2002) The UK Land Cover Map 2000: construction of a parcel-based vector map from satellite images. *Cartographic J.* 39, 15–25.

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

Kay, D., Edwards, A. C., McDonald, A. T., Stapleton, C. M., Wyer, M. D. & Crowther, J. (2007) Catchment microbial dynamics: the emergence of a research agenda. *Progress in Physical Geography* 31, 1–18.

Macklin, M. G., Jones, A. F. & Lewin, J. (2009) River response to rapid Holocene environmental change: evidence and explanation in British catchments. *Quaternary Science Reviews* 29, 1555–1576.

Shepherd, J. & Bibby, P. (2004) Rural and urban area classification 2004. http:/www.statistics.gov.uk/geography/nrudp.asp.

Walling, D. E. & Collins, A. L. (2008) The catchment sediment budget as a management tool. *Environmental Science and Policy* 11, 136–143.

Williams, J. R., Jones, C. A. & Dyke, P. T. (1984). A modeling approach to determining the relationship between erosion and soil productivity. *Trans. ASAE* 27, 129–144.

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

Yarnell, S. M., Mount, J. F. & Larsen, E. W. (2006) The influence of relative sediment supply on riverine habitat heterogeneity. *Geomorphology* 80, 310–324.