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Establishing fine-grained sediment budgets for the Pang and Lambourn LOCAR catchments, UK

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Summary An integrated approach to data collection, combining the use of ^{137}Cs measurements, sediment source fingerprinting, bed sediment surveys and conventional river monitoring, has been successfully employed to establish the fine-grained sediment budgets of two lowland groundwater-fed catchments in the UK. Gross surface erosion is higher on cultivated land (Pang: 55 263 t yr^{-1} or 507 t km^{-2} yr^{-1}; Lambourn: 79 997 t yr^{-1} or 437 t km^{-2} yr^{-1}) than on pasture (Pang: 1960 t yr^{-1} or 140 t km^{-2} yr^{-1}; Lambourn: 1425 t yr^{-1} or 95 t km^{-2} yr^{-1}) in both study areas and a substantial proportion of the mobilized sediment is sequestered within the fields (Pang: 28 058 t yr^{-1} or 228 t km^{-2} yr^{-1}; Lambourn: 55 575 t yr^{-1} or 281 t km^{-2} yr^{-1}) and between the individual fields and the river channel network (Pang: 28 672 t yr^{-1} or 233 t km^{-2} yr^{-1}; Lambourn: 24 782 t yr^{-1} or 125 t km^{-2} yr^{-1}). The sediment contribution from banks and subsurface sources is relatively low and typically ca. 5 t yr^{-1} in the Pang and ca. 11 t yr^{-1} in the Lambourn, representing only about 1% of the suspended sediment output from each study catchment. The mean level of fine-grained sediment storage in the main channel system is equivalent to 38% (Pang) and 21% (Lambourn) of the respective mean annual suspended sediment yields of the two catchments. The estimated sediment delivery ratio for both study catchments is ca. 1%.

The context

The Chalk streams of southern and eastern England are characterized by essentially unique hydrological regimes and aquatic habitats. Flow and thermal regimes evidence high stability, due to the dominance of groundwater inputs. High mineral concentrations and the high light penetration associated with the low turbidities encourage extensive macrophyte growth (e.g. *Ranunculus pencillatus var.*), whilst the abundance of plants and detritus supports a diverse community of benthic invertebrates, including mayfly nymphs, caddis larvae, oligochaete worms, stoneflies and white-clawed crayfish (Westlake et al., 1972; Berrie, 1992). Many aspects of the hydrological and ecological func-

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tioning of lowland permeable catchments draining areas of Chalk are, however, relatively poorly understood.

The unique characteristics of Chalk streams make them particularly susceptible to anthropogenic impacts associated with water abstraction, urban and infrastructure development, agricultural activities, land drainage, effluent discharges and flood alleviation schemes. Consequently, an Environment Agency survey undertaken in 2000 (UK Biodiversity Action Plan Steering Group for Chalk Rivers, 2004) showed that only 37% of Chalk streams in England could be classed as 'very good' in terms of chemical and biological quality. Increased suspended sediment concentrations, which result in increased turbidities and reduced light penetration as well as the siltation of salmonid spawning gravels, the accumulation of sediment within channel and channel-margin habitats, and the presence of increased sediment-associated nutrient and contaminant loadings, have frequently been cited as important contributors to the degradation of Chalk stream ecosystems and the associated 'Chalk stream malaise' (UK Biodiversity Action Plan Steering Group for Chalk Rivers, 2004). Whilst point inputs of suspended solids from watercress beds and sewage treatment works contribute to these 'sediment problems', changing agricultural land use and, more particularly, the increase in arable cultivation and the associated expansion of the area of autumn-sown cereals and fodder maize, which in turn result in increased rates of soil erosion and sediment mobilization and sediment transfer to the streams, are frequently cited as a key cause. Sedimentation problems are often exacerbated by groundwater extraction, which reduces flows and the natural flushing action of higher discharges, compounding their negative impacts on macrophyte communities (Clarke and Wharton, 2001), invertebrate biodiversity (Scullion, 1983) and fish populations (Acornley and Sear, 1999). Developing an improved understanding of the fine sediment dynamics of UK Chalk stream catchments, including, sediment sources, sediment mobilization, transfer and storage, and sediment yields, must be seen as a key requirement to inform the development and implementation of improved sediment control strategies and catchment management policies.

In response to the need to develop an improved understanding of the hydrology and ecology of lowland permeable catchments in the UK and for reliable information to assist the management of these fragile hydroecological systems, the UK Natural Environment Research Council established the LOCAR (Lowland Catchment Research) thematic programme. LOCAR targeted its investigations and field-based monitoring in three main study areas, namely, the Frome/Piddle in Dorset, the upper Tern in Shropshire and the Pang/Lambourn in Berkshire. A project aimed at undertaking a detailed investigation of the fine sediment budgets of the study catchments was included within the LOCAR research programme and this contribution reports some of the findings of the investigations undertaken with the Pang and Lambourn catchments. Whilst focusing on these two catchments, the results are likely to be of relevance to Chalk catchments in the UK, more generally, and they also afford a useful and timely contribution to ongoing international research on catchment sediment budgets. The important need for field-based studies of catchment sediment budgets has, for example, been explicitly emphasized by Trimble and Crosson (2000).

The study areas

The Pang (~166 km^2) and Lambourn (~234 km^2) catchments are both underlain by the Chalk aquifer of the West Berkshire Downs. The mean annual precipitation (1961–1990) over the Pang catchment lies in the range 647–706 mm, whilst that for the Lambourn catchment is slightly higher and in the range (698–793 mm). Intensive arable agriculture has become increasingly widespread in the Pang catchment over the past few decades and there has also been an expansion of Christmas tree cultivation and free range pig rearing. Recent years have also seen a substantial increase in groundwater abstraction for public supply, and the reduced flows, coupled with the increased risk of soil erosion within the catchment associated with land use change, have resulted in increased concern for 'sediment problems' and their impact on the local EC-designated salmonid fishery. The Lambourn catchment is less intensively farmed and is characterized by a more natural stream system, supporting good populations of trout and grayling and considerable invertebrate diversity. It is one of 27 rivers in the UK designated as a Site of Special Scientific Interest (SSSI). Routine water quality monitoring stations were installed in association with the LOCAR programme at Frilsham, Bucklebury and Tidmarsh Mill in the Pang catchment, and at East Shefford and Shaw in the Lambourn catchment (see Fig. 1).

Methodology

The sediment budget approach

The sediment budget concept provides a valuable framework for assembling the information necessary for understanding and interpreting fine sediment mobilization, delivery, storage and output at the catchment scale (Dietrich and Dunne, 1978; Swanson et al., 1982; Golosov et al., 1992; Nelson and Booth, 2002). Establishing a sediment budget provides a means of clarifying the link between upstream erosion and downstream sediment yield and the role of sediment storage (Walling, 1983, 1999; Dunne, 1994; Trimble, 1995; Trimble and Crosson, 2000; Slaymaker, 2003). Storage frequently equals or exceeds sediment output (Phillips, 1991; Walling et al., 1998).

Despite the obvious utility of the sediment budget concept, it remains difficult to assemble the necessary information for anything other than a small (e.g. <10 km^2) drainage basin. Traditional techniques available for investigating sediment mobilization by erosion and sediment storage, within a catchment, are hampered by significant spatial and temporal sampling constraints (Peart and Walling, 1988; Loughran, 1989; Phillips, 1991; Collins and Walling, 2004), numerous operational problems and the costs incurred in assembling representative datasets (Slaymaker, 2003).

Although there is no commonly accepted and generally applicable methodology for establishing a catchment sediment budget, recent work at the University of Exeter has successfully developed and tested an integrated approach

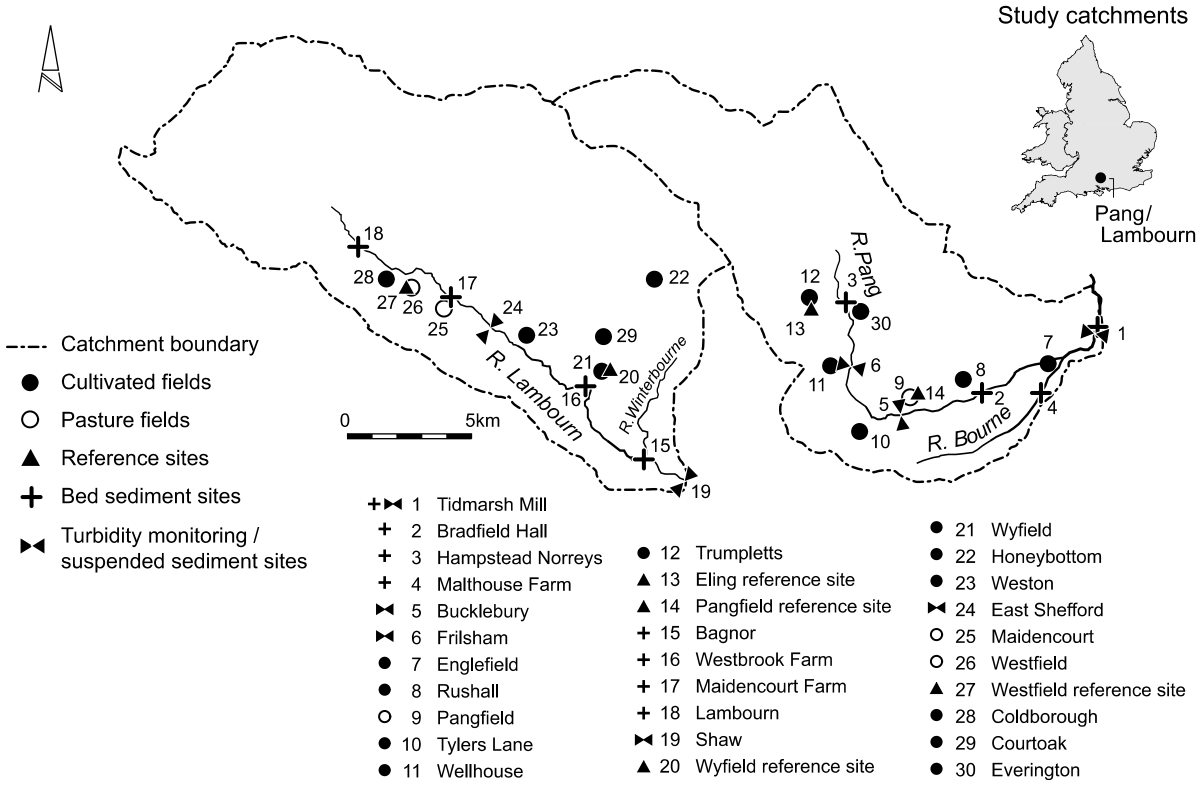

Figure 1 Location maps of the Pang and Lambourn study catchments, showing the ^{137}Cs soil coring, channel bed and suspended sediment sampling and water quality monitoring sites.

(see Fig. 2) to assembling the required information (see Walling and Collins, 2000; Walling et al., 2001, 2002). Caesium-137 (^{137}Cs) measurements are used to provide representative information on sediment mobilization and redistribution rates on the catchment slopes; sediment fingerprinting procedures are employed to establish the relative importance of major sediment sources to the sediment output from the catchment; a re-suspension technique is used to quantify channel bed sediment storage; and conventional river monitoring provides information on the suspended sediment flux at the catchment outlet. Where overbank sedimentation on floodplains represents a significant sediment sink, this can also be quantified using ^{137}Cs measurements. Synthesis of the information assembled for the individual budget components, including fine sediment mobilization, storage and delivery, provides the basis for establishing the catchment suspended sediment budget. Floodplain deposition was not included as a storage term in the sediment budget for the two study catchments reported here, because contemporary records indicated that overbank inundation rarely occurs, due to the impact of groundwater abstraction on the local flow regimes.

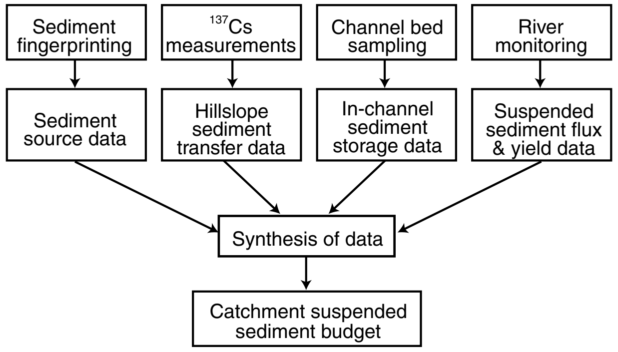

Figure 2 The integrated approach for establishing the study catchment suspended sediment budgets.

Estimating sediment mobilization and redistribution on catchment slopes

Soil and sediment mobilization and redistribution on the slopes of the Pang and Lambourn study catchments were investigated using ^{137}Cs. Caesium-137 is an artificial fallout radionuclide that was released into the environment by the atmospheric testing of thermonuclear weapons between the early 1950s and the 1970s. Following its introduction into the stratosphere, ^{137}Cs was distributed globally and deposited as fallout, primarily in association with rainfall. Due to its strong affinity for soil and sediment particles, fallout ^{137}Cs reaching the land surface is readily and strongly adsorbed by the surface soil, with the result that its subsequent redistribution reflects the physical processes of erosion, transport and deposition. By comparing the inventories measured at different points on a slope with the local reference inventory, which represents the inventory currently associated with a location that has experienced neither erosion nor deposition during the period since the ^{137}Cs fallout was received, it is possible to identify eroding (reduced ^{137}Cs inventories) and depositional (increased ^{137}Cs inventories) areas. Conversion models can be used to quantify the erosion and deposition rates involved (e.g. Walling and He, 1999). These rates will represent the mean erosion or deposition rate associated with the period between the onset of ^{137}Cs fallout in the mid 1950s and the time of sample collection. The ^{137}Cs approach possesses a number of key advantages including the potential for obtaining retrospective medium-term (~40 yr) information on the basis of a single site visit, the provision of spatially distributed information on rates of erosion and deposition and its applicability in many different areas of the world (Walling, 1998, 2002; Zapata, 2003).

Existing conversion models, used to estimate the rate of erosion or deposition for a sampling point from the loss or gain in the ^{137}Cs inventory measured at that point, relative to the local reference inventory, can be grouped into two main types, namely, empirical relationships and theoretical models. The precise procedures employed by these models vary according to whether the study site is on cultivated or uncultivated land. Because of the many problems associated with empirical conversion models (see Walling and Quine, 1990; Walling and He, 1999), theoretical conversion models are used in most investigations. For cultivated land, theoretical approaches have traditionally involved either the proportional model (e.g. Vanden Berghe and Gulinck, 1987) or various mass balance algorithms (e.g. Kachanoski, 1993), whilst for uncultivated land the profile distribution model has commonly been employed (e.g. Zhang et al., 1990). More recently, improved versions of these models have been documented by Walling and He (1999). In the case of cultivated soil, the improved versions of the mass balance model take account of the time-variant fallout inputs of ^{137}Cs to the land surface, the removal of freshly deposited ^{137}Cs fallout prior to its incorporation into the plough layer by tillage, the grain size selectivity of sediment mobilization and redistribution and the effects of tillage translocation. For uncultivated land, the profile distribution model has been refined to take explicit account of the post-fallout redistribution of ^{137}Cs within the soil profile as a consequence of physicochemical and biological processes and the resulting model has been referred to as the diffusion and migration model. These improved models have been successfully employed to document soil redistribution rates in various parts of the world (e.g. Walling et al., 1999a; Collins et al., 2001a; Schuller et al., 2003; Zhang et al., 2003; Theocharapoulos et al., 2003; Fulajtar, 2003; Belyaev et al., 2005).

A total of four carefully selected reference locations were used to estimate the ^{137}Cs reference inventories for the Pang and Lambourn study catchments (see Fig. 1). At each reference location, individual bulk soil cores (15 or 18) were collected from a sampling area of ca. 16–24 m^2, using a grid sampling strategy with three replicates at each intersection. In addition, a single sectioned core (1 cm depth increments) was retrieved from the sampling area at each reference location. The spatial variability of ^{137}Cs inventories within areas under both arable cultivation and pasture in each study catchment was characterized using a comprehensive slope transect-based soil sampling programme, yielding a further 461 soil cores. This component of the sediment budget investigation focused on a representative sample of 11 cultivated and three pasture fields, respectively (see Fig. 1). Two parallel downslope transects were used in each sampled field and the individual bulk cores collected along these transects, whilst being spaced at approximately 10 m intervals, were located to take account of local conditions, and more particularly localized changes in topography and visually important features e.g. areas of significant deposition. Additional sectioned cores were also collected from representative points along the slope transects. The bulk soil cores obtained from both the reference sites and the transects within individual fields were collected to a minimum depth of ca. 35 cm using a custom-made steel core tube (internal diameter = 6.9 cm), which was propelled into the soil using a motorized percussion driver and subsequently extracted by means of a portable winch. The sectioned cores were collected using a larger core tube (internal diameter = 10 cm) and the cores were sectioned in the laboratory after their removal from the core tube.

Upon return to the laboratory, all bulk soil cores and sectioned cores were oven-dried at 40 °C, disaggregated and mechanically sieved to <2 mm. The ^{137}Cs content of each individual soil core or section was measured by gamma spectrometry, using high-resolution coaxial HPGe gamma detectors. Caesium-137 activity was counted at 662 keV for ca. 45 000 s, yielding a precision of ca. ±10% at the 95% level of confidence. In order to provide the grain size information required by the calibration models, the absolute particle size composition of the soil associated with a representative range of cores was measured using a laser diffraction granulometer, following sample pre-treatment to destroy organic matter and chemical/ultrasonic dispersion.

Quantitative estimates of soil erosion and redistribution rates for the individual slope sampling transects were obtained using the improved conversion models outlined above (cf. Walling and He, 1999), which relate the reduction or gain in the measured inventory, relative to the reference inventory, to the rate of erosion or deposition, respectively. The mass balance model incorporating tillage translocation, proposed by Walling and He (1999), was used for the transects located in cultivated areas, whilst the diffusion and migration model proposed by the same workers, was employed to estimate soil and sediment redistribution rates on uncultivated land. These conversion models provided point estimates of erosion or deposition rates ($\mathrm{g\ m^{-2}\ yr^{-1}}$) for each soil core collected along individual slope transects. Assuming that each sampling transect can be represented as a 1 m wide strip and that the point samples are representative of the section of that strip extending half way towards the next core, both upslope and downslope, the erosion and deposition rates for the individual sections were summed to provide an overall budget for the entire slope transect, comprising estimates of gross or total erosion, total deposition and net erosion ($\mathrm{g\ m^{-2}\ yr^{-1}}$).

Identifying sediment sources

The relative contribution of the four primary potential sediment source types identified within the Pang and Lambourn study catchments, namely, channel banks/subsurface sources, and areas of the catchment surface under arable cultivation, pasture and woodland, to the suspended sediment yield at the catchment outlets was established using the fingerprinting approach. Sediment fingerprinting is founded upon the link between the geochemical properties of suspended sediment and those of its source material. Assuming potential source materials can be distinguished on the basis of their geochemical properties or 'fingerprints', the likely provenance of the suspended sediment can be established by comparing the properties of the sediment with those of the potential individual sources. Although a wide range of soil and sediment properties has traditionally been used as a means of discriminating potential sediment sources, including mineralogy (Hillier, 2001), mineral-magnetism (Slattery et al., 2000), geochemistry (Walling and Kane, 1984), environmental radionuclides (Walling and Woodward, 1992) and organic substances (Hasholt, 1988), most source fingerprinting studies now employ 'composite fingerprints'. Composite signatures comprise a range of different diagnostic properties influenced by contrasting environmental controls and thereby greatly improve the reliability of sediment source discrimination (Walling et al., 1993; Collins and Walling, 2002). Composite fingerprints have been successfully employed to establish the relative importance of individual sediment source types in a number of different contexts (e.g. Collins et al., 1997a; Walling et al., 1999b; Russell et al., 2001; Collins et al., 2001b; Wallbrink et al., 2003; Motha et al., 2004; Walling and Collins, 2005).

Source material sampling within the study catchments (total $n = 104$ for the Pang catchment and 120 for the Lambourn catchment) focused on obtaining representative samples from the potential sediment sources and was stratified to encompass surface soils supporting woodland, pasture and cultivation, and channel banks/subsurface sources. Samples collected from potential surface sources comprised topsoil (i.e. 0–2 cm) susceptible to mobilization by water and subsequent routing to the river channel network, whilst those used to represent channel banks and subsurface sources were collected from actively eroding channel margins and ditches.

Representative suspended sediment samples for use in the source fingerprinting studies were collected at the water quality monitoring stations at the outlets of the two study catchments (see Fig. 1), using time-integrating sampling traps, previously developed at the University of Exeter (Phillips et al., 2000; Russell et al., 2000). Two samplers were installed at each location, in order to minimise the problems of sampler failure and to provide sufficient sample mass for subsequent laboratory analyses. Deployment of these samplers provided a basis for collecting time-integrated suspended sediment samples and thereby avoided the problems of non-representative sampling associated with 'spot' river water sampling strategies and the logistical problems arising from the need to visit several sampling sites during individual storm events. A total of six individual time-integrated sediment samples was collected from the sampling station for the Pang catchment at Tidmarsh Mill, whilst three samples were obtained for the sampling station for the Lambourn catchment at Shaw.

Upon return to the laboratory, all source material samples were oven-dried at 40 °C, disaggregated using a pestle and mortar, and dry sieved to <63 μm, in order to facilitate direct comparison with the suspended sediment samples. The latter were recovered from the water samples provided by the routine emptying of the time-integrating trap samplers, by means of sedimentation and centrifugation, prior to freeze-drying in preparation for chemical analyses. All sediment samples were homogenized and passed through a 63 μm sieve prior to analysis of their geochemical properties. The source material and suspended sediment samples were analyzed for a range of fingerprint properties. Following acid digestion, ICP-MS was used to measure the total concentration of Al, As, Ba, Bi, Ca, Cd, Ce, Co, Cr, Cs, Cu, Dy, Er, Eu, Fe, Ga, Gd, Ge, Hf, Ho, La, Li, Mg, Mn, Mo, Na, Nd, Ni, Pb, Pd, Pr, Rb, Sb, Sc, Sm, Sn, Sr, Tb, Ti, Tl, V, Y, Yb, Zn and Zr. Inorganic, organic and total P were determined by pyrolysis by UV/Visible spectrophotometry, following the molybdenum blue extraction procedure described by Mehta et al. (1954). Radionuclide activities (^{137}Cs, unsupported ^{210}Pb and ^{226}Ra) were assayed by gamma spectrometry using either high-resolution n-type coaxial (source material samples) or well-type (suspended sediment samples) HPGE detectors (Walling and Collins, 2000). C and N content was determined by pyrolysis using a Carlo Erba automatic analyzer. The absolute grain size composition of source material and suspended sediment samples was measured using a laser diffraction granulometer, following pre-treatment with hydrogen peroxide to remove the organic fraction and chemical/ultrasonic dispersion.

The quantitative composite fingerprinting procedure described by Collins et al. (1997b) was used to establish the relative importance of the four potential sediment source types identified in the two study catchments. This procedure comprised two key stages, namely, the use of a statistical verification procedure to identify an optimum composite fingerprint for discriminating the four primary source types and, secondly, the use of a multivariate mixing model to compare the properties of the individual suspended sediment samples with those of the potential sources and to establish the relative contribution of each source type to the suspended sediment flux sampled at each gauging station. Stage one was based on the use of the Kruskal–Wallis H-test and stepwise multivariate discriminant function analysis within the SPSS computer software package. The sediment-mixing model incorporated correction factors for contrasts in particle size composition and organic matter content between source material and suspended sediment samples, as well as a weighting factor to take account of the differing levels of precision associated with laboratory measurements of individual fingerprint properties (see Collins et al., 1997b). The mixing model was optimised by minimizing the sum of the squares of the weighted relative errors, in order to determine the relative contribution of each potential source. The model was executed using the Solver function in Microsoft Excel. To provide an indication of the uncertainty associated with the mixing model, goodness-of-fit tests comparing the fingerprint property concentrations measured in the suspended sediment samples, with the corresponding values predicted by the model, based on the optimized contributions from the individual source types to those samples, indicated a typical relative error of ±14% (cf. Collins et al., 1997b). This level of uncertainty is equivalent to that associated with other components of the sediment budget. The optimised mixing model was therefore judged to provide a meaningful prediction of the concentrations of the fingerprint properties measured in the sediment samples collected using the time-integrating traps. A load-weighting procedure, based on the magnitude of the suspended sediment load for the individual periods of sampler deployment, was used to establish the mean contributions from the individual sediment source types during the winter and summer and over the entire monitoring period. This procedure ensured that mixing model estimates of source contributions for sediment samples collected during periods of higher sediment loadings were assigned greater weight when calculating the mean contribution associated with a particular source (cf. Walling et al., 1999b; Collins et al., 2001b).

Estimating fine sediment storage on the channel bed

The amount of fine-grained sediment stored on the channel bed of each study river was determined at regular intervals using the method proposed by Lambert and Walling (1988). A metal cylinder (height = 1 m; area = 0.16 m^2) was carefully lowered onto, and pushed into, the channel bed with minimal disturbance, in order to create a seal and to permit a known area of the river bed to be sampled. The water and upper 5 cm of the channel bed enclosed within the cylinder were then stirred rigorously with a metal rod, in order to remobilize the fine sediment stored both on the surface and within the surface horizon of the river bed gravels. Representative samples of the sediment present in suspension within the cylinder following agitation were collected using 0.5 l bottles and the sediment concentrations associated with these samples were used to provide an estimate of the amount of sediment remobilized and the sediment storage per unit area of bed (g m^{-2}). The sampling procedure was repeated twice at different points at each sampling site, as a means of taking account of local spatial variations in fine sediment storage associated with variations in water depth or channel bed morphology and texture (cf. Adams and Beschta, 1980; Diplas and Parker, 1992; Walling and Quine, 1993). One sample was retrieved from the thalweg, where fine sediment storage was expected to be lowest, and a second from close to the river bank visually evidencing the greatest storage. The average of the two measurements was considered to provide a meaningful estimate of fine bed sediment storage at each sampling site at the time of sampling. The sampling sites were selected to be representative of the surrounding reach. For some sampling campaigns, coverage of the sampling sites was restricted by lack of water in the channel, and this problem was most frequently encountered at the Hampstead Norreys and Lambourn sampling sites (see Fig. 1).

Upon return to the laboratory, the concentration of fine sediment in the 0.5 l bottles was determined gravimetrically using vacuum filtration. The amount of fine sediment released from the channel bed per unit surface area (g m^{-2}), which was used as a measure of sediment storage, was estimated as the product of the sediment concentration within the cylinder (g m^{-3}) and the volume of water contained within the cylinder (m^3) divided by the area of the channel bed (m^2) enclosed within the sampling cylinder (Lambert and Walling, 1988). Estimates (total $n = 74$) of fine-grained sediment storage within the channel were obtained approximately bimonthly at four sites along the main channel systems of each of the study catchments (see Fig. 1) during the period February 2003–September 2004.

The estimates of mean fine sediment storage obtained for the individual sampling sites were scaled up to estimate the mean total channel bed storage of fine sediment in the study catchments. For this purpose, each study river was divided into reaches, defined by the individual sampling sites, and the estimates of fine sediment storage obtained for those sampling sites were assumed to be representative of the associated reach. Sediment storage within the individual reaches was estimated using information on the length and width of the reaches obtained from field measurements, coupled with the estimates of mean fine sediment storage obtained for the individual reaches, derived as the mean of the values for the sampling points at the two boundaries of the reach. The storage values for the individual reaches were summed to provide an estimate of the mean total channel bed storage of fine sediment (cf. Walling et al., 1998; Owens et al., 1999; Collins et al., 2005).

Monitoring suspended sediment fluxes

There are many uncertainties and potential errors associated with the use of low frequency manual suspended sediment sampling programmes, coupled with conventional interpolation or extrapolation procedures, to derive estimates of the suspended sediment yield from a catchment (see Walling and Webb, 1988; Webb et al., 1997). High frequency sediment concentration data can be assembled using automatic sampling equipment, but this approach requires substantial effort in the laboratory to determine the sediment concentrations of the water samples and significant manpower in the field to assist with equipment servicing and maintenance (Walling, 1994). In response to these problems, turbidity sensors are being increasingly employed as a cost-effective means of assembling reliable, quasi-continuous, information on suspended sediment concentrations (e.g. Walling and Webb, 1987; Wass and Leeks, 1999; Heywood and Walling, 2003; Old et al., 2003). Self-cleaning, infra-red, optical backscatter (OBS) turbidity probes linked to data loggers were installed at each of the suspended sediment monitoring stations within the study catchments. These turbidity probes were calibrated with commercial turbidity standards to check their long-term stability and the turbidity data were converted to records of suspended sediment concentration, using site-specific concentration/turbidity calibration relationships, based on suspended sediment samples collected both manually and by automatic samplers. Suspended sediment loads were calculated by combining the records of suspended sediment concentration provided by the turbidity sensors with the continuous records of water discharge available for the monitoring sites.

Results and discussion

The individual components of the sediment budget

Soil and sediment redistribution on the slopes

Summary statistics for the ^{137}Cs inventories of the soil cores collected from the four reference locations are presented in Table 1. For the Pang catchment, mean reference inventory values of 1614 and 1921 Bq m^{-2} were obtained for the Pangfield and Eling reference sites, respectively, whilst for the Lambourn catchment the corresponding values for the Wyfield and Westfield reference sites were 1743 and 2199 Bq m^{-2}. The standard deviation values, associated with the ^{137}Cs inventories measured for each individual sam-

Table 1 Summary statistics for the ^{137}Cs inventories measured in the soil cores collected from the reference locations sampled in the Pang and Lambourn study catchments

Catchment	Sampling site	Mean (Bq m^{-2})	Median (Bq m^{-2})	Standard deviation (Bq m^{-2})	S.E. mean (Bq m^{-2})	CV (%)	No. of soil cores collected
Pang	Eling	1921	1878	305	72	16	18
	Pangfield	1614	1501	440	104	27	18
Lambourn	Westfield	2199	2259	258	67	12	15
	Wyfield	1743	1815	452	117	26	15

pling location, emphasize the need to use more than a single core to provide a meaningful estimate of the reference inventory (Wallbrink et al., 1994; Ruse and Peart, 1999; Collins et al., 2001a).

Due to the problems encountered in identifying suitable undisturbed sampling locations for estimating ^{137}Cs reference inventories within the intensively farmed landscape of the Pang and Lambourn study catchments and the limited number of reference sites sampled, a spatial interpolation procedure was employed to estimate the reference inventories for the individual slope transect sampling locations. Use of a reference inventory specific to each slope transect sampling location was deemed necessary, on account of the spatial variability of the measured ^{137}Cs reference values demonstrated in Table 1. The interpolation procedure was based upon the results of stepwise linear regression analysis, relating the mean ^{137}Cs inventories obtained for the four sampled reference locations to three independent variables selected to represent factors likely to influence the spatial variability of the reference inventory across the study catchments, namely, longitude, latitude and altitude. Altitude (*m*) was selected by the regression analysis as the most important causal factor governing the spatial variation in the measured ^{137}Cs reference inventories ($^{137}\mathrm{Cs}_{\mathrm{ri}}$ Bq m^{-2}) across the study areas, as indicated by the relationship:

$$^{137}\mathrm{Cs}_{\mathrm{ri}} = 8.63 * \mathrm{altitude} + 812.3 \quad (r^2 = 0.998;\ \mathrm{significance} = 0.01) \qquad (1)$$

No further independent variables were selected by the stepwise multiple regression routine. The significance of altitude is likely to reflect the trend for mean annual rainfall to increase towards the more elevated areas in the north of the study catchments. On the basis of the regression relationship, the reference inventories estimated for the individual slope transect sampling locations ranged between 1516 and 2259 Bq m^{-2}.

As examples, the results of using the appropriate ^{137}Cs-based conversion models to document medium-term (~40 yr) erosion and deposition rates along four slope transects, selected to be representative of cultivated and pasture fields within the study catchments, are presented in Fig. 3. Both erosion and deposition are evident along each transect. In the case of the Everington sampling transect for cultivated land in the Pang catchment (see Fig. 3a), erosion rates for individual coring points range between 87 and 5193 g m^{-2} yr^{-1}, whilst deposition rates vary from 91 to 9951 g m^{-2} yr^{-1}. Deposition is particularly evident at the base of the slope. A similar pattern is shown by the Courtoak sampling transect for a cultivated field in the Lambourn catchment (see Fig. 3c), where deposition ranges between 10 and 251 g m^{-2} yr^{-1} and is primarily focused along the concave basal portion of the slope profile. In the case of the pasture transects, the point estimates of erosion and deposition rates are in most cases significantly lower than those obtained for the cultivated transects. Erosion rates range between 37 and 599 g m^{-2} yr^{-1} and 9 and 343 g m^{-2} yr^{-1} and deposition rates vary beween 29 and 260 g m^{-2} yr^{-1} and 14 and 330 g m^{-2} yr^{-1} for the Pangfield (Pang) and Maidencourt (Lambourn) sampling sites, respectively (see Fig. 3b and d).

The information provided by the individual coring points along each transect was used to estimate the total or gross erosion, deposition and net soil loss, associated with the individual transects. The results for the two transects sampled within each field were subsequently averaged (see Table 2). Table 2 again indicates that both gross and net erosion rates are significantly higher on cultivated land than on pasture and that values for the Pang catchment are generally higher than for the Lambourn catchment. The values for gross and net erosion rates listed in Table 2 are comparable with those documented for pasture and cultivated fields using the ^{137}Cs technique in other lowland regions of the UK (cf. Owens et al., 1997; Walling et al., 2002; Quine and Walling, 1991), but are somewhat lower than the rates of soil redistribution reported for Chalk environments elsewhere in Europe (cf. Soileau et al., 1990; Wicherek and Bernard, 1995). The mean in-field sediment delivery ratios for pasture fields are higher (53%) in the Lambourn than in the Pang (14%), whereas the opposite is true for cultivated fields (68% in the Pang and 34% in the Lambourn).

In the absence of erosion rate estimates from a greater range of fields, that would enable the influence of a range of controlling variables to be assessed and used as a basis for spatial extrapolation of the erosion and deposition rates derived from the ^{137}Cs measurements, the range of values for the sampled fields used to represent each land use in the individual study catchments were considered to be representative of those catchments (see Table 2).

Sediment sources

The sediment properties included in the optimum composite fingerprints identified by the discriminant function analysis for use in establishing the relative importance of the various potential suspended sediment sources in the Pang and Lambourn catchments are listed in Table 3. For both catchments, the composite fingerprint comprises a range of properties, including both trace metals and nutrients, and, in the case of the Lambourn catchments, the radionuclide ^{137}Cs.

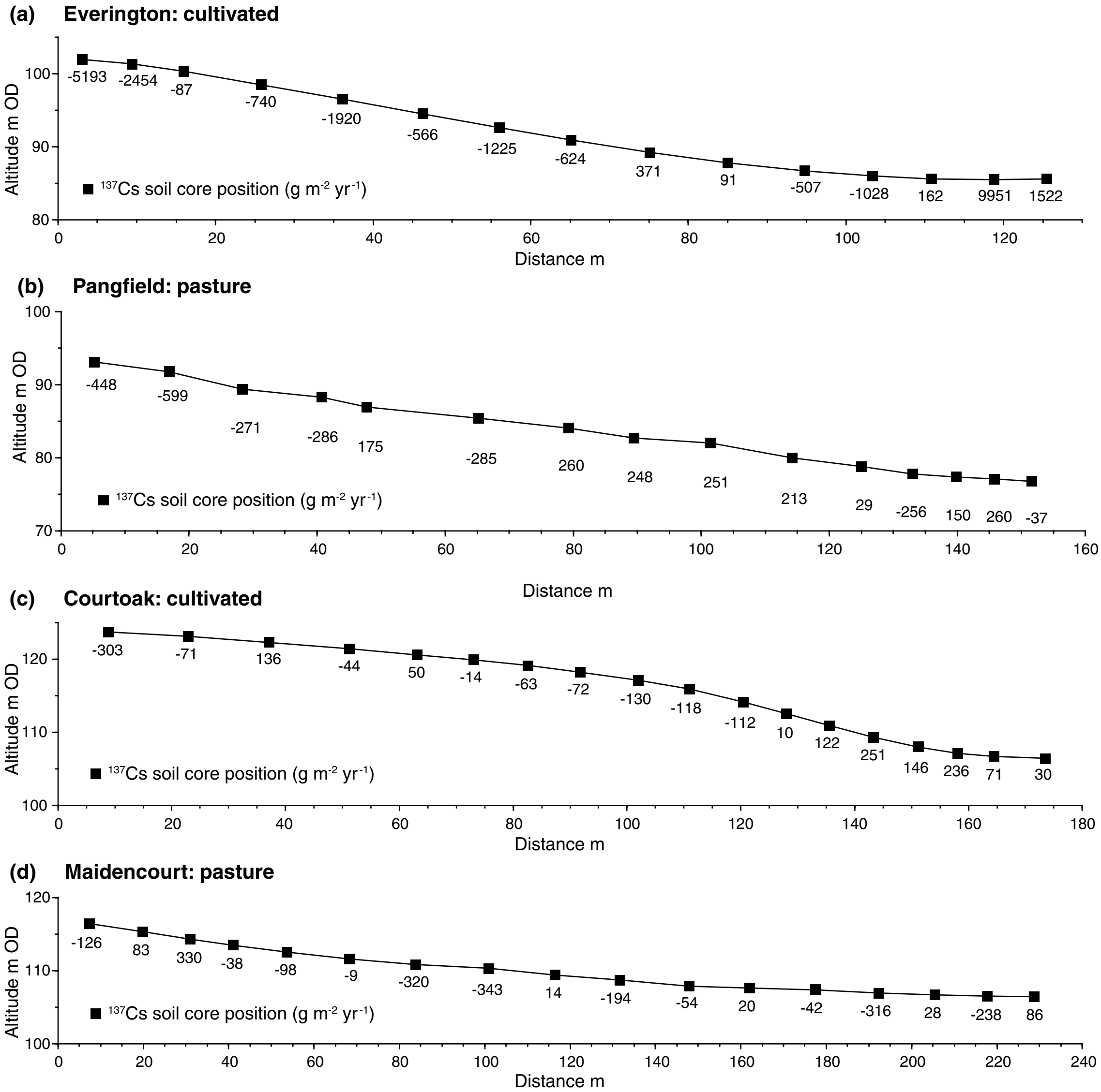

Figure 3 ^{137}Cs-based estimates of soil erosion and deposition rates for a selection of transects representative of areas of pasture and cultivation in the Pang and Lambourn study catchments.

The composite fingerprint identified for the Lambourn catchment provides a higher level of discrimination of the available source samples (97.5%) than that for the Pang catchment (88.3%), but the analysis of relative errors described previously, indicated that both were likely to provide an effective basis for defining the sediment sources in the two catchments. Information on the provenance of the suspended sediment fluxes sampled at the outlets of the Pang and Lambourn study catchments provided by the sediment fingerprinting investigations is summarized in Fig. 4. Load-weighted mean relative contributions from the four individual sediment source types are quite similar for both study areas. For example, surface soils from woodland areas do not represent a significant sediment source in either catchment and eroding channel banks/subsurface sources contribute only ca. 1% of the sediment output from each study catchment. The absence of high magnitude flow events, commonly considered to be responsible for bank erosion, and the subdued cross-sections of chalk stream channels, characterized by very limited bank development and exposure, mean that channel margins are typically of limited importance as potential sediment sources in these particular lowland permeable catchments. The surface soils of cultivated areas are the most important sediment source in both catchments, contributing 67% and 50% of the suspended sediment yield from the Pang and Lambourn catchments, respectively (see Fig. 4). The exposure of bare tilled soils to winter rainfall, associated with the growing of autumn-sown cereal crops, promotes the mobilization of sediment on cultivated land and its subsequent delivery downslope is assisted by vehicle wheelings and tracks. Surface soils under pasture are also an important sediment source, contributing 32% and 49% of the sediment output from the Pang and Lambourn catchments respectively. The importance of pasture areas as a sediment source reflects the widespread poaching of such areas by livestock, during the winter period.

Table 2 Mean erosion and deposition rates estimated for the slope transect sampling locations used to represent areas of pasture and cultivation within the Pang and Lambourn study catchments, based on ^{137}Cs measurements

Catchment	Sampling site	Land use	Max. slope angle (°)	Max. slope length (m)	Gross erosion (g m^{-2} yr^{-1})	Deposition (g m^{-2} yr^{-1})	Net soil loss g m^{-2} yr^{-1})	SDR[a] (%)
Pang	Trumpletts	Cultivated	8.9	275.0	1020	60	960	94
	Everington	Cultivated	12.0	125.5	790	170	620	79
	Wellhouse	Cultivated	4.6	170.8	460	350	110	24
	Tylers Lane	Cultivated	7.6	235.1	270	150	120	44
	Rushall	Cultivated	5.3	251.1	520	320	200	39
	Englefield	Cultivated	8.2	210.4	740	170	570	77
	Pangfield	Mean			633	203	430	68
		Pasture	13.1	151.6	140	120	20	14
		Mean			140	120	20	14
Lambourn	Coldborough	Cultivated	9.9	189.5	750	220	530	71
	Weston	Cultivated	5.8	278.1	320	280	40	13
	Wyfield	Cultivated	14.9	87.9	380	260	120	32
	Honeybottom	Cultivated	7.3	154.2	480	430	50	10
	Courtoak	Cultivated	12.0	173.5	430	370	60	14
		Mean			472	312	160	34
	Maidencourt	Pasture	5.5	234.0	110	40	70	64
	Westfield	Pasture	23.0	98.9	80	50	30	38
		Mean			95	45	50	53

[a] SDR = slope sediment delivery ratio.

Table 3 The fingerprint properties included in the composite fingerprints identified for the Pang and Lambourn catchments using discriminant function analysis

Catchment	Fingerprint property	Cumulative % source samples classified correctly
Pang	V	51.5
	Sn	62.1
	K	68.9
	Mn	71.8
	Ge	77.7
	Zr	77.7
	Nd	79.6
	P	81.6
	N	88.3
Lambourn	N	60.8
	Mn	64.2
	Cd	75.8
	^{137}Cs	78.3
	Ge	87.5
	Ca	89.2
	Zr	92.5
	Sn	93.3
	Ga	92.5
	Ce	95.5
	Zn	95.8
	K	97.5

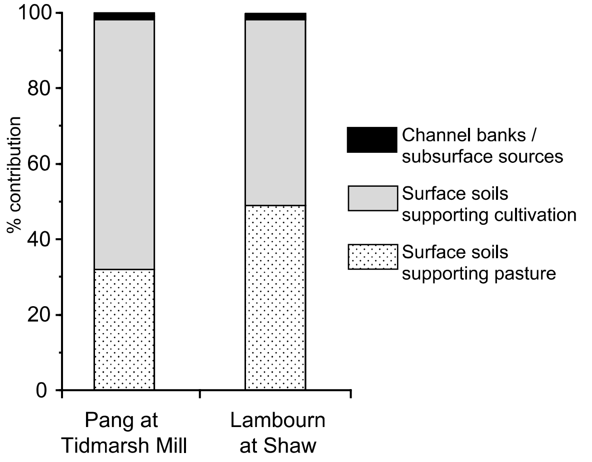

Figure 4 Load-weighted mean relative contributions from individual sediment source types.

Bed sediment storage

Table 4 summarises the results provided by the sediment resuspension technique, used to investigate the storage of fine-grained sediment on the channel bed of the study rivers. The data presented represent mean values of fine sediment storage associated with the periodic measurements undertaken at the individual sampling sites over the period extending from February 2003 to September 2004. For the River Pang, values range from 470 g m^{-2} at Malthouse Farm on the Bourne tributary to 2290 g m^{-2} at Bradfield Hall on the main channel (see Fig. 1). For the River Lambourn, the equivalent values range between 770 and 1760 g m^{-2} for the Lambourn and Westbrook Farm sampling sites, respectively (see Fig. 1). These values are assumed to provide meaningful estimates of the amount of fine-grained sediment sequestered in transient storage on and within the upper 5 cm of the channel bed. The coefficients of variation (CV) listed in Table 4 demonstrate the existence of substantial temporal variations in fine sediment storage on

Table 4 Mean storage of fine-grained sediment on the channel bed of the Pang and Lambourn study catchments, determined using a re-suspension technique

Catchment	Sampling site	n^a	Storage (g m^{-2})	CV (%)
Pang	Tidmarsh Mill	10	1000	110
	Bradfield Hall	10	2290	91
	Hampstead Norreys	8	500	100
	Malthouse Farm	10	470	40
Lambourn	Bagnor	10	1630	63
	Westbrook Farm	10	1760	78
	Maidencourt Farm	9	860	50
	Lambourn	7	770	120

[a] Number of sampling visits.

the channel bed at each sampling site during the field sampling programme.

The values of channel bed storage of fine sediment obtained for the individual sampling sites within the Pang and Lambourn study rivers compare closely with those reported for other rivers in the UK and elsewhere. For example, Lambert and Walling (1988), who used a similar procedure, reported that the average fine sediment storage on the bed of the River Exe in Devon, UK, was 400 g m^{-2}. Working on the River Severn, UK, Walling and Quine (1993) estimated that bed storage ranged between 630 and 8000 g m^{-2}, while Droppo and Stone (1994) reported values ranging between 660 and 2200 g m^{-2} for three rivers in Ontario, Canada. Collins et al. (2005) estimated that fine sediment storage on the channel bed of the Rivers Frome and Piddle in Dorset, UK, ranged between 410–2630 g m^{-2} and 260–4340 g m^{-2}, respectively.

Fig. 5 presents the results of extrapolating or upscaling the measurements of channel bed sediment storage obtained for each individual sampling site, using information on reach length and width, to provide estimates of storage for individual reaches and for the entire main channel system of each study catchment. In the Pang catchment, channel bed storage increases downstream from 10 t (3 t km^{-1}) in the reach between the source and Hampstead Norreys, to 83 t (13 t km^{-1}) in the reach between Bradfield Hall and Tidmarsh (see Fig. 5). Estimates of bed sediment storage at Malthouse Farm were considered representative of the entire channel length of the Bourne tributary. The mean total amount of fine sediment stored on the bed of the main channel system of the Pang catchment is estimated to be 191 t, whilst the mean specific bed sediment storage is 5 t km^{-1}. For the River Lambourn, sediment storage also increases downstream, ranging from 6 t (2 t km^{-1}) for the reach between the source and Lambourn, to 118 t (16 t km^{-1}) in the reach between Maidencourt and Westbrook Farm (see Fig. 5). Values of bed sediment storage obtained for Lambourn and Maidencourt Farm were averaged to estimate sediment storage in the Winterbourne tributary. The total mass of sediment stored within the main channel system of the Lambourn catchment is estimated to be 229 t, providing a mean specific bed sediment storage of 7 t km^{-1}. These patterns reflect both the downstream increase in the surface area of the channel bed and the spatial variability of bed sediment storage reported in Table 4. Similar downstream trends have been reported for other river systems (e.g. Walling et al., 1998; Collins et al., 2005).

The estimates of the average amount of fine sediment stored within the main channel systems of the Rivers Pang and Lambourn presented above (191 t and 229 t, respectively) indicate that substantial amounts of channel storage occur in both catchments. However, these values do not in themselves confirm that this storage should be viewed as 'active' storage, with significant quantities of sediment passing into and out of storage during the year. Comparison of the upscaled storage estimates obtained for different sampling campaigns during the study period confirmed that the total amount of fine sediment contained in the channel stores of the two study catchments varied substantially throughout the year and that the amounts entering and leaving storage during a typical year were likely to exceed the average storage values. In the absence of more precise

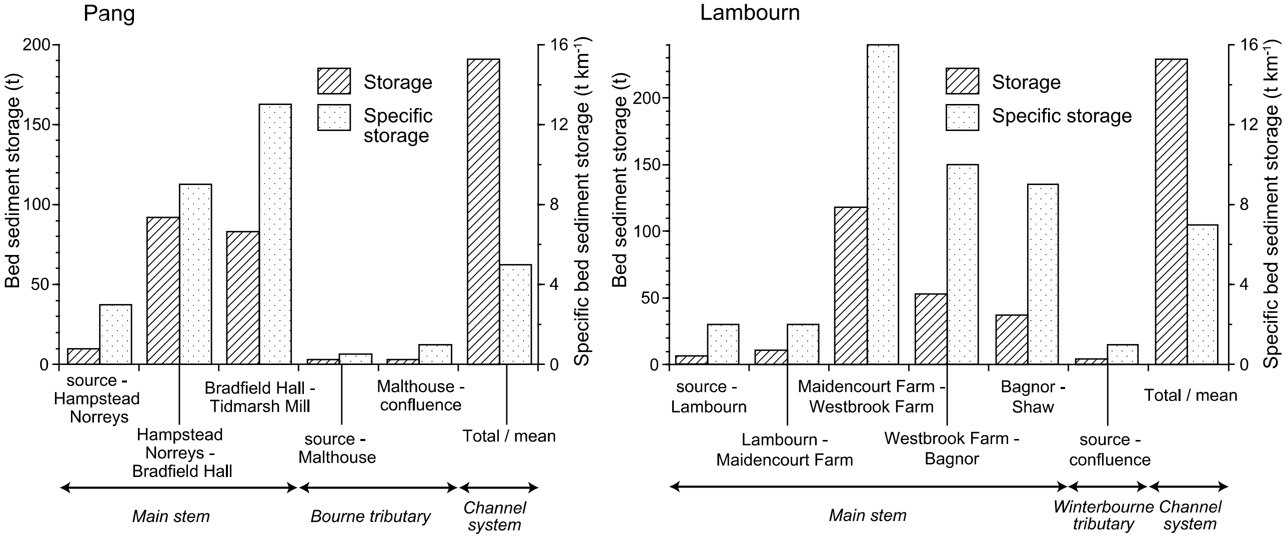

Figure 5 Estimates of the storage of fine-grained sediment on the bed of the main channel systems of the Pang and Lambourn study catchments.

estimates, it is suggested that the average values of total channel storage for the two catchments should be viewed as values of active storage, with at least this amount of sediment passing into and out of storage during a typical year.

Suspended sediment yield

Based on the continuous turbidity records, the mean annual specific suspended sediment yields from the study catchments were estimated to be 2.4 t km^{-2} yr^{-1} at Tidmarsh Mill at the outlet of the Pang catchment and 3.7 t km^{-2} yr^{-1} at Shaw at the outlet of the Lambourn catchment. Fig. 6 presents suspended sediment concentration and load duration curves for each of the two gauging sites. For the Pang at Tidmarsh the suspended sediment concentration record is characterized by values of 20 mg l^{-1} or less for 92% of the study period and a maximum concentration of 686 mg l^{-1} (Fig. 6a). For the Lambourn at Shaw, the concentration record is characterized by values of 10 mg l^{-1} or less for 94% of the monitoring period and a maximum concentration of 626 mg l^{-1} (Fig. 6a). The suspended sediment load duration curves for the monitoring period indicate that fine sediment transport is more episodic in the Pang than in the Lambourn, with 70% of the suspended sediment load being delivered in just 19% of the time at Tidmarsh Mill, compared to 72% of the time at Shaw (Fig. 6b). Although suspended sediment concentrations are generally higher in the River Pang, this has the lower specific suspended sediment yield because of a lower total runoff for the study period.

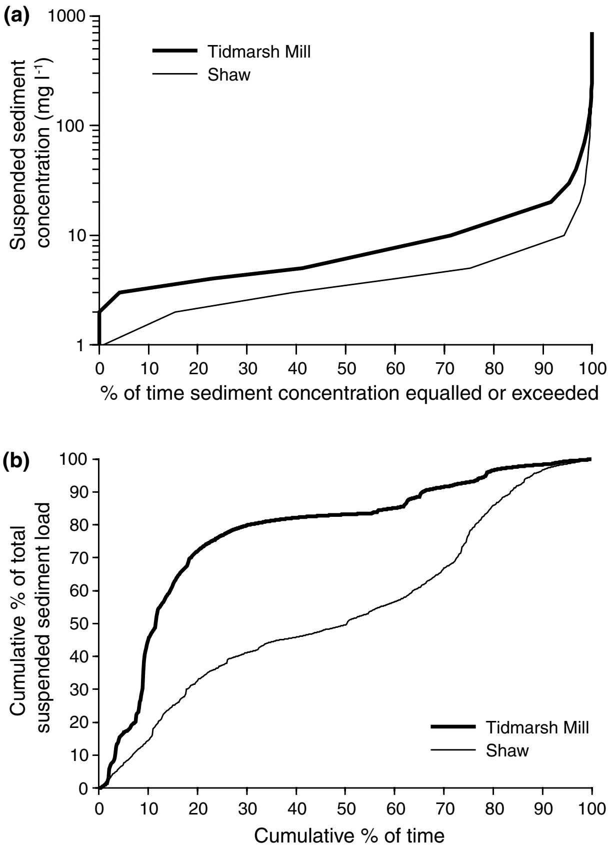

Figure 6 Suspended sediment concentration duration curves (a) and cumulative load versus cumulative time plots (b) for the Pang and Lambourn study catchment outlet monitoring stations.

The catchment suspended sediment budgets

The information provided by the individual components of the data collection programme described above has been synthesized to establish an annual suspended sediment budget for each study catchment (see Fig. 7). For several elements of the sediment budget, this synthesis has involved substantial spatial extrapolation, due to the limited number of field measurements available. As a result, the final budgets necessarily involve a number of uncertainties. However, notwithstanding this limitation, they are seen as providing an important advance in current understanding of the key features of the sediment budgets of permeable lowland agricultural catchments in the UK.

Estimates of gross erosion rates associated with individual fields under different land use within the study catchments, provided by the ^{137}Cs measurements, were combined with information on the area of each study catchment occupied by the corresponding land use and the relative frequency of fields similar to the sampled fields, to estimate this component of the overall sediment budget. Although Table 2 indicates that gross surface erosion rates within cultivated fields in the Pang study catchment range between 270 and 1020 g m^{-2} yr^{-1}, reconnaissance field surveys suggested that the lower rates were likely to be representative of a major proportion of the cultivated area. Spatial extrapolation was therefore weighted according to the relative frequency of fields similar to the sampled fields and the mean annual rate of sediment mobilization from the catchment slopes supporting cultivation was estimated to be 55263 t yr^{-1} (507 t km^{-2} yr^{-1}) (see Fig. 7). The ^{137}Cs-based estimates of within-field deposition for cultivated land in the Pang catchment, listed in Table 2, range between 150 and 350 g m^{-2} yr^{-1}, and use of a similar weighted extrapolation procedure provided an estimate of the mean annual in-field deposition rate of 26378 t yr^{-1} (242 t km^{-2} yr^{-1}) (see Fig. 7). Subtraction of the value for in-field deposition from the gross erosion rate provides a mean annual net soil loss from cultivated fields in the Pang catchment of 28885 t yr^{-1} (265 t km^{-2} yr^{-1}). The single estimate of soil redistribution rates for pasture fields provided by the ^{137}Cs survey were considered to be representative of the much smaller portion of the Pang catchment (i.e. 14 km^2) represented by this particular land use. The gross erosion (140 g m^{-2} yr^{-1}) and deposition (120 g m^{-2} yr^{-1}) rates for this pasture field (see Table 2) were extrapolated to the total area of pasture within the catchment to provide estimates of 1960 t yr^{-1} (140 t km^{-2} yr^{-1}) and 1680 t yr^{-1} (120 t km^{-2} yr^{-1}) for the gross erosion and within-field deposition components of the catchment sediment budget, respectively (see Fig. 7). These values in turn provide an estimated total net soil loss from pasture fields of 280 t yr^{-1} (20 t km^{-2} yr^{-1}).

Conventional river monitoring at Tidmarsh Mill, at the outlet of the Pang study catchment, over the duration of the project, provided an estimate of 398 t yr^{-1} (2.4 t km^{-2} yr^{-1}) for the mean annual suspended sediment output from the catchment. Scrutiny of the available flow records indicated, however, that the mean annual discharge at Tidmarsh Mill during the study period was equivalent to ca. 80% of the

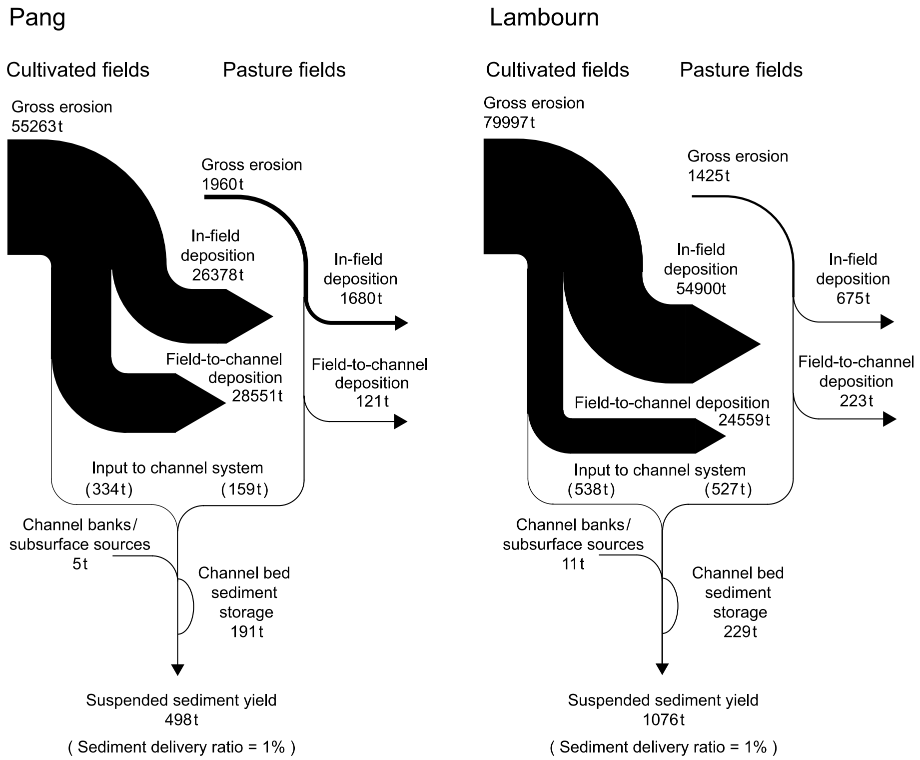

Figure 7 The annual suspended sediment budgets for the Pang and Lambourn study catchments.

longer-term (1961—1995) annual average. Assuming a linear relationship between annual flow and annual sediment flux, the estimate of mean annual sediment yield was therefore increased to 498 t yr^{-1} (3 t km^{-2} yr^{-1}) to provide a value more representative of the longer-term response at this gauging site. The latter value was apportioned using the information on the relative contributions of each individual potential sediment source provided by the fingerprinting investigation (see Fig. 4), to estimate the mass of sediment delivered to the channel network from cultivated land (334 t yr^{-1}), pasture (159 t yr^{-1}) and channel banks/subsurface sources (5 t yr^{-1}) (see Fig. 7). As expected, the two former estimates are appreciably lower than the equivalent values of net soil loss from fields within the two land use classes provided by the ^{137}Cs technique. For example, whilst the sediment source fingerprinting results estimate that 334 t yr^{-1} is delivered to the channel system from cultivated land, the corresponding mean annual net soil loss from cultivated fields is estimated to be 28885 t yr^{-1} (265 t km^{-2} yr^{-1}). The difference between the two estimates (28551 t yr^{-1} or 262 t km^{-2} yr^{-1}) can be attributed to conveyance losses associated with the delivery of mobilised sediment from individual cultivated fields to the channel network (see Fig. 7). The equivalent estimates of field-to-channel conveyance losses for pasture areas within the Pang catchment (121 t yr^{-1} or 9 t km^{-2} yr^{-1}) were derived in the same manner and are considerably lower than the values for the cultivated area, reflecting both the much lower net erosion rates associated with the pasture areas and the close juxtaposition of many pasture fields to the river channel. Mean levels of fine sediment storage on the channel bed within the Pang catchment are estimated to be 191 t yr^{-1} (see Fig. 7). As indicated above, this storage is considered to be active storage, although it is assumed that there is no appreciable net conveyance loss to channel storage at the annual timescale. This sediment mass is equivalent to 38% of the annual suspended sediment yield from the catchment and this value indicates that a substantial proportion of the suspended sediment flux from the Pang catchment passes through short-term channel storage, before reaching the catchment outlet. The overall sediment delivery ratio for the Pang study catchment is estimated to be 1%.

The suspended sediment budget for the Lambourn catchment (see Fig. 7) was constructed in the same manner. With cultivated fields accounting for 183 km^2 of the catchment, and on the basis of a similar weighted spatial extrapolation procedure, the total mean annual gross sediment contribution from cultivated fields is estimated to be 79997 t yr^{-1} (437 t km^{-2} yr^{-1}), whilst the corresponding in-field deposition is estimated to be 54900 t yr^{-1} (300 t km^{-2} yr^{-1}) (see Fig. 7). The total mean annual net soil loss from cultivated fields is estimated to be 25097 t yr^{-1} (137 t km^{-2} yr^{-1}). In contrast, fields supporting pasture (total area = 15 km^2) are estimated to contribute 1425 t yr^{-1} (95 t km^{-2} yr^{-1}) to the sediment budget, of which 675 t yr^{-1} (45 t km^{-2} yr^{-1}) is sequestered as in-field storage and a further 223 t yr^{-1} (15 t km^{-2} yr^{-1}) is accounted for by field-to-river conveyance losses. In the absence of long-term flow records, the gauged flow at Shaw during the monitoring period was again assumed to be ca. 80% of the longer-term average and the measured suspended sediment yield for the study period (3.7 t km^{-2} yr^{-1}) was increased to 4.6 t km^{-2} yr^{-1} to provide a more representative estimate of the longer-term mean. On the basis of a mean annual suspended sediment flux of 1076 t yr^{-1} (4.6 t km^{-2} yr^{-1}), channel and subsurface sources contribute 11 t yr^{-1}, whilst cultivated and pasture areas contribute 538 t yr^{-1} (3 t km^{-2} yr^{-1}) and 527 t yr^{-1} (35 t km^{-2} yr^{-1}) respectively. Field-to-channel conveyance losses are estimated to be 24559 t yr^{-1} (134 t km^{-2} yr^{-1}) for cultivated areas and 223 t yr^{-1} (15 t km^{-2} yr^{-1}) for pasture areas. The mean total bed sediment storage is estimated to be 229 t yr^{-1}, which is equivalent to 21% of the mean annual suspended sediment yield from the catchment, and the overall catchment sediment delivery ratio is again estimated to be ca. 1%.

Conclusion

Tentative fine-grained sediment budgets have been successfully constructed for the Pang and Lambourn study catchments, using the integrated approach to data collection developed at the University of Exeter. This combines the use of ^{137}Cs measurements to provide information on rates of sediment mobilization from cultivated and pasture fields, sediment source fingerprinting, periodic measurements of channel storage of fine sediment using a bed sediment re-suspension technique and conventional river monitoring. In both study catchments, substantial amounts of sediment are mobilized from the catchment slopes by erosion, although gross erosion rates are shown to be considerably higher for cultivated fields than for pasture fields. A large proportion of the material mobilized from the individual fields is, however, subsequently deposited either within the field of origin or at intermediate locations between the source field and the channel network (i.e. field-to-channel conveyance loss). Channel bank and subsurface sediment sources are relatively unimportant in the two study catchments. The mean fine sediment storage on the channel bed is shown to be equivalent to 38% and 21% of the mean annual suspended sediment yield from the Pang and Lambourn catchments, respectively. Although this temporary store is unlikely to represent a significant net conveyance loss at the annual timescale, and thus within the annual sediment budget, it must be seen as representing an important short-term sink within the overall catchment sediment budget, with a significant proportion of the sediment output from the catchment passing through channel storage. The overall sediment delivery ratios (1%) indicate that approximately 99% of the sediment mobilized by erosion within the study catchments is subsequently deposited before reaching the monitoring stations at the basin outlets. As such, the low sediment outputs from the study catchments should be seen as reflecting the importance of conveyance losses and storage rather than a lack of sediment mobilization from the catchment surface.

Comparison of the sediment budgets for the two study catchments presented in Fig. 7 confirms broad similarities between the two catchments, particularly in terms of the dominance of the catchment surface as the primary sediment source, and thus the limited contribution of channel erosion as a sediment source, the importance of both within-field deposition and field-to-channel conveyance losses in reducing sediment inputs to the channel system, the similar importance of cultivated and pasture fields as a source of the sediment reaching the channel system, despite the greater spatial extent of the cultivated areas in the two study catchments, and the much greater gross erosion rates associated with cultivated fields, the significance of temporary channel bed storage relative to the annual sediment output from the catchment, and, finally, the low sediment delivery ratios. However, a number of contrasts in the structure of the sediment budgets of the two catchments are also apparent. Firstly, the specific mean annual gross erosion rates for both cultivated and pasture fields are higher in the Pang catchment (507 t km^{-2} yr^{-1} and 140 t km^{-2} yr^{-1}) than the Lambourn catchment (437 t km^{-2} yr^{-1} and 95 t km^{-2} yr^{-1}), despite the latter being characterized by steeper slopes. Secondly, specific mean annual in-field deposition for both land uses is higher in the Lambourn catchment (281 t km^{-2} yr^{-1}) than in the Pang catchment (228 t km^{-2} yr^{-1}). Thirdly, specific mean annual field-to-channel conveyance losses for both land uses are higher in the Pang catchment (233 t km^{-2} yr^{-1}) than the Lambourn catchment (125 t km^{-2} yr^{-1}). In-field and field-to-channel sediment deposition rates associated with cultivated land are of approximately similar magnitude in the Pang catchment, whereas the former is considerably higher than the latter in the Lambourn study catchment. For pasture fields, in-field deposition rates are considerably higher than field-to-channel conveyance losses in the Pang, whereas these particular terms of the sediment budget are approximately similar in the Lambourn study area.

Despite its utility, the integrated approach to catchment sediment budgeting employed by this investigation inevitably involves a number of limitations and uncertainties. One important limitation is the different time base associated with the various methods used to assemble information on the individual components of the sediment budget. Thus, for example, whereas the ^{137}Cs-based estimates of mean annual soil redistribution rates represent average values for the medium-term (i.e. ~40 yr), the estimates of annual suspended sediment yield from the two study catchments are based on a much shorter (ca. 2 yr) monitoring period, although they have been scaled up to be more representative of the longer-term mean. Equally, the medium-term estimates of soil loss documented using ^{137}Cs measurements may not be representative of the contemporary period represented by the sediment yield measurements. However, available evidence suggests that the study period is reasonably representative of the longer-term, in terms of annual rainfall and runoff, and no major land use changes have occurred during the period represented by the ^{137}Cs-based data. Furthermore, because the conveyance losses associated with field-to-channel transfer were estimated as the difference between the net soil loss from cultivated or pasture fields and the portion of sediment load estimated by the source fingerprinting investigations to have been derived from cultivated or pasture fields, there is no independent confirmation of the balancing of the budget (cf. Kondolf and Matthews, 1991). Each individual component of the sediment budget will necessarily involve potential errors and these will be propagated through the budget calculations. Similarly, the extrapolation of the relatively small number of estimates of gross and net soil loss provided by the transects used for ^{137}Cs measurements involved a number of assumptions regarding the representativeness of those values and their relative weighting, which would undoubtedly benefit from more rigorous testing. There is clearly scope for future work to provide more explicit recognition of these and other uncertainties and to assign confidence limits to each key term.

The sediment budgets presented in Fig. 7 provide important background information, which could be used to support the design of targeted sediment control and management strategies in the study catchments and similar areas. A knowledge of both the principal sediment sources and stores is of key importance in designing cost-effective sediment control measures for a catchment. The limited sediment contributions from channel banks in the study catchments would, for example, imply that additional riparian zone protection measures (e.g. river bank fencing) typically employed in impermeable catchments, where channel bank degradation by livestock is frequently an important sediment source, would be of limited value. Equally, the similar importance of contributions from cultivated and pasture areas in accounting for sediment inputs to the channel systems of the study catchments indicates that attention should be directed to areas under both cultivation and pasture. In addition, the importance of within-field deposition and field-to-channel conveyance losses in both study catchments emphasises that large quantities of sediment are sequestered within the catchments. Small changes in sediment delivery efficiency resulting in reduced in-field deposition or reduced field-to-channel conveyance losses could cause a significant increase in the amount of sediment entering the channel system. Similarly, remobilization of sequestered sediment could potentially release large amounts of sediment to the system and increase the sediment flux at the catchment outlet. Any assessment of the potential impact of changes in land management and climate change on catchment sediment yields should clearly take account of possible changes in the functioning of the sediment budget, and, more particularly, changes in delivery efficiency and remobilization of stored sediment and associated nutrients and contaminants, as indicated above. Sediment remobilization as a result of perturbations in erosion and sediment delivery dynamics due to either management strategies or climate change could generate significant increases in sediment yield and the transfer of sediment-associated nutrients and contaminants.

Acknowledgements

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References

Acornley, R.M., Sear, D.A., 1999. Sediment transport and siltation of brown trout (*Salmo Trutta L.*) spawning gravels in chalk streams. Hydrological Processes 13, 447—458.

Adams, J.N., Beschta, R.L., 1980. Gravel bed composition in Oregon coastal streams. Canadian Journal of Fisheries and Aquatic Sciences 37, 1514—1521.

Belyaev, V.R., Wallbrink, P.J., Golosov, V.N., Murray, A.S., Sidorchuk, A.Yu., 2005. A comparison of methods for evaluating soil redistribution in the severely eroded Stavropol region, southern European Russia. Geomorphology 65, 173—193.

Berrie, A.D., 1992. The chalk stream environment. Hydrobiologia 248, 3—9.

Clarke, S.J., Wharton, G., 2001. Sediment nutrient characteristics and aquatic macrophytes in lowland English rivers. The Science of the Total Environment 266, 103—112.

Collins, A.L., Walling, D.E., 2002. Selecting fingerprint properties for discriminating potential suspended sediment sources in river basins. Journal of Hydrology 261, 218—244.

Collins, A.L., Walling, D.E., 2004. Documenting catchment suspended sediment sources: problems, approaches and prospects. Progress in Physical Geography 28, 159—196.

Collins, A.L., Walling, D.E., Leeks, G.J.L., 1997a. Fingerprinting suspended sediment sources in larger river basins: combining assessment of spatial provenance and source type. Geografiska Annaler 79A, 239—254.

Collins, A.L., Walling, D.E., Leeks, G.J.L., 1997b. Source type ascription for fluvial suspended sediment based on a quantitative composite fingerprinting technique. Catena 29, 1—27.

Collins, A.L., Walling, D.E., Sichingabula, H.M., Leeks, G.J.L., 2001a. Using ^{137}Cs measurements to quantify soil erosion and redistribution rates for areas under different land use in the Upper Kaleya River basin, southern Zambia. Geoderma 104, 299—323.

Collins, A.L., Walling, D.E., Sichingabula, H.M., Leeks, G.J.L., 2001b. Suspended sediment source fingerprinting in a small tropical catchment and some management implications. Applied Geography 21, 387—412.

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. Walling, D.E., Horowitz, A.J. (Eds.), Sediment Budgets 1, IAHS Publ. No. 291. IAHS Press, Wallingford, pp. 259—268.

Dietrich, W.E., Dunne, T., 1978. Sediment budget for a small catchment in mountainous terrain. Zeitschrift fur Geomorphologie N.F. Suppl. Bd. 29, 191—206.

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

Droppo, I.G., Stone, M., 1994. In-channel surficial fine-grained sediment laminae. Part I: physical characteristics and formation processes. Hydrological Processes 8, 101—111.

Dunne, T., 1994. Hydrogeomorphology: an introduction. Transactions Japanese Geomorphological Union 15A, 1—4.

Fulajtar, E., 2003. Assessment of soil erosion on arable land using ^{137}Cs measurements: a case study from Jaslovske Bohunice, Slovakia. Soil and Tillage Research 69, 139—152.

Golosov, V.N., Ivanova, N.N., Litvin, L.F., Sidorchuk, A.Yu., 1992. Sediment budget in river basins and small river aggradation. Geomorphologiya 4, 62—71 (in Russian).

Hasholt, B., 1988. On identification of sources of sediment transport in small basins with special reference to particulate phosphorus. In: Bordas, M.P., Walling, D.E. (Eds.), Sediment Budgets, IAHS Publ. No. 174. IAHS Press, Wallingford, pp. 241—250.

Heywood, M.T., Walling, D.E., 2003. Suspended sediment fluxes in chalk streams in the Hampshire Avon catchment, UK. Hydrobiologia 494, 111—117.

Hillier, S., 2001. Particulate composition and origin of suspended sediment in the R. Don, Aberdeenshire, UK. The Science of the Total Environment 265, 281—293.

Kachanoski, R.G., 1993. Estimating soil loss from changes in soil cesium-137. Canadian Journal of Soil Science 73, 515—526.

Kondolf, G.M., Matthews, W.V.G., 1991. Unmeasured residuals in sediment budgets: a cautionary note. Water Resources Research 27, 2483—2486.

Lambert, C.P., Walling, D.E., 1988. Measurement of channel storage of suspended sediment in a gravel-bed river. Catena 15, 65—80.

Loughran, R.J., 1989. The measurement of soil erosion. Progress in Physical Geography 13, 216—233.

Mehta, N.C., Legg, J.O., Goring, C.A.I., Black, C.A., 1954. Determination of organic phosphorus in soils. I: Extraction methods. Soil Science Society America Journal 18, 443—449.

Motha, J.A., Wallbrink, P.J., Hairsine, P.B., Grayson, R.B., 2004. Unsealed roads as suspended sediment sources in an agricultural catchment in south-eastern Australia. Journal of Hydrology 286, 1—18.

Nelson, E.J., Booth, D.B., 2002. Sediment sources in an urbanizing mixed land-use watershed. Journal of Hydrology 264, 51—68.

Old, G.H., Leeks, G.J.L., Packman, J.C., Smith, B.P.G., Lewis, S., Hewitt, E.J., Holmes, M., Young, A., 2003. The impact of a convectional summer rainfall event on river flow and fine sediment transport in a highly urbanized catchment, Bradford, West Yorkshire. The Science of the Total Environment 314—316, 495—512.

Owens, P.N., Walling, D.E., Shanahan, J., Foster, I.D.L., 1997. The use of caesium-137 measurements to establish a sediment budget for the Start catchment, Devon, UK. Hydrological Sciences Journal 42, 405—423.

Owens, P.N., Walling, D.E., Leeks, G.J.L., 1999. Deposition and storage of fine-grained sediment within the main channel system of the River Tweed, Scotland. Earth Surface Processes and Landforms 24, 1061—1076.

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

Phillips, J.D., 1991. Fluvial sediment budgets in the North Carolina piedmont. Geomorphology 4, 231—241.

Phillips, J.M., Russell, M.A., Walling, D.E., 2000. Time-integrated sampling of fluvial suspended sediment: a simple methodology for small catchments. Hydrological Processes 14, 2589—2602.

Quine, T.A., Walling, D.E., 1991. Rates of soil erosion on arable fields in Britain: quantitative data from caesium-137 measurements. Soil Use and Management 7, 169—176.

Ruse, M.E., Peart, M.R., 1999. ^{137}Cs reference site characteristics in Hong Kong — some considerations. Physics and Chemistry of the Earth 10, 887—891.

Russell, M.A., Walling, D.E., Hodgkinson, R.A., 2000. Appraisal of a simple sampling device for collecting time-integrated fluvial suspended sediment samples. In: Stone, M. (Ed.), The Role of Erosion and Sediment Transport in Nutrient and Contaminant Transport, IAHS Publ. No. 263. IAHS Press, Wallingford, pp. 119—127.

Russell, M.A., Walling, D.E., Hodgkinson, R.A., 2001. Suspended sediment sources in two small lowland agricultural catchments in the UK. Journal of Hydrology 252, 1—24.

Schuller, P., Ellies, A., Castillo, A., Salazar, I., 2003. Use of ^{137}Cs to estimate tillage- and water-induced soil redistribution rates on agricultural land under different land use and management in central-south Chile. Soil and Tillage Research 69, 69—83.

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

Slattery, M.C., Walden, J., Burt, T.P., 2000. Use of mineral magnetic measurements to fingerprint suspended sediment sources: results from a linear mixing model. In: Foster, I.D.L. (Ed.), Tracers in Geomorphology. Wiley, Chichester, pp. 309—322.

Slaymaker, O., 2003. The sediment budget as conceptual framework and management tool. Hydrobiologia 494, 71—82.

Soileau, J.M., Hajek, B.F., Touchton, J.T., 1990. Soil erosion and deposition evidence in a small watershed using fallout cesium-137. Soil Science Society of America Journal 54, 1712—1719.

Swanson, F.J., Janda, R.J. Dunne, T., Swanston, D.N., 1982. Sediment Budgets and Routing in Forested Drainage Basins. USDA Forest Service General Technical Report PNW-141.

Theocharapoulos, S.P., Florou, H., Walling, D.E., Kalantzakos, H., Christou, M., Tountas, P., Nikolaou, T., 2003. Soil erosion and deposition rates in a cultivated catchment area in central Greece, estimated using the ^{137}Cs technique. Soil and Tillage Research 69, 153—162.

Trimble, S.W., 1995. Catchment sediment budgets and change. In: Gurnell, A.M., Petts, G. (Eds.), Changing River Channels. Wiley, Chichester, pp. 201—215.

Trimble, S.W., Crosson, P., 2000. U.S. soil erosion rates: myth and reality. Science 289, 248—250.

UK Biodiversity Action Plan Steering Group for Chalk Rivers, 2004. The State of England's Chalk Rivers. Environment Agency, Bristol.

Vanden Berghe, I., Gulinck, H., 1987. Fallout ^{137}Cs as tracer for soil mobility in the landscape framework of the Belgian loamy region. Pedologie 37, 5—20.

Wallbrink, P.J., Olley, J.M., Murray, A.S., 1994. Measuring soil movement using ^{137}Cs: implications of reference site variability. In: Olive, L.J., Loughran, R.J., Kesby, J.A. (Eds.), Variability in Stream Erosion and Sediment Transport, IAHS Publ. No. 224. IAHS Press, Wallingford, pp. 95—102.

Wallbrink, P.J., Martin, C.E., Wilson, C.J., 2003. Quantifying the contributions of sediment, sediment-P and fertilizer-P from forested, cultivated and pasture areas at the landuse and catchment scale using fallout radionuclides and geochemistry. Soil and Tillage Research 69, 53—68.

Walling, D.E., 1983. The sediment delivery problem. Journal of Hydrology 65, 209—237.

Walling, D.E., 1994. Measuring sediment yield from river basins. In: Lal, R. (Ed.), Soil Erosion Research Methods. Soil and Water Conservation Society, Ankeny, Iowa, pp. 39—80.

Walling, D.E., 1998. Use of ^{137}Cs and other fallout radionuclides in soil erosion investigations: progress, problems and prospects. In: Use of ^{137}Cs in the Study of Soil Erosion and Sedimentation. IAEA-TECHDOC, 1028. International Atomic Energy Agency, Vienna, pp. 39—62.

Walling, D.E., 1999. Linking land use, erosion and sediment yields in river basins. Hydrobiologia 410, 223—240.

Walling, D.E. 2002. Recent advances in the use of environmental radionuclides in soil erosion investigations. In: Proceedings of the International Symposium on Nuclear Techniques in Integrated Plant Nutrient, Water and Soil Management. IAEA C & S Paper Series 11/C. International Atomic Energy Agency, Vienna, pp. 279—301.

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

Walling, D.E., Webb, B.W., 1987. Suspended load in gravel-bed rivers: UK experience. In: Thorne, C.R., Bathurst, J.C., Hey, R.D. (Eds.), Sediment Transport in Gravel-bed Rivers. Wiley, Chichester, pp. 691—723.

Walling, D.E., Webb, B.W., 1988. The reliability of rating curve estimates of suspended sediment yield: some further comments. In: Bordas, M.P., Walling, D.E. (Eds.), Sediment Budgets, IAHS Publ. No. 174. IAHS Press, Wallingford, pp. 337—350.

Walling, D.E., Quine, T.A., 1990. Calibration of caesium-137 measurements to provide quantitative erosion rate data. Land Degradation and Rehabilitation 2, 161—175.

Walling, D.E., Woodward, J.C., 1992. Use of radiometric fingerprints to derive information on suspended sediment sources. In:

Bogen, Walling, D.E., Day, T. (Eds.), Erosion and Sediment Transport Monitoring Programmes in River Basins, IAHS Publ. No. 210. IAHS Press, Wallingford, pp. 153—164.

Walling, D.E., Quine, T.A., 1993. Using Chernobyl-derived fallout radionuclides to investigate the role of downstream conveyance losses in the suspended sediment budget of the River Severn, United Kingdom. Physical Geography 14, 239—253.

Walling, D.E., He, Q., 1999. Improved models for estimating soil erosion rates from cesium-137 measurements. Journal of Environmental Quality 28, 611—622.

Walling, D.E., Collins, A.L., 2000. Integrated Assessment of Catchment Sediment Budgets. University of Exeter, Exeter.

Walling, D.E., Collins, A.L., 2005. Suspended sediment sources in British rivers. In: Walling, D.E., Horowitz, A.J. (Eds.), Sediment Budgets 1, IAHS Publ. No. 291. IAHS Press, Wallingford, pp. 123—133.

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

Walling, D.E., Owens, P.N., Leeks, G.J.L., 1998. The role of channel and floodplain storage in the suspended sediment budget of the River Ouse, Yorkshire, UK. Geomorphology 22, 225—242.

Walling, D.E., He, Q., Blake, W., 1999a. Use of ^{7}Be and ^{137}Cs measurements to document short- and medium-term rates of water-induced soil erosion on agricultural land. Water Resources Research 35, 3865—3874.

Walling, D.E., Owens, P.N., Leeks, G.J.L., 1999b. Fingerprinting suspended sediment sources in the catchment of the River Ouse, Yorkshire, UK. Hydrological Processes 13, 955—975.

Walling, D.E., Collins, A.L., Sichingabula, H.H., Leeks, G.J.L., 2001. Integrated assessment of catchment suspended sediment budgets: a Zambian example. Land Degradation and Development 12, 387—415.

Walling, D.E., Russell, M.A., Hodgkinson, R.A., Zhang, Y., 2002. Establishing sediment budgets for two small lowland agricultural catchments in the UK. Catena 47, 323—353.

Wass, P.D., Leeks, G.J.L., 1999. Suspended sediment fluxes in the Humber catchment, UK. Hydrological Processes 13, 935—953.

Webb, B.W., Phillips, J.M., Walling, D.E., Littlewood, I.G., Watts, C.D., Leeks, G.J.L., 1997. Load estimation methodologies for British rivers and their relevance to the LOIS RAC(S) programme. The Science of the Total Environment 194/195, 379—389.

Westlake, D.F., Casey, H., Dawson, H., Ladle, M., Mann, R.H.K., Marker, A.F.H., 1972. The chalk stream ecosystem. In: Kajak, Z., Hillbricht-Ilkowska, A. (Eds.), Productivity Problems of Feshwaters. PWN, Warsaw, pp. 615—635.

Wicherek, S.P., Bernard, C., 1995. Assessment of soil movements in a watershed from Cs-137 data and conventional measurements (example: the Parisian basin). Catena 25, 141—151.

Zapata, F., 2003. Handbook for the Assessment of Soil Erosion and Sedimentation Using Environmental Radionuclides. Kluwer Academic Publishers, Amsterdam.

Zhang, X.B., Higgitt, D.L., Walling, D.E., 1990. A preliminary assessment of the potential for using caesium-137 to estimate rates of soil erosion in the Loess Plateau of China. Hydrological Sciences Journal 35, 267—276.

Zhang, X., Zhang, Y., Wen, A., Feng, M., 2003. Assessment of soil losses on cultivated land by using the ^{137}Cs technique in the Upper Yangtze River Basin of China. Soil and Tillage Research 69, 99—106.