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Reconstructing upland sediment budgets in ungauged catchments from reservoir sedimentation and rainfall records calibrated using short-term streamflow monitoring

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Abstract The estimation of sediment yield in upland environments is a difficult task, compounded by the scarcity of long-term environmental monitoring. This is a significant problem when assessing sedimentation in upland reservoirs where sediment budget information is limited. Concerns about climate change and the likelihood of more frequent extreme events emphasise the need for predictive capability without reliance on gauging records. The results reported in this paper form part of an EU-funded programme (WARMICE) investigating the potential impact of sedimentation on water resource management in upland environments. Evaluation of the sediment transfer system of a representative reservoir catchment in the North Pennines, UK, has used reservoir core records to reconstruct sediment accumulation rates and infer changes in sediment supply. The paper examines how geomorphological evidence, coupled with short-term monitoring and rainfall records, can be used to construct approximate sediment budgets. It also demonstrates how recent climatic variations identified in the region have impacted on the sediment transfer system.

Key words reservoir sedimentation; sediment budget; uplands

INTRODUCTION

Estimating sediment yield and constructing sediment budgets in upland catchments is a challenging task. Sediment can be supplied from various parts of the catchment, and detachment and transport of material from hillslopes and from channel stores is not related in a linear fashion to rainfall intensity and flow magnitude. Given that few upland areas are adequately gauged, it is important to develop methods for erosion and sediment transport prediction in ungauged basins. In the uplands of Europe, reservoirs are abundant and used for water storage, flood protection and power generation. In several parts of Europe, reservoir sedimentation is an existing and acute problem; in others, the limited information about upland sediment transport processes leave water resources managers uncertain about future impacts. As climate change begins to affect Europe the likelihood of more frequent extreme events has implications for water resource management (Jones, 1993). *Water Resource Management in a Changing*

Environment: The impact of sediment on sustainability (WARMICE) is an interdisciplinary project funded under the European Union Framework IV programme on Climate and Environment. This paper reports on part of the field investigations undertaken by the UK project team. The broad aims of the project are to improve methods for predicting the impact of sediments on the sustainability of upland water resources. Sediment supply from upland catchments can have a number of adverse effects on both operational procedures and on environmental quality. Sedimentation is not only a long-term threat to reservoir storage capacity but also poses shorter-term difficulties such as intake into HEP turbines or high turbidity of extraction water. In the context of environmental change, the ability to forecast sediment-related management problems from climate change scenarios would be useful.

Before the task of forecasting future impacts of sedimentation in upland catchments can be addressed it is evident that information about the controls on contemporary sediment transfer dynamics must be obtained. Four broad approaches to the evaluation of upland sediment budgets can be observed in the literature. These are reservoir sedimentation studies (Butcher *et al.*, 1993), stream monitoring (Leeks & Marks, 1997), hydrological modelling, and rapid appraisal techniques (Grieve *et al.*, 1995; Reid & Dunne, 1996; McHugh *et al.*, 2002). In many situations, management agencies need advice on sediment dynamics in a time frame that inhibits any field monitoring. Such consultancy advice may not require full articulation of a sediment budget nor be concerned with a precise estimate of sediment flux. The question that arises is whether, in studies where a longer and more considered approach is possible, an array of techniques can overcome the requirement for a gauged record. Indeed a remit of the WARMICE project has been to integrate field-based and modelling approaches to sediment budget characterization that enable regional extrapolation to ungauged catchments.

This paper concerns upland sediment dynamics in the Northern Pennines, UK. There are several water supply reservoirs in the region with catchments draining mainly moorland and pasture. Monitoring of sediment concentration by official agencies has been limited in the region though there are data from a number of research projects (Crisp, 1966; Evans & Warburton, 2001). Limited baseline data on the extent and rates of upland erosion inhibit the assessment of erosional trends and make it difficult to distinguish between natural and human-induced processes. The Royal Commission on Environmental Pollution has identified erosion as a significant problem in some upland areas of the UK in its report on the sustainable use of soil (Royal Commission on Environmental Pollution, 1996). Furthermore, recent initiatives to protect upland environments and habitats require that erosion dynamics are understood (DETR/MAFF, 2001).

STUDY AREA: THE NORTH PENNINES

The North Pennines is an upland area in Northern England comprising an upthrust block of Carboniferous lithologies of limestones, shales and sandstones. The western scarp slope is relatively steep, but the summit plateau is gently undulating and dominated by blanket peat, which has developed over glacial and soliflucted diamict (Warburton, 1998). Burnhope Reservoir, the subject of this case study, was impounded in 1936 and has a surface area of 0.8 km^2 and storage capacity is 6445 Ml. Land use in the catchment consists of gently sloping expanses of upland blanket peat and open moorland that is dissected by small valleys. The natural catchment area of the reservoir is 17.8 km^2 and the principal tributaries are Burnhope Burn and Langtae Burn. Localized gullying of the peat cover is evident but incised gullies are only coupled to the channel near the head of the network. There is some evidence to suggest that the gullies in the Northern Pennines are stabilizing and revegetating (Higgitt *et al*., 2001). Though there is mining legacy in the catchment of both tributaries (hydraulic mining, channel rerouting, small waste heaps) activity ceased well before reservoir construction and is not an obvious sediment source. The main land uses for these moorlands throughout the twentieth century has been grazing and game management, and can be considered to have been relatively constant throughout the lifetime of the reservoir.

RESEARCH METHODS

Field measurements

A large variety of techniques have been used in the estimation of the sediment budgets. Reservoir sedimentation has been derived from a bathymetric survey coupled to retrieval of sediment cores. The bathymetric survey (June 2000) employed a SonarLite portable single beam echo sounder, attached to an inflatable boat. The vessel also carried a Magellan Pro mark GPS receiver recording location at one-second intervals. The survey involved some 30 transects across the reservoir. Ten sediment cores were obtained using a 1-m Mackereth corer. Extraction in deep (>20 m) water is not easy and some difficulty was experienced at some locations. Consequently the distribution of cores does not reflect a full grid pattern and care is needed in interpolating the sedimentation estimates. Retrieved cores were sliced at 1 cm intervals and subject to loss on ignition and to particle size analysis using a Coulter laser granulometer. Dating control has been obtained from three cores using ^{137}Cs chronology and recognition of pre-impoundment surface. An Ortec well detector was used to count gamma ray emissions from samples of approximately 3 g mass.

Water and sediment fluxes into the reservoir were monitored on the two main input streams for a period of ten months between May 2000 and March 2001. There are no existing measurements of sediment input into the reservoir so two temporary gauging stations were established a short distance upstream of the reservoir limits on Burnhope Burn and Langtae Burn. Stage was recorded by pressure transducer linked to a Campbell CR10X data logger. Velocity–area–discharge measurements were undertaken at different stages to derive a discharge rating. Sediment concentration was determined from filtering of water samples collected using Rock and Taylor pump samplers. Water samples were collected at six hourly intervals but were also triggered by rising stage to collect samples every 15 minutes during storm events. This short data series (truncated prematurely by the incidence of Foot and Mouth Disease in the UK) was used to derive rating relationships between rainfall, runoff and sediment transfer. Although limited in temporal extent, these data provide an opportunity to use existing rainfall records in ungauged catchments to derive synthetic discharge series.

Secondary data

Most reservoirs in the North Pennine region have operated raingauges for at least some part of their history and these data can be used to infer discharge series. Daily rainfall measurements from 1936 to 1998 exist for the Burnhope. The next step in deriving sediment flux from the synthetic discharge series is more problematic. In addition, daily rainfall records do have limitations for identifying storm events. The upland Pennine catchments respond rapidly to rainfall, and hydrographs rise and fall rapidly over short intervals so that sediment transport potential may be masked in a daily discharge record. However, it can be argued that daily data are better than no data and can be used to identify sequences of wet or dry conditions, extreme seasons and enhanced seasonal contrasts. Following observations of the increasing significance of winter rainfall (Jones & Conway, 1997) the data were used to identify seasonal influences on sediment flux. Variations in the rainfall characteristics can be linked directly to the reservoir sediment sequence.

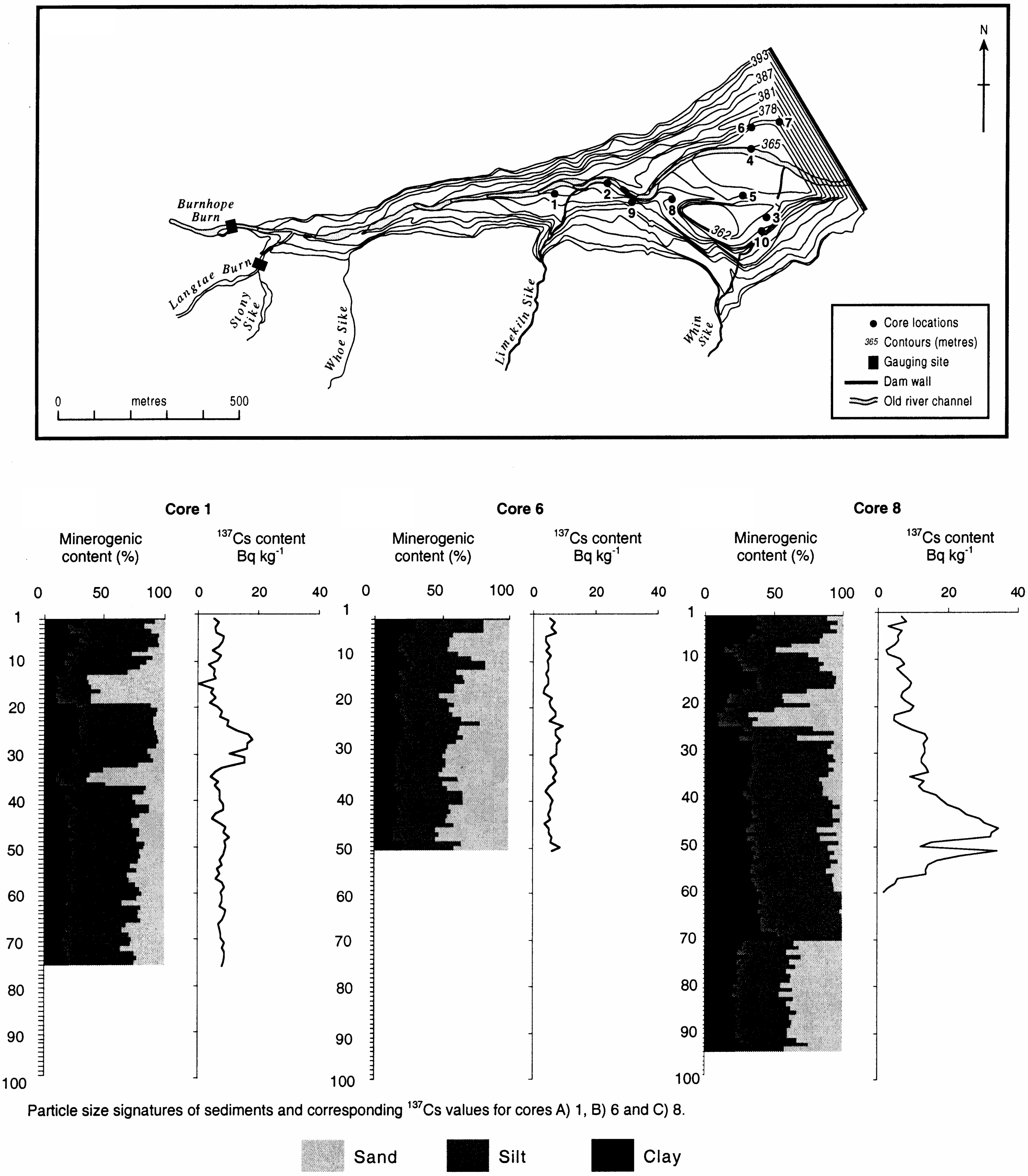
Verification

The combination of analysis of reservoir sediments, short-term stream monitoring and reconstructed discharge provides a methodology for evaluating sediment flux. However, this empirical approach is subject to problems of equifinality. Verification procedures to evaluate the interpretations are needed and these can be provided through other evidence. These include analysis of both vertical and oblique aerial photographs, evaluation of historical photographs of the catchment, and geomorphological mapping to identify sediment sources. For example, each of the tributary streams has been mapped to determine the location of coarse overbank flood deposits. Lichenometry provides a means of establishing the age of boulder surfaces which can, in turn, be related to reservoir sedimentation.

RESULTS

Reservoir sedimentation

The bathymetric survey and core evidence reveals that sedimentation in the reservoir since construction is low. The error margins associated with the echo sounding are as great as the estimated sediment thickness in most parts of the reservoir. The low sedimentation rate is confirmed by the cores, which in some instances penetrate the consolidated pre-impoundment lining material. Although the bathymetry enables the present topography of the reservoir bed to be calculated, it is clear there has been limited modification of the pre-existing land surface. This also accounts for some of the problems in obtaining cores at locations where the reservoir bed slopes steeply. Total sedimentation within the reservoir is estimated as 37899 ± 3800 t, equivalent to a specific sediment yield of 33.3 t km^{-2} year^{-1}, of which 15% is organic material. More detail on the derivation of the sediment budget and its associated errors are given in Holliday *et al.* (2003). Sediment retrieved from the cores enables average sediment



Particle size signatures of sediments and corresponding ^{137}Cs values for cores A) 1, B) 6 and C) 8.

Fig. 1 Burnhope Reservoir bathymetry, location of core samples and details of cores 1, 6 and 8.

ation rates to be calculated and variations in the physical properties of the sediments to be identified. Results from the cores with complete ^{137}Cs assay are shown (Fig. 1). The ^{137}Cs profile is characteristic of depositional sediments where there is limited supply of additional ^{137}Cs from the catchment area, reflecting ambient atmospheric fallout. This implies that surface material is not a major component of the sediment budget. This is confirmed by geomorphological mapping, which identifies the channel and channel margins as the dominant sediment source areas. There is no evidence that there was significant radioactive fallout from the Chernobyl accident (1986) and hence no clear secondary marker in the upper profile. However, the original reservoir base is evident in Core 1. The sharp peak of ^{137}Cs in the profile of Core 1 represents maximum atmospheric concentrations in 1963 from which deposition rates are estimated to be 12.4 mm year^{-1}. The reservoir lining is intercepted at a depth of 0.71 m, which is consistent with the estimated sedimentation rate. Interpretation of the other two cores is more problematic. Despite a marked peak in Core 8, ^{137}Cs activity is detectable well below this depth. It should be noted that the higher ^{137}Cs concentration in the upper part of the core is associated with higher silt-clay content and is only half the concentration of peak activity in Core 8. The ^{137}Cs chronology of Core 6 is incomplete at the core base (0.52 m) indicating sedimentation rates at least exceeding 10 mm year^{-1}. It is suggested that the unusual ^{137}Cs profile of Core 1 is due to local reworking of sediment as this location is within a part of the reservoir that has been exposed during periods of drawdown.

It is evident that there is a marked change in the character of sediment towards the upper part of the cores. The upper 0.40 m and 0.25 m of cores 1 and 8, respectively, record an influx of coarse-grained sediments. Assuming that sedimentation rates are relatively uniform across the lifetime of the reservoir, the phase of sandier deposition can be tentatively dated as post-1977 and the reconstructed hydrological series for this period investigated further.

Historic rainfall records

As land use and management practices have remained relatively unchanged during the lifetime of the reservoir, the minerogenic variation is likely to reflect runoff patterns. The daily rainfall records have been investigated for evidence of trends over the period from 1936 to 1998. Average annual rainfall is approximately 2000 mm. Five-year running means indicate a general decrease in annual rainfall totals from 1950 to 1970, which became a more rapid decline in the mid-1970s. This period also records a sharp increase in the number of days per year without rainfall. However, the most dramatic indicator of variation in precipitation is apparent when winter and summer totals are compared. From the beginning of the record to the 1970s, winter (October to March) and summer (April to September) rainfall totals are in phase but diverge from 1976 onwards. This year is well known in UK as a drought year and it heralds a sequence of years with higher winter rainfall totals. The 1990s experienced a sequence of dry summers. The implications for water resource management are that the changing rainfall regime accentuates the variations in water level within the reservoir. Draw-down coincides with particularly dry summers when fortnightly variations in water volume can be as high as 4000 Ml (approximately 60% of maximum reservoir capacity). Consequently it is proposed that the coarse influx in the reservoir reflects two phases of dry summers followed by wet winters in the mid to late 1970s and the early to mid 1990s. This interpretation is consistent with the ^{137}Cs chronology. It also explains the atypical ^{137}Cs signal in Core 1 as a result of sediment reworking during periods of low water volumes.

Sediment rating and budget

The inference that a changing rainfall regime is reflected in the sedimentation in the reservoir can be tested in two ways. First, short-term monitoring of the actual suspended sediment loads allows the rating relationships between rainfall, runoff and sediment yield to be evaluated. Second, there may be visual evidence of large events preserved within the catchment. Specific sediment yield estimated from the combined catchment area of the two main streams (Burnhope Burn and Langtae Burn) is 26.1 t km^{-2} $year^{-1}$, a figure slightly lower than the estimate of longer-term sedimentation in the reservoir. Rating relationships between runoff and sediment concentration are notoriously scattered but the short-term monitoring of rainfall, runoff and sediment concentration emphasize the significance of event thresholds. Using bias correction procedures (Ferguson, 1987) on suspended sediment rating enables a time series of annual sediment transport to be constructed (Fig. 2). It is noticeable that the sediment flux does not display any marked trend but that changing runoff patterns may be reflected in the characteristics of the sediment.

Morphological mapping of the Langtae Burn catchment reveals substantial evidence of historical flooding and channel change. Dating of the flood deposits using lichenometry indicates three periods of activity: the 1820s, 1870s–1940s and 1980 to present day. From the size of boulders preserved in the dated flood deposits, it appears that flood magnitude has varied over historical time, with the 1820s, early 1900s and 1980–2000 being periods from which the largest boulders are preserved, indicating higher magnitude floods. The frequency of historical floods appears to correlate fairly well with regional rainfall between 1800 and 1930, and with daily local rainfall totals since the 1930s.

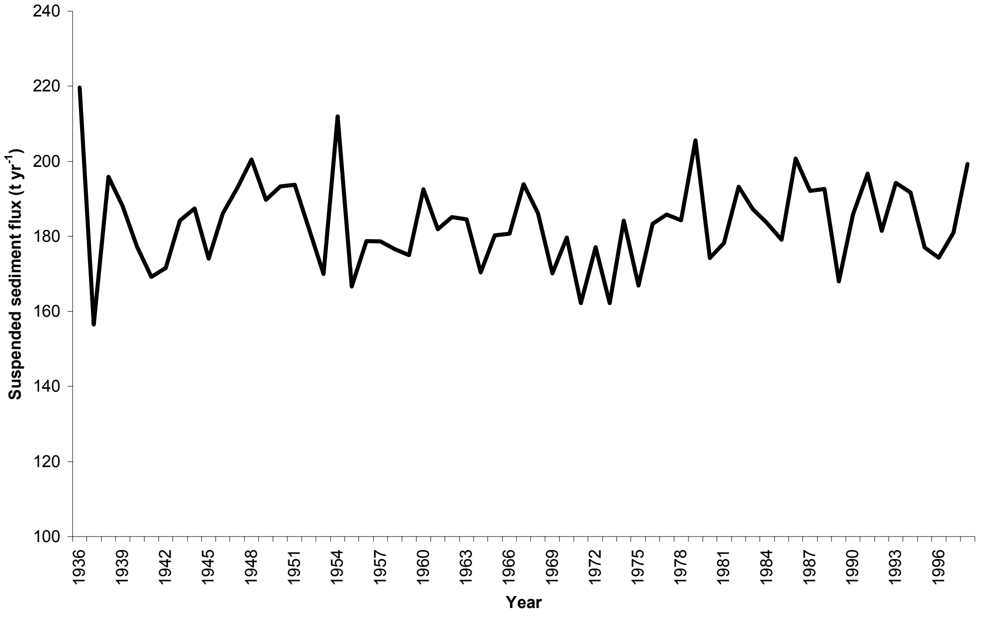


Fig. 2 Annual suspended sediment yields calculated from 1936–1998 annual rainfall totals using the Ferguson corrected rating relationship for Burnhope Burn.

DISCUSSION AND SUMMARY

The field investigation has enabled the components of the sediment budget to be estimated. The influx of coarse sediment in the upper part of the cores is consistent with the onset of a period of wetter winters and drier summers. The limited period of flow monitoring has allowed preliminary sediment rating and rainfall–runoff rating relationships to be constructed in order to provide a method of reconstructing sediment discharge from daily rainfall measurements. Despite the simple approach, the results derived from the reconstruction are similar to the sediment yield estimates from reservoir coring. A number of options are available for improving the sophistication of this approach.

The first option concerns the connectivity between sediment sources and stream channels and their representation in hydrological models. Field mapping indicates that coupled sediment sources are limited in extent and spatially heterogeneous. Hydrological models require a stochastic routine to simulate the coincidence of available supply and transport capacity (Benda & Dunne, 1997). Other components of the WARMICE project have considered the application of distributed hydrological models to the prediction of sediment transport in upland catchments. The distinction between supply-limited and transport-limited controls is crucial in model representation and difficult to validate without additional data. In many of the upland environments where erosion prediction is required, the amount of data available for model calibration is necessarily limited.

Second, the rating relationships between rainfall, runoff and sediment transport can be examined in greater detail. Alternative bias reduction procedures using Generalized Linear Models are being developed using the Burnhope and other Northern Pennine data (Cox *et al.*, 2003). There is also potential in extending monitoring to a full year to characterize full seasonal variability.

The present study has demonstrated that the retrieval of cores from a reservoir combined with short-term monitoring and analysis of historical rainfall records has enabled the sediment flux of the catchment to be defined. The larger aim of the work has been to develop methodologies to enable sediment budgets to be derived from ungauged catchments. Here, it is argued that the monitoring of stream flow and sediment transport over a short period on each of the main tributary streams was important in deriving a rating relationship. Understanding the general sediment transfer relationships and having a working knowledge of the catchment sediment budget, even over the short-term, provides valuable tools for considering sediment problems in similar catchments. In the absence of any gauged records, the use of reservoir sediments is helpful in identifying both net sediment yield and changes in the nature of sedimentation over time. The influx of coarse-grained material observed in the reservoir cores is attributed to the flushing of sediment in wet winters that follow dry summers. The last 25 years have witnessed a marked change in precipitation patterns in the uplands of Northern England. This study demonstrates that the change in precipitation regime is reflected in the sediment transport record preserved in reservoirs and overbank flood deposits along the main tributary streams. With climate change scenarios forecasting wetter winters, the results have some significance for the prediction of erosion and sediment yield from ungauged basins.

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REFERENCES

Benda, L. & Dunne, T. (1997) Stochastic forcing of sediment supply to the channel network from landsliding and debris flow. *Water Resour. Res.* **33**, 2849–2863.

Butcher, D. P., Labadz, J. C., Potter, A. W. R. & White, P. (1993) Reservoir sedimentation rates in the Southern Pennine Region, UK. In: *Geomorphology and Sedimentology of Lakes and Reservoirs* (ed. by J. McManus & R. W. Duck), 73–92. Wiley, Chichester, UK.

Cox, N. J., Warburton, J., Armstrong, A., Evans, M. G. & Holliday, V. J. (2003) Suspended sediment rating curves, generalised linear models and residual plots. *Earth Surf. Processes Landf.* (in prep.).

Crisp, D. T. (1966) Input and output of minerals for an area of Pennine moorland: the importance of precipitation, drainage, peat erosion and animals. *J. Appl. Ecol.* **3**, 327–348.

DETR/MAFF (2001) The Draft Soil Strategy for England: A consultation paper. DETR, London, UK.

Evans, M. G. & Warburton, J. (2001) Transport and dispersal of organic debris (peat blocks) in upland fluvial systems. *Earth Surf. Processes Landf.* **26**, 1087–1102.

Ferguson, R. I. (1987) Accuracy and precision of methods for establishing river loads. *Earth Surf. Processes Landf.* **12**, 95–104.

Grieve, I. C., Davidson, D. A. & Gordon, J. E. (1995) Nature, extent and severity of soil erosion in upland Scotland. *Land Degradation and Rehabilitation* **6**, 41–55.

Higgitt, D. L., Warburton, J. & Evans, M. G. (2001) Sediment transfer in upland environments. In: *Geomorphological Processes and Landscape Change: Britain in the Last 1000 Years* (ed. by D. L. Higgitt & E. M. Lee), 190–214. Blackwell, Oxford, UK

Holliday, V. J., Warburton, J. & Higgitt, D. L. (2003) Historic and contemporary sediment transfer in an upland Pennine catchment. *Earth Surf. Processes Landf.* (in press).

Jones, D. K. C. (1993) Global warming and geomorphology. *Geogr. J.* **159**, 124–130.

Jones, P. D. & Conway, D. (1997) Precipitation in the British Isles: an analysis of area-average data updated to 1995. *Int. J. Climat.* **17**, 427–438.

Leeks, G. J. L. & Marks, S. (1997) Dynamics of river sediment in forested headwater streams: Plynlimon. *Hydrol. Earth System Sci.* **1**, 438–497.

McHugh, M., Harrod, T. & Morgan, R. (2002) The extent of soil erosion in upland England and Wales. *Earth Surf. Processes Landf.* **27**, 99–107.

Reid, L. M. & Dunne, T. (1996) *Rapid Evaluation of Sediment Budgets*. Catena Verlag, Reiskirchen, Germany.

Royal Commission on Environmental Pollution (1996) *Sustainable Use of Soil*. Nineteenth Report CM3165. HMSO, London, UK.

Warburton, J. (1998) General description of the North Pennine Upland Region. In: *Geomorphological Studies in the North Pennines: Field guide* (ed. by J. Warburton), 1–16. British Geomorphological Research Group, Durham, UK.