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Sediment yields in a changing environment: a historical reconstruction using reservoir bottom-sediments in three contrasting small catchments, North York Moors, UK

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Abstract The last one hundred years have witnessed a significant change in land use in northeast England resulting from an intensification of cultivation, increased areas of improved pasture and a significant expansion of managed upland forests. Three small contrasting reservoir catchments have been selected for a detailed investigation of the impact of changes in land use on erosion and sediment yields over the last *ca.* 100 years. Sediment yields have been reconstructed using multiple core correlation of reservoir bottom-sediments and Pb-210 and Cs-137 dating of a master core from each reservoir. A number of fingerprinting techniques will be used in the future to document the changing sediment sources within the catchments but, in this preliminary paper, radionuclide fingerprinting of the catchment soils has been employed to determine the sources of the most recent sediments accumulating in the reservoirs.

INTRODUCTION

Lake and reservoir bottom-sediments have been widely used by hydrologists and geomorphologists for reconstructing recent (*ca.* last 100 years) changes in suspended sediment yields and for identifying sediment source changes in the contributing catchments (cf. Foster *et al.*, 1986; Laronne, 1990; McManus & Duck; 1993; Desloges & Gilbert, 1994; Foster & Walling, 1994; Foster, 1995; Foster *et al.*, 1996). Many of the sediment yield changes identified can be directly attributed to human impact and changes in land use within catchments; especially afforestation (cf. Leeks, 1992). However, in the UK there is uncertainty first, as to the significance of headwater catchments in contributing to the sediment yields of major lowland rivers and, secondly, whether sediment yields are sensitive to what have been generally relatively small land use changes. Features such as riparian buffer strips may, for example, reduce the sensitivity of sediment yields to changes in soil erosion through their influence on sediment delivery (cf. Walling, 1983).

This paper presents preliminary results of the application of palaeoenvironmental reconstruction methods to three reservoir-catchments in the North York Moors, northeast England, which were selected to encompass a range of topographic and land use contrasts in the area. The study forms part of a broader investigation of short- and longer-term changes in suspended sediment fluxes to the North Sea via the Humber and Tweed estuaries being undertaken by the authors. The specific objectives of this paper are:

(a) To present a preliminary assessment of recent historical changes in suspended sediment yields.
(b) To identify the most significant environmental factors which control changes in sediment yield through time.
(c) To identify the most likely source of contemporary reservoir sediment deposits using the radionuclide signatures of potential source materials.

STUDY AREA, RESEARCH METHODOLOGY AND CORE CHRONOLOGIES

The study area

The North York Moors (Fig. 1) is an upland region of northeast England ranging in altitude from below 20 m in the Derwent Valley to over 430 m above Ordnance Datum (AOD) at Danby High Moor, centred on the Cleveland Dome. Geologically, the region comprises a thick sequence of Middle Jurassic sandstones, grits and shales with thin coal seams, covering Lower Jurassic shales. The whole region is folded into a series of domes and basins and the major part of the upland consists of an eastward tilted scarp-edged plateau (Fig. 1). Extensive areas of boulder clay fringe the northeast coast and large areas of alluvium are to be found in the Derwent valley and in the southerly draining river valleys whose drainage originates from the high moors. The diverse land use embraces upland moorland and forestry plantations at high altitudes and on the heavily dissected scarp slopes; and sheep grazing and arable cultivation on the lower ground and in the Derwent valley.

Three reservoirs, Elleron Lake, Boltby Reservoir and Newburgh Priory Pond, were selected for detailed reconstruction of the historical record of suspended sediment yield (Fig. 1). The reservoirs all have simple bathymetries; their drainage basins are all less than 7 km^2 and the catchments range in altitude from 76 m to 366 m AOD. Elleron Lake, impounded in 1919, has a catchment dominated by pasture and parkland whilst Boltby Reservoir (built in 1882) has an almost entirely afforested catchment with upland coniferous plantations. Newburgh Priory Pond (built in 1760) drains a lowland catchment of mixed agricultural land use comprising arable (mainly cereal), improved pasture and some planted forestry. Summary information describing the reservoirs, their contributing catchments and land use histories is provided in Tables 1 and 2.

Field survey

All three lakes were surveyed and sampled in October and November 1994. A Mackereth type pneumatic corer was used to retrieve 1.2 m long undisturbed

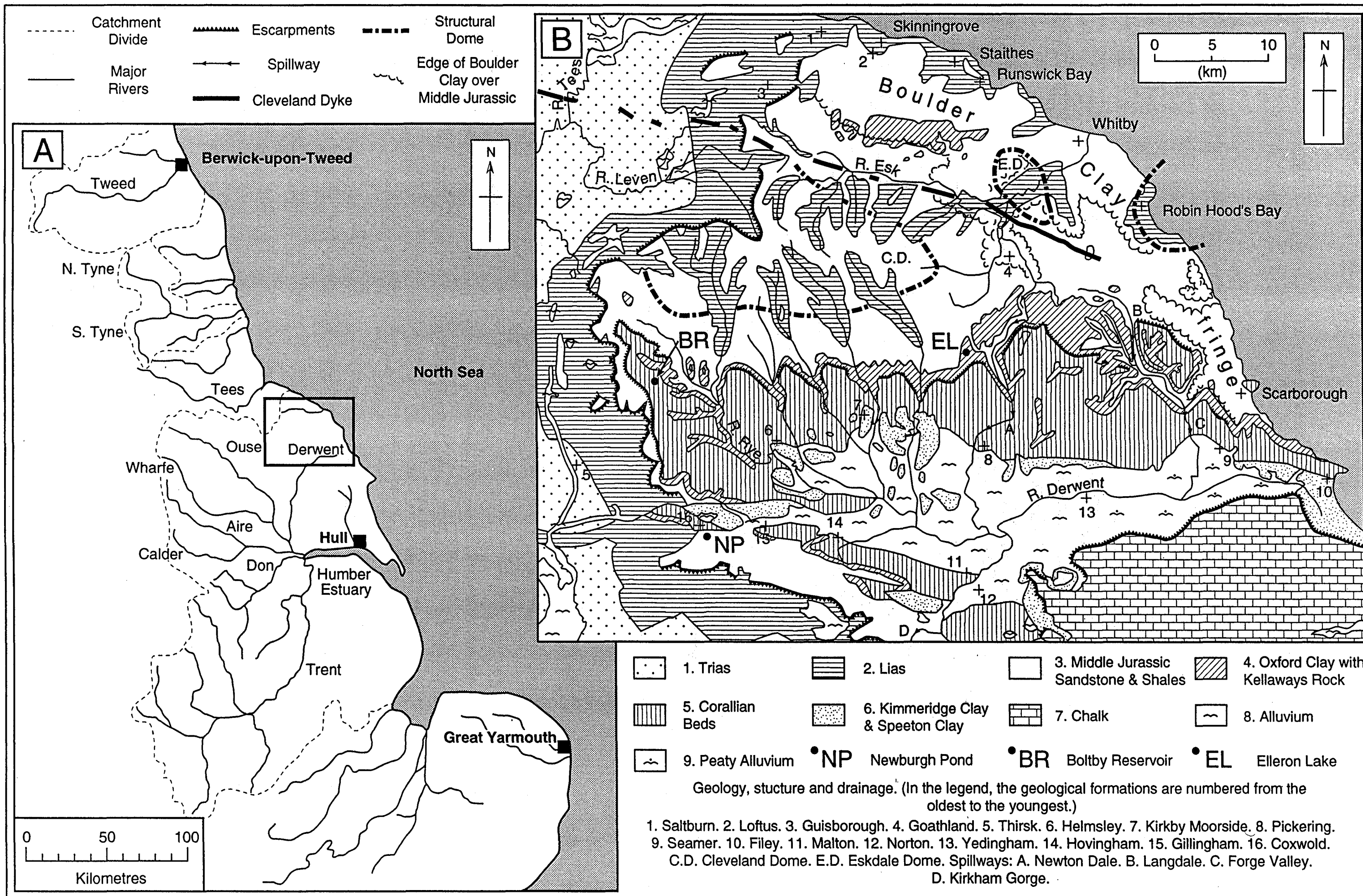

Fig. 1 Location of the study area (A) and the geology and structure of the North York Moors showing the location of Elleron Lake, Boltby Reservoir and Newburgh Priory Pond (B).

Table 1 Characteristics of the three reservoir catchments.

Site	Elleron Lake	Boltby Reservoir	Newburgh Priory Pond
Year impounded	1919	1882	1760
Catchment area (km^2)	2.74	3.41	6.33
Reservoir area (ha)	30.5	3.10	3.16
Max. reservoir depth (m)	3.25	14.10	1.40
Lake:catchment area ratio	90	110	200
Altitude range (m)	140-229	220-366	76-122
Dominant land use	parkland/pasture/woodland	coniferous woodland	pasture/arable/woodland

Table 2 Changing land use (%) within the study catchments (Based on Ordnance Survey and the 1937 land use maps).

Elleron Lake		1913	1937	1950	Present
Meadow and improved grassland		0	44	0	70
Rough pasture, common, heath		90	36	94	0
Mixed woodland		10	5	6	11
Arable land		0	15	0	19
Boltby Reservoir	**1895**	**1914**	**1937**	**1950**	**Present**
Coniferous woodland	0	0	39	49	85
Broad-leaved woodland	5	6	1	0	0
Improved grassland	0	0	0	5	5
Rough pasture, common, heath	95	94	60	46	10
Arable	0	0	0	0	0
Newburgh Priory Pond			**1937**		**Present**
Meadow and improved grassland			47		37
Mixed woodland			29		30
Arable land			15		25
Rough pasture, common, heath			9		8

sediment cores from Elleron Lake and Boltby Reservoir and a manually operated Livingstone-type corer was used to retrieve samples from Newburgh Priory Pond (cf. Foster *et al.* (1990) for a description of coring methods). At all three sites, cores were retrieved from pre-surveyed locations and the sampling exercise resulted in the collection of 17 deep-water cores from Elleron Lake, and 14 each from Boltby Reservoir and Newburgh Priory Pond. A range of potential catchment source materials were also sampled. These included representative surface samples collected from the range of soil types and land uses found within each catchment and samples of channel bank material collected from locations adjacent to major streams.

Laboratory analysis

The reservoir sediment cores were extruded vertically in the laboratory and sub-sectioned at 1.5 cm depth increments. Each sub-section was oven dried at 40°C and stored for subsequent analysis. A range of physical, mineral magnetic and radiometric measurements have been made on the reservoir bottom-sediment samples for two purposes. First, to provide data for establishing core chronologies and for core correlation purposes and, secondly, to permit comparisons with potential source materials. Dry and wet bulk density were determined gravimetrically following extrusion and drying of samples and mineral magnetic and gamma spectrometry measurements were made on the oven-dried samples. Pb-210, Pb-214 and Cs-137 activities of samples from a master core taken from each reservoir have been measured using a Eurisys hyper-pure germanium well detector at Coventry University. Because of the expected differences in the particle size composition of reservoir sediments and source materials, the latter were screened through a 63 μm sieve in order to make them more directly comparable with reservoir bottom sediment (cf Walling & Woodward, 1992; Foster & Walling, 1994; He & Owens, 1995). Cs-137 activities of source samples were measured using an EG&G Ortec hyper-pure germanium well detector at Exeter University.

Core chronologies

An attempt was made to determine a Pb-210 chronology for each master core using a modified form of the CRS model described by Appleby & Oldfield (1978) (Appleby, 1995, personal communication). The CRS Pb-210 dating model has been successfully applied in a range of UK reservoirs where sedimentation rates have changed significantly through time (cf. Oldfield & Appleby, 1984; Foster *et al.* 1985; Foster *et al.*, 1986) and it is generally considered to be more appropriate than the CIC Pb-210 dating model where unsupported Pb-210 profiles show an irregular rather than an exponential decline with depth in the sediment column (Flower *et al.*, 1989). However, the CRS model is sensitive to sediment focusing within lakes and reservoirs which may bias the depth-age relationship (Foster *et al.*, 1985). The sediment cores retrieved from all three reservoirs were correlated reliably using bulk density and mineral magnetic characteristics and show little spatial variability in sedimentation rates in the deep water zones, suggesting that sediment focusing is unlikely to bias the depth-age relationship. It is recognized that downcore changes in particle size can affect the calculated chronology, but the preliminary results presented here do not take account of particle size effects.

RESULTS AND DISCUSSION

Sedimentation rates and sediment yields

The Pb-210 chronologies established for Elleron Lake and Boltby Reservoir appear to be consistent with the known date of impoundment (Figs 2(a) and (b)). The Pb-210 dating of Newburgh Priory Pond has proved problematic, however, since unsupported Pb-210 activities are low (generally below 20 Bq kg^{-1}). Such activities are between 5 and 10 times lower than those measured in the sediments of Boltby Reservoir and Elleron Lake and, in consequence, the chronology is subject to significant errors associated with gamma counting. The Cs-137 profile for the lake sediments of Newburgh Priory Pond (Fig. 2(c)) was subsequently used to subdivide the sediment column into three time zones between 1954 and 1994. This coarsely resolved chronology provides only limited information on changing sedimentation rates in Newburgh Priory Pond since the 1950s.

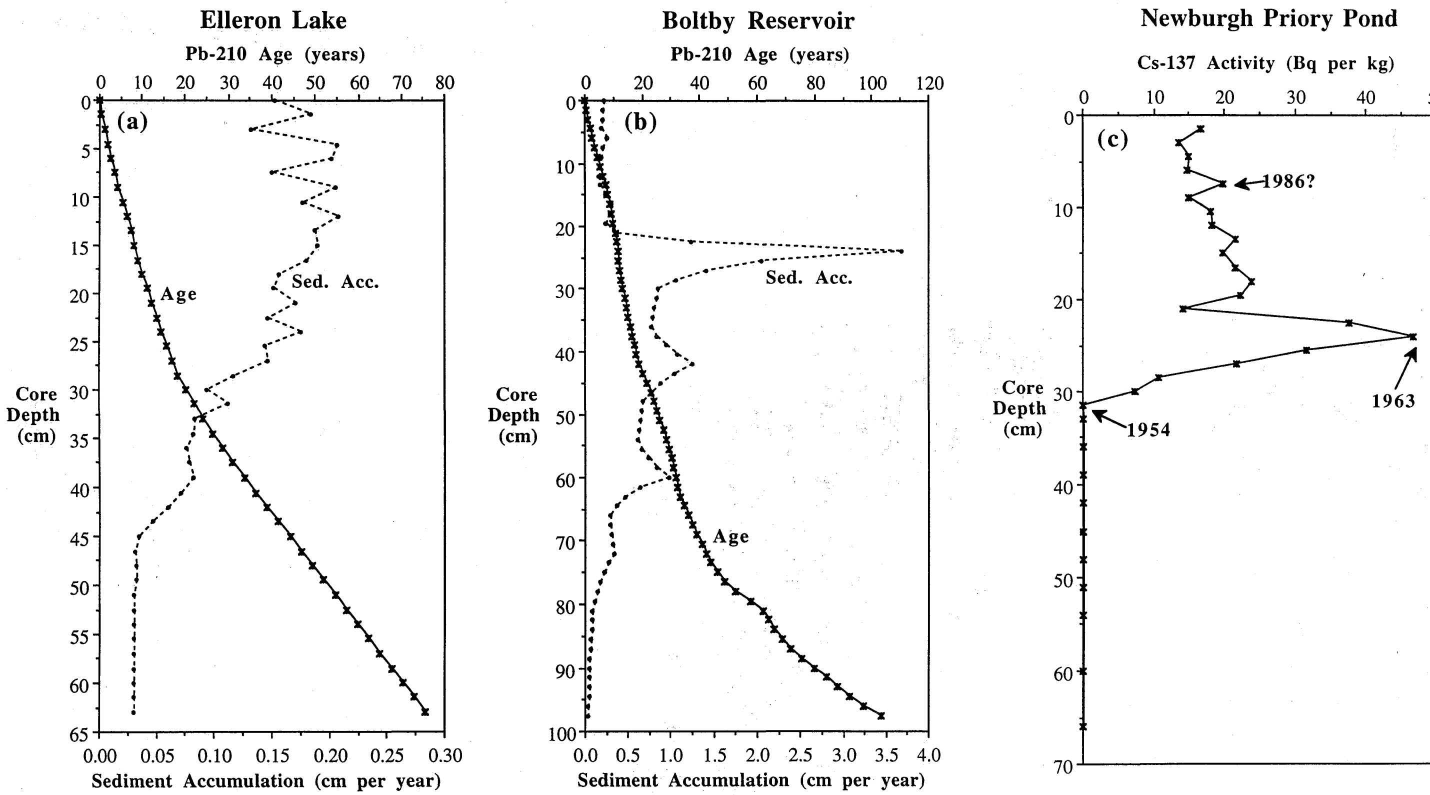

Fig. 2 Pb-210 derived depth-age curves and sedimentation rates (CRS model) for Elleron Lake (a) and Boltby Reservoir (b). Cs-137 profile for Newburgh Priory Pond (c).

The Pb-210 chronologies for Elleron Lake and Boltby Reservoir suggest significant variations in sedimentation rates since 1919 and 1921 respectively (Figs 2(a) and (b)). Sedimentation rates in Elleron Lake range from less than 0.1 to just above 0.2 cm year^{-1}. In contrast, sedimentation rates in Boltby Reservoir range from less than 0.1 to more than 3.5 cm year^{-1}. The high sedimentation rates in Boltby Reservoir can be dated to the mid 1970s, a period when extensive forest planting was undertaken over substantial areas of the catchment.

Temporal trends in the suspended sediment yields reaching the three reservoirs were established using the chronologies established for the dated master cores. Sedimentation volumes between synchronous time zones in each reservoir were determined using 14 correlated cores from Elleron Lake, 13 correlated cores from Boltby Reservoir and 14 correlated cores from Newburgh Priory Pond. Cores were correlated using low frequency magnetic susceptibility for Elleron and dry bulk density for Boltby and Newburgh. A field-determined sedimentation limit was defined for each reservoir and total sediment mass was calculated using sedimentation area rather than reservoir area. No attempt has been made at this preliminary stage to correct for the autochthonous contribution to the reservoir sediments or for the trap efficiencies of each reservoir (cf. Foster *et al.*, 1985) since insufficient data are currently available to estimate these components.

The resulting sediment yield estimates for each of the three catchments reveal some significant trends and contrasts relating to the variable impact of catchment land use changes. First, the earliest periods in Elleron Lake and Boltby Reservoir appear to be associated with relatively low sediment yields of between 2.5 and 7.5 t km^{-2} year^{-1}. From the mid 1970s in Elleron Lake and the late 1940s in Boltby Reservoir, the reconstructed changes in sediment yield appear to reflect changes in land use within the contributing catchments. Sediment yields increase significantly in Elleron Lake from *ca.* 1973 to 1994, rising from less than 5 t km^{-2} year^{-1} to nearly 10 t km^{-2} year^{-1} . The land use within the catchment changed considerably between 1950 and the present day, with an increase in the area under meadow and improved pasture and a decline in the area under rough pasture, common and heathland (Table 2). Small increases in woodland (mainly coniferous plantation) also occurred between 1950 and 1994. The rise in sediment yield seems to be consistent with patterns found in other parts of the UK, more particularly Warwickshire and South Devon (Foster *et al.*, 1986; Foster & Walling, 1994), where increased grazing pressures in the riparian zone appear to be the most significant cause of the recent historical increase in sediment yields. Expansion of the area under coniferous plantation, however, may also have had an impact on increased sediment yields.

The highest uncorrected sediment yields in Boltby Reservoir are recorded between 1948 and 1986. Yields decline from a peak of around 25 t km^{-2} year^{-1} in the 1970s and early 1980s to *ca.* 5 t km^{-2} year^{-1} in the most recent period. The rapid increase in sediment yield which commenced in the late 1940s is most likely to be associated with a significant expansion of afforestation in this area which now covers some 85% of the catchment. Land use histories taken from Ordnance Survey and the 1937 land use maps are presented in Table 2. These show an increase in forestry in the Boltby catchment from 39% in 1937 to 49% in 1950 to 85% at the present time. Detailed forest plantation records have been compiled in order to establish the most likely sediment contributing areas during this 45 year period, and the recorded

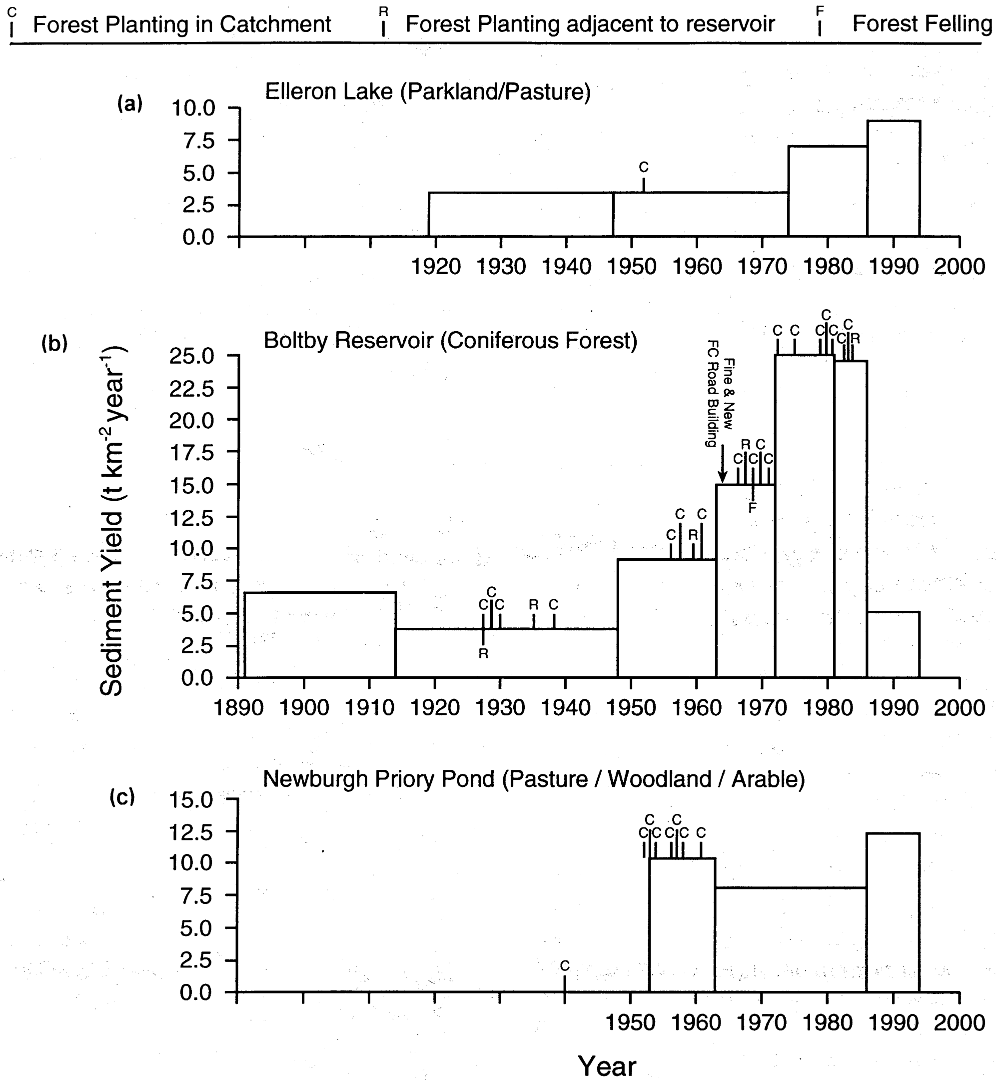

Fig. 3 Estimates of sediment yield derived from a dated master core and multiple core correlation for Elleron Lake (a), Boltby Reservoir (b) and Newburgh Priory Pond (c). Forest planting and felling periods are annotated.

planting phases have been found to be associated with increased sediment yields particularly in the 1970s and early 1980s (Fig. 3(b)). Data reported elsewhere in the UK have shown that afforestation causes sediment yields to increase by up to 1 to 2 orders of magnitude above pre-afforestation levels. The increase in sediment yield at Boltby is in a similar range, although the yield per unit area is lower than that found in other UK studies (cf. Robinson & Blyth, 1982; Burt *et al.*, 1984; Leeks, 1992). In part this is a function of the calculation method employed, since the sediment yields presented in Fig. 3 are uncorrected for trap efficiency.

Sediment yields for Newburgh Priory Pond since 1954 range between 8 and 12 t km^{-2} year^{-1}. There is no apparent increase in yield associated, for example, with known changes to agricultural practice in this area in the early 1970s which was associated with a change from spring to autumn sown cereals. The land use history shows that there has been an increase in arable land (14% to 25 %) over the last 50 years (Table 2), most of which is located close to the Pond, but this change does not appear to be reflected in an increased sediment yield. Such a response appears to be consistent with recent studies in catchments with intensive cereal cultivation in the English Midlands (Foster *et al.*, 1986; 1994) which have demonstrated that whilst some evidence exists for increased soil erosion, the opportunity for eroded sediments from cultivated land to reach the river networks is limited by the existence of narrow uncultivated buffer strips adjacent to drainage lines. This appears to be the case in the Newburgh catchment where little opportunity exists for mobilised sediment to be delivered to the stream channels.

Sediment sources

Table 3 presents data on the Cs-137 activities of representative source materials within each catchment and the uppermost sediment sample from the dated master cores collected in each reservoir. The Cs-137 activity of the latter directly reflects the Cs-137 activity of the sediment inputs from the contributing catchments since there has been no significant atmospheric fallout of Cs-137 in recent years (cf. He *et al.*, 1996). Even though the source materials have been screened through a 63 μm sieve, consideration must be given to the fact that reservoir sediments will generally be finer than the source materials and thus have a higher Cs-137 concentration. The most recent sediment deposited in Elleron Lake has a relatively high Cs-137 activity (*ca.* 55 Bq kg^{-1}) which suggests that the reservoir sediment is predominantly derived from the erosion of topsoil, most probably from both woodland and pasture sources, with only a negligible amount of sediment being derived from channel bank and subsoil sources.

In Boltby Reservoir, the Cs-137 activity of the most recent reservoir sediment is high (*ca.* 75 Bq kg^{-1}) and differs significantly from that of the catchment subsoil and channel bank materials. Concentrations most closely resemble values for forest topsoil. In Newburgh Priory Pond the contemporary reservoir sediment has a low Cs-137 activity (*ca.* 15 Bq kg^{-1}). Concentrations are less than half of those recorded in local woodland topsoils, and lie somewhere between those of cultivated and pasture topsoils.

Table 3 Average Cs-137 activities (Bq kg^{-1}) for catchment source materials and for the uppermost (most recent) reservoir sediments.

Site	Elleron	Boltby	Newburgh
Reservoir sediment	55	75	15
Woodland topsoil	71.9	70.1	33.6
Pasture topsoil	17.5	23.0	22.2
Arable topsoil	13.9	-	9.4
Subsoil (*ca.* 30 cm depth)[a]	<1	<1	<1
Channel bank (30-90 cm)[b]	3.4-10.1	4.1-12.3	3.2-9.7

[a] Below detection limits (*ca.* 1 Bq kg^{-1}).
[b] Cs-137 activities for a range of bank heights between 30 and 90 cm are based on a combination of sampling and theoretical calculation.

CONCLUSIONS

A preliminary assessment of recent historical changes in suspended sediment yields has been presented for three catchments in the North Yorkshire Moors, UK. The reconstructed sediment yields for the three catchments of diverse land use history are highly variable through time. The absolute sediment yields reported above must, however, be treated with some caution, since they are uncorrected for trap efficiency. Nevertheless, the patterns of sediment yield history for each basin are internally consistent and demonstrate the significant human impact on sediment yields over the last century. The Boltby Reservoir catchment records the impact of upland afforestation. Since planting in the 1930s, few areas have been felled (Fig. 3); a process which may lead to a significant increase in sediment yield in the future. Nevertheless, the history of forest planting shows a sustained impact on sediment yield which increases by around an order of magnitude in comparison with the pre-afforestation period. Cs-137 analysis suggests that forest topsoils are the most likely source of contemporary sediments in the reservoir. Expansion of the area of improved pasture in the Elleron catchment in the 1970s and a small increase in the area under coniferous plantation has resulted in an increase in sediment yield to around three times the early 20th century rates since the early 1970s. Cs-137 analysis suggests that contemporary reservoir sediments contain a significant contribution from forest topsoils. Sediment yields to Newburgh Priory Pond have remained reasonably constant since the early 1950s and Cs-137 analysis suggests that a combination of pasture and arable topsoils dominate the most recently accumulating sediments.

Future work will include quantitative sediment source modelling using mineral magnetic and geochemical techniques, in addition to radionuclide signatures, and the sediment yield estimates will be revised to take account of autochthonous contributions and reservoir trap efficiencies.

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REFERENCES

Appleby, P. G. & Oldfield, F. (1978) The calculation of Pb-210 dates assuming a constant rate of supply of unsupported Pb-210 to the sediment. *Catena* **5**, 1-8.

Burt, T. P., Donohoe, M. A. & Vann, A. R. (1984) A comparison of suspended sediment yields from two small upland catchments following open ditching for forestry drainage. *Z. Geomorphol. N.S.* **51**, 51-62.

Desloges, J. R. & Gilbert, R. (1994) Sediment sources and hydroclimatic inferences from glacial lake sediments: the postglacial and sedimentary record of Lillooet Lake, British Columbia. *J. Hydrol.* **159**, 375-393.

Flower, R. J., Stevenson, A. C., Dearing, J. A , Foster, I. D. L., Airey, A., Rippey, B., Wilson, J. P. F. & Appleby, P. G (1989) Catchment disturbance inferred from studies of three contrasted sub-humid environments in Morocco *J. Palaeolimnol.* **1**, 293-322.

Foster, I. D. L. (1995) Lake and reservoir bottom sediments as a source of soil erosion and sediment transport data in the UK. In: *Sediment and Water Quality in River Catchments.* (ed. by I. D. L. Foster, A. M. Gurnell, & B. W. Webb.), 265-283 Wiley, Chichester, UK.

Foster, I. D. L. & Walling, D. E. (1994) Using reservoir deposits to reconstruct changing sediment yields and sources in the catchment of the Old Mill reservoir, South Devon, UK over the past 50 years. *Hydrol. Sci. J.* **39** (4), 347-368.

Foster, I. D. L., Dalgleish, H. Y., Dearing, J. A. & Jones, E. D. (1994) Quantifying soil erosion and sediment transport in drainage basins; some observations on the use of Cs-137. In: *Variability in Stream Erosion and Sediment Transport* (ed. by L. J. Olive, R. J. Loughran & J. A. Kesby) (Proc. Canberra Symp., December 1994) 55-64. IAHS Publ no. 225.

Foster, I. D. L., Dearing, J. A., Grew, R. G. & Orend, K. (1990) The sedimentary data base: an appraisal of lake and reservoir sediment based studies of sediment yield. In: *Erosion, Transport and Deposition Processes* (ed. by D. E. Walling, A. Yair & S. Berkowicz) (Proc. Jerusalem Workshop, March-April 1987) 19-43. IAHS Publ no. 189.

Foster, I. D. L., Dearing, J. A., Simpson, A., Carter, A. D. & Appleby, P. G. (1985) Lake catchment based studies of erosion and denudation in the Merevale catchment, Warwickshire, UK. *Earth Surf. Processes and Landforms* **10**, 45-68.

Foster, I. D. L., Dearing J. A. & Appleby, P. G (1986) Historical trends in catchment sediment yields: a case study in reconstruction from lake sediment records in Warwickshire, UK. *Hydrol. Sci. J.* **31** (3), 427-443.

Foster, I. D. L., Owens, P. N. & Walling, D. E. (1996) Sediment yields and sediment delivery in the catchments of Slapton Lower Ley, South Devon, UK. *Field Studies* **8**, 629-661.

He, Q. & Owens, P. (1995) Determination of suspended sediment provenance using caesium-137, unsupported lead-210 and radium-226: a numerical mixing model approach. In: *Sediment and Water Quality in River Catchments.* (ed. by I. D. L. Foster, A. M. Gurnell, & B. W. Webb), 207-227. Wiley, Chichester, UK.

He, Q., Walling, D. E. & Owens, P. N. (1996) Interpreting the ^{137}Cs profiles observed in several small lakes and reservoirs in southern England. *Chem. Geol.* **129**, 115-131.

Laronne, J. (1990) Probability distribution of event sediment yields in the northern Negev, Israel. In: *Soil Erosion on Agricultural Land.* (ed. by J. Boardman, I. D. L. Foster, & J. A. Dearing), 481-492. Wiley, Chichester, UK.

Leeks, G. J. L. (1992) Impact of plantation forestry on sediment transport processes. In: *Dynamics of Gravel Bed Rivers.* (ed. by P. Billi, R. D. Hey, C. R. Thorne & P. Tacconi,), 651-670. Wiley, Chichester, UK.

McManus, J. & Duck, R. W. (eds) (1993) *Geomorphology and Sedimentology of Lakes and Reservoirs.* Wiley, Chichester, UK.

Oldfield, F. & Appleby, P. G. (1984) Empirical testing of ^{210}Pb dating models for lake sediments. In: *Lake Sediments and Environmental History* (ed. by E. Hawarth & J. Lund), 93-124. Leicester University Press.

Robinson, M. & Blyth, K. (1982) The effect of forestry drainage operations on upland sediment yields. *Earth Surf. Processes and Landforms* **7**, 85-90.

Walling, D. E. (1983) The sediment delivery problem. *J. Hydrol.* **65**, 209-237.

Walling, D. E. & Woodward, J. C. (1992) Use of radiometric fingerprints to derive information on suspended sediment sources. In: *Erosion and Transport Monitoring Programmes in River Basins* (ed. by J. Bogen, D. E. Walling & T. J. Day) (Proc. Oslo Symp., August 1992), 153-164. IAHS Publ. no. 210.