Pergamon

Phys. Chem. Earth, Vol. 20, No. 2, pp. 199–206, 1995.

0079-1946/95 $9.50 + 0.00

0079-1946(95)00024-0

Temporal Variability in Catchment Sediment Yield Determined from Repeated Bathymetric Surveys: Abbeystead Reservoir, U.K.

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ABSTRACT

Situated an upland area of Northwest England, Abbeystead Reservoir has experienced severe sedimentation problems. Presently, only 6 % of the original capacity and 30 % of the original surface area remains and the deposition process is considered to have reached a quasi-equilibrium condition. Temporal variations in storage capacity losses were determined from morphometric analysis of 7 bathymetric surveys (1851-1991) and indirectly using a time-dependent relationship between storage capacity and water surface area. The sediment yield between successive surveys was obtained by gravimetric conversion of storage capacity losses, corrected for untrapped sediment lost directly over the spillway. The analysis highlights uncertainties in the use of empirical trap efficiency relationships, particularly in very dynamic systems. The long-term (140 years) sediment yield of the Upper Wyre catchment was estimated as 192 t km^{-2} yr^{-1}, containing a mean organic matter content of 18.5 %. Decadal-scale variations in sediment yield ranged from 78 to 390 t km^{-2} yr^{-1}. Two periods with elevated yields were distinguished and linked to phases of construction and land drainage within the catchment.

KEYWORDS

Reservoir; bathymetric survey; sedimentation; trap efficiency; sediment yield

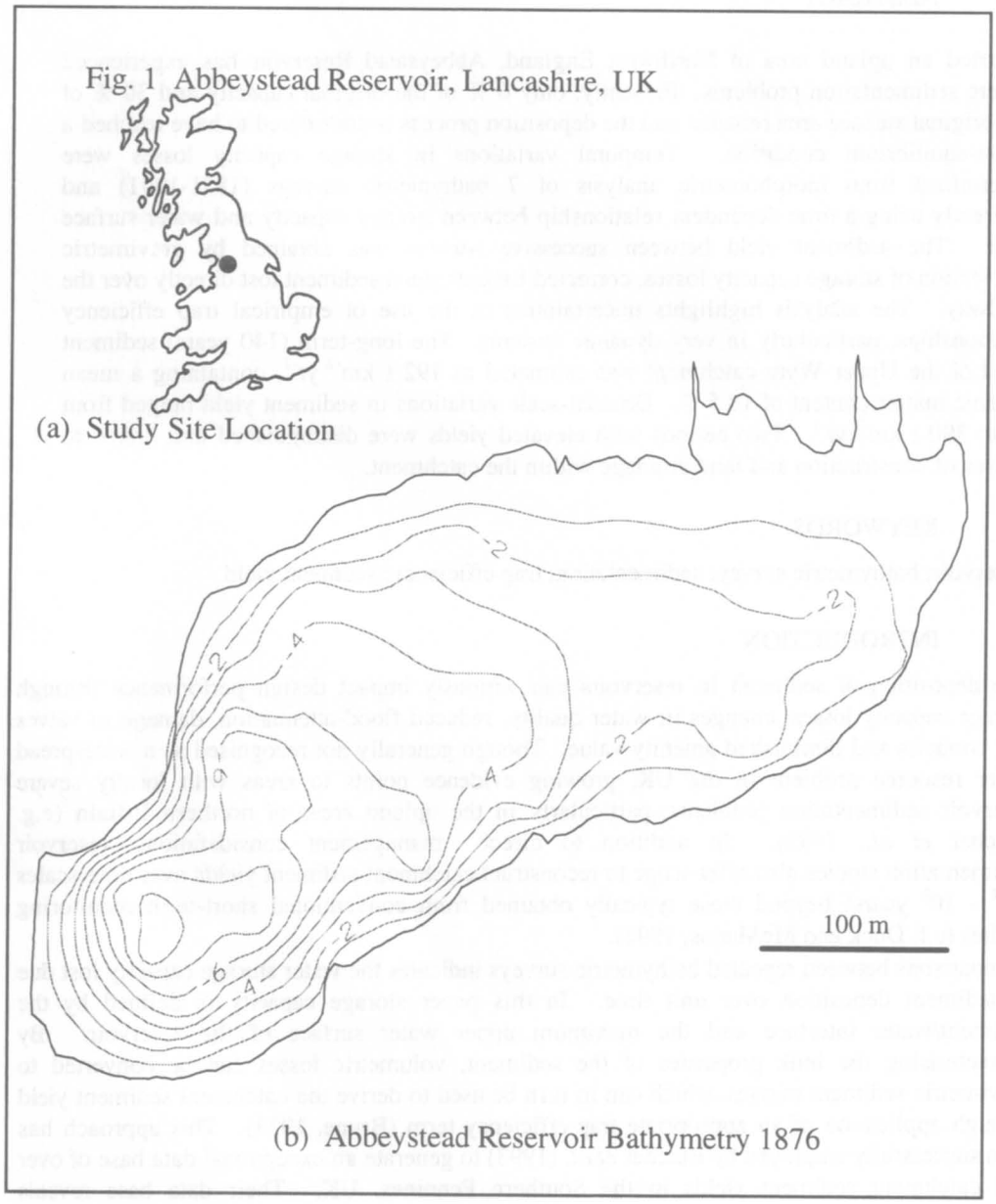
INTRODUCTION

The deposition of sediment in reservoirs can variously impact design performance through storage capacity losses, changes in water quality, reduced flood-attenuation, damage to valves and conduits and diminished amenity value. Though generally not recognised as a widespread water resource problem in the UK, growing evidence points to areas with locally severe reservoir sedimentation problems, particularly in the upland areas of northern Britain (e.g. Butcher *et al.*, 1993). In addition to direct management considerations, reservoir sedimentation studies also offer scope to reconstruct catchment sediment yields over time-scales (10^1 - 10^2 years) beyond those typically obtained from conventional short-term monitoring studies (c.f. Duck and McManus, 1994).

Comparisons between repeated bathymetric surveys indicates the water storage capacity lost due to sediment deposition over unit time. In this paper storage capacity is defined by the sediment/water interface and the maximum upper water surface of the reservoir. By characterising the bulk properties of the sediment, volumetric losses can be converted to gravimetric sediment masses, which can in turn be used to derive the catchment sediment yield through application of an appropriate trap-efficiency term (Brune, 1953). This approach has been successfully employed by Butcher *et al.* (1993) to generate an exceptional data base of over 100 catchment sediment yields in the Southern Pennines, UK. Their data base reveals

significant spatial variations in yield estimates, ranging from 3 to almost 300 t km^{-2} yr^{-1}. The upper values of this range are considerably in excess of the UK national average sediment yield of 50 t km^{-2} yr^{-1} proposed by Walling and Webb (1987).

Where detailed survey data are available, important information on the temporal and spatial patterns of deposition can also be revealed. This paper explores the value of sequential bathymetric surveys to elucidate temporal variations in sedimentation rate for the single site of Abbeystead Reservoir, situated 10 km south-east of Lancaster (Fig. 1a). The historical importance of the site for regional water resource development has meant is it unusually well documented by bathymetric surveys - 1876, 1930, 1970, 1980, 1989, 1991, including the pre-inundation capacity derived from an 1845 topographic map. Moreover, complementary information from aerial photography and historical map sources (1948, 1963, 1984, 1988) has been used reconstruct the development of sub-aerial delta deposits to develop a time-dependent sedimentation relationship between these two control data sets. This relationship was used to reconstruct catchment sediment yields over 7 discrete time periods over the past 140 years.



BACKGROUND

Abbeystead Reservoir was originally constructed in 1851 as a compensation facility in conjunction with a water abstraction scheme diverting spring-fed and headwater flows to the city of Lancaster. The site has undergone several phases of expansion and was completed in its present form in 1876, with a maximum surface area of 19.6 ha and a mean depth of 3.7 m (Fig. 1b). It was latterly maintained as a flood attenuation structure, but the near complete siltation of the site has now rendered it obsolete for both functions. The catchment area of 48.7 km^2 ranges in height from 108 to 572 m. The geology is dominated by Carboniferous sandstone and shales (Namurian) overlain by till and head deposits. Blanket peats are extensive on the rolling interfluve areas, but these are presently highly degraded. Mean annual precipitation ranges from 1300-1800 mm yr^{-1}, and the Tarnbrook and Marshaw Wyre tributaries have a combined mean daily flow of c. 4 $m^3 s^{-1}$.

STUDY APPROACH

A key element of the project was to collate and standardise the bathymetric survey data set. All surveys, including that of 1991 (JSR), were carried out by transect and line/rod methods and therefore subject to the usual errors i.e. uncertainties in defining geo-locations and in the definition of the mud-water interface (c.f. Rauch and Heinemann, 1984). In spite of these limitations, the very high sedimentation rates (maximum > 80 mm yr^{-1}), suggests these data can be treated with a circumspect confidence.

Survey data were digitised from original survey maps onto a common co-ordinate base and interpolated using kriging procedures in the SURFER® mapping package to produce digital elevation models (DEM) of bathymetry. This approach permitted direct comparison of DEMs from different survey dates and determination of storage capacity losses over a range of sampling intervals. Following mass conservation the sediment yield was estimated from the expression:

$$\frac{dS}{dt} = Yi - Yo = YiE \qquad (1)$$

Where S is the stored volume of sediment in the reservoir, Y_i is the effective volumetric inflow (i.e. sediment yield), Y_o is the effective volumetric outflow of sediment, and E is the system trap efficiency.

$$E \equiv \frac{Yi - Yo}{Yi} \qquad (2)$$

To convert volumetric changes to gravimetric sediment yield the material properties of the deposited sediment were also investigated using a variety of surface sampling and coring techniques e.g. Livingstone corers to 3 m (Table 1). The exceptional decline in storage capacity to 6 % of the 1876 volume also highlighted need to consider trap efficiency as a dynamic term.

Table 1 Physical properties of Abbeystead sediment from core and grab samples

Property	number	mean	95 % CI
Dry bulk density (t m^{-3})	111	0.7	0.65 - 0.76
Moisture content (%)	195	49.3	48.0 - 50.6
Organic matter (%)	210	18.1	16.9 - 19.2
Grain size (mm)	40	$D_{30} = 0.063$	
		$D_{50} = 0.125$	
		$D_{90} = 3.2$	

STORAGE CAPACITY LOSSES OVER TIME

An illustration of changes in storage capacity and delta development at the site is shown in Fig. 2a. Of particular note is the growth of the sub-aerial delta after 1930 and the concomitant decline in the volumetric loss rate after 1970 as the reservoir effectively filled with sediment. Regression analysis using reservoir surface area as the independent variable indicates the time-dependent sedimentation process can be closely described by the exponential expression Vol. = $6527e^{0.25\ AREA}$ (Fig. 2b).

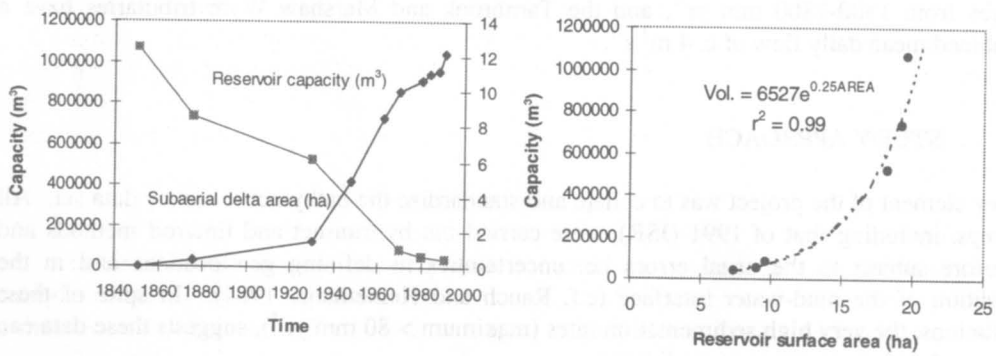


Fig. 2 Storage capacity and subaerial delta growth [1851 - 1991] (a) capacity loss and delta extension over time (b) regression between storage capacity and surface area

This relationship was used to interpolate storage capacities during inter-survey periods, most importantly for the years 1948 and 1963 when air photographs of the site were available and converted to sediment yields using equations 1 and 2. The results, summarised in Table 2, includes the 1930 survey values reported by Conway (1970). Selection of the trap efficiency terms is discussed in a following section.

Table 2 Sediment yield over time derived from morphometric data (1851-1991)

Time	Capacity ($m^3 \times 10^3$)	Delta Area (ha)	Trap Efficiency (%)	Sediment Yield ($t\ km^{-2}\ yr^{-1}$)	Observation Period (yr.)
1851	1066.7	0.0	82.1	-	-
1876	736.0	0.4	76.0	242	1851-1876
1930	527.3	1.44	69.5	78	1876-1930
1948	257.5	4.91	52.6	373	1930-1948
1963	106.2	8.46	31.4	369	1948-1963
1970	85.3	10.02	26.9	170	1963-1970
1980	53.3	10.61	18.7	208	1970-1980
1991	42.6	12.18	15.5	96	1980-1991
Mean				192	1851-1991

SEDIMENT DEPOSITION PROCESSES

The bathymetric surveys provide information on the sedimentation patterns between successive surveys, however space limits discussion. Nevertheless a clear impression of the in-filling mechanisms can be inferred from Fig. 3 which illustrates the development of the sub-aerial delta over the period 1876 to 1991. Two dominant sediment facies can be distinguished, namely coarse clastic facies forming the main delta area and sub-aerial bars, and fine-grained lacustrine facies accumulating in low energy slackwater areas distant from the channel entrant.

The delta has prograded by deposition of coarse clastic sediments at the point where the channel debauches into the open-water body and loses competence due to flow-section expansion. The distal margin of coarse sediment deposition advanced mainly parallel to the southern flank of the reservoir at rates exceeding 100 m^2 yr^{-1}, such that coarse channel gravels D_{50} = 4 mm (D_{max} 32 mm) are presently found within 30 m of the spillway. Deposition of fine sediments is presently restricted to the main open-water area where silty lacustrine muds (D_{50} = 0.04 mm) are the dominant substrate, though even here distributary channels introduce clastic sediments as small fan and bar structures.

The presence of arcuate bar and spit features at the margins of the delta (e.g. 1963 map in Fig. 3) indicate that secondary processes including wave action have influenced the morphological development of the delta. Vegetation has also played an important role by the stabilising effects of plant colonisation on emergent sand bars. The median grainsize from a data set of 40 samples was 0.0125 mm, representing fine sand. As reported in Table 1, 70 % of the sediments lie in the size range of fine-sand to coarse gravels. These data area important for subsequent trap efficiency determinations.

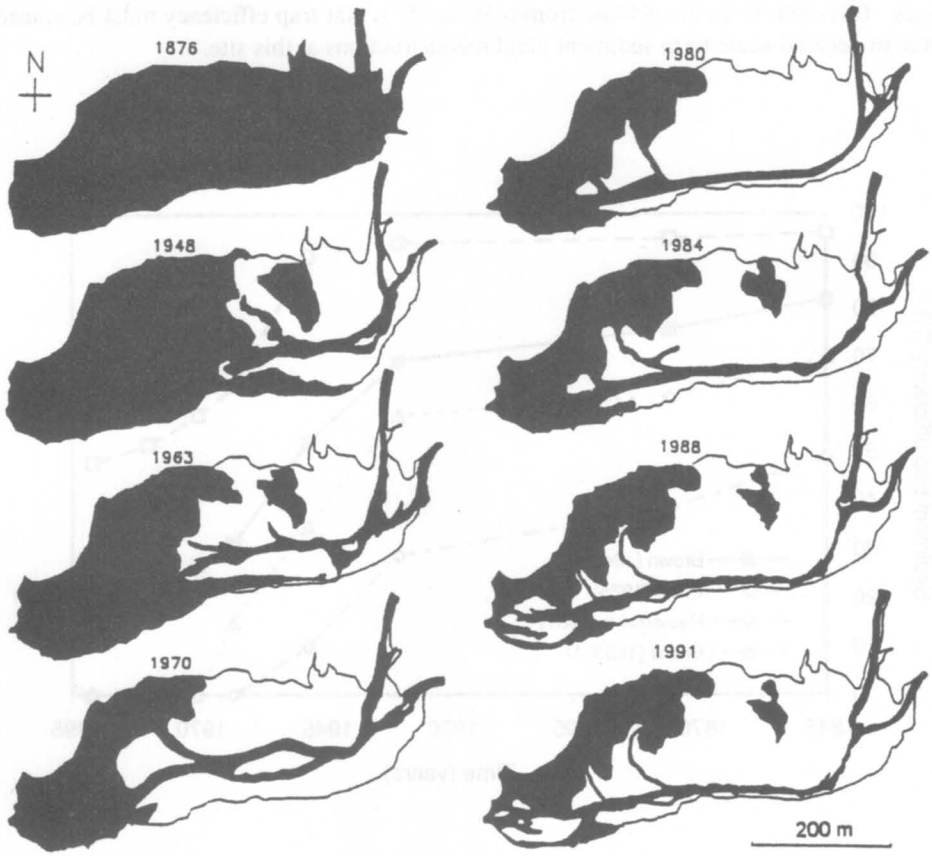


Fig. 3 Progradation of subaerial delta deposits at Abbeystead Reservoir (1876-1991)

TRAP EFFICIENCY

The trap efficiency of a reservoir is defined as the percentage of the catchment sediment yield retained in the basin. Trap efficiency depends on a range of factors, the most important of which are hydraulically defined by sediment size, flow characteristics, reservoir shape and flood retention time (Heinemann, 1981). Much of the work to date has been empirically defined from USA data sets, and depends upon simple ratios such as the capacity:area ratio (Brown, 1944), or capacity:inflow ratio (Brune, 1953). For this study a range of potential trap-efficiency values were derived and plotted against time on Fig. 4. Several of the curves intercept zero by 1970 demonstrating their failure to characterise the Abbeystead system because sedimentation continued after this period (Table 2). By contrast, the more sophisticated grain-size specific curves of Chen (1975) use a basin area:outflow ratio (d= 0.0016 mm in Fig. 4) which takes into account runoff and sediment transport duration terms. The necessary data were derived from a nearby catchment, but in this case the resulting curve under predicts trap efficiency because turbulent channel flows reach the spillway during flood events and the effective mixing volume is much smaller than the total basin area.

The importance of defining an appropriate trap efficiency term is illustrated by comparison of the ratios of the upper and lower limits shown in Fig. 4 which vary with time from 200 % (1876) to infinity (1970). The uncertainty in trap efficiency implies an uncertainty in the mean annual sediment yield in the range of 50 % overestimation to 200 % underestimation. In the absence of sufficient direct measurements of trap-efficiency (c.f. Goodwill *et al.*, 1995), the intermediate curve of Brown (1944) was adopted for sediment yield reconstruction. This was justified by the fact that the reservoirs used in Brown's study more closely approximate to the hydrological regime of the British uplands, and permits direct comparison with the sediment yield estimates of Butcher *et al.* (1992) who previously used this method in the Southern Pennines. It is clear from the decline from > 80 to 15 % that trap efficiency must be considered dynamic in decadal-scale term sediment yield reconstructions at this site.

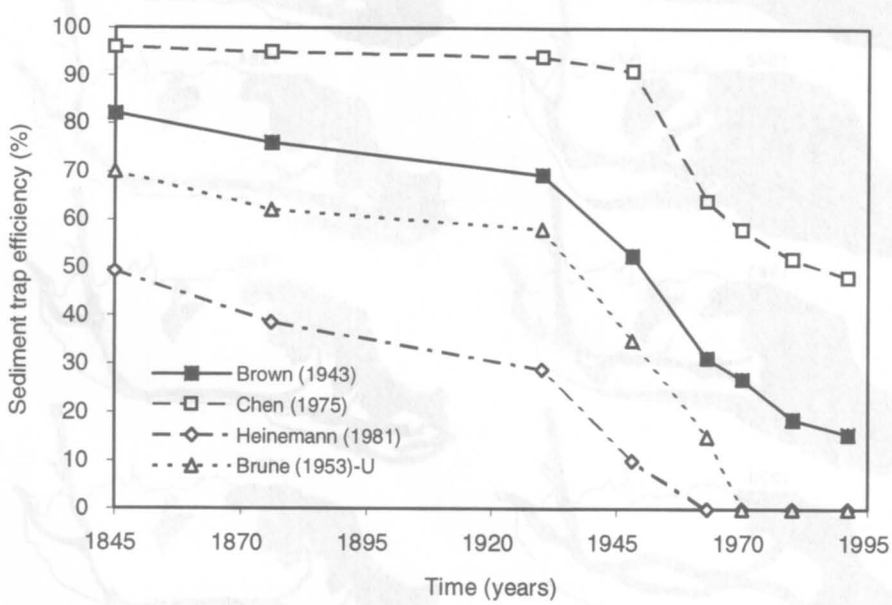


Fig. 4 Trap Efficiency determinations using reported empirical relationships

SEDIMENT YIELD RECONSTRUCTION FOR UPPER WYRE BASIN (1851 - 1991)

Volumetric changes were converted using mean bulk density values of 0.7 t m^{-3} for storage capacity losses and a value of 1 t m^{-3} to account for the sub-aerial delta component. Sediment yields for specific periods were then determined and corrected for trap efficiency losses (Table 2). The pattern of sediment yield over time has clearly varied over time as shown graphically in Fig. 5. The relatively high values for the 1851-1876 period most probably relates to the extensive water abstraction works undertaken in the northern headwaters of Tarnbrook Fell area which necessitated the construction of the compensation reservoir at Abbeystead. The engineering work involved construction of water collectors and pipes in the headwaters with obvious destabilising effects on erosion-sensitive stream-head channel systems (Mansergh, 1988). Between 1876 and 1930 the system appears to have undergone a period of geomorphological recovery when yield values declined to the lowest value of 78 t km^{-2} yr^{-1}.

The highest sediment yields were identified for the period 1930-1948 when the sediment yield peaked at 373 t km^{-2} yr^{-1}. This increased activity is provisionally linked to agricultural land improvement in the drive to increase domestic food production associated with the Second World War. Extensive drain laying operations were typical of the period, particularly in marginal upland areas, where forage production and stocking densities could be increased by improving field drainage (cf. Duck and McManus, 1984; Heathwaite *et al.*, 1994). Drainage operations continued after this period until the 1960s when Government sponsored grant schemes were withdrawn. Subsequently, yields have declined to c. 200 t km^{-2} yr^{-1}. The relatively low value for the most recent period is thought to be a minimal value because sluice valves were opened in 1981 to encourage sediment flushing (D. Wickham, NWW, *pers comm.*).

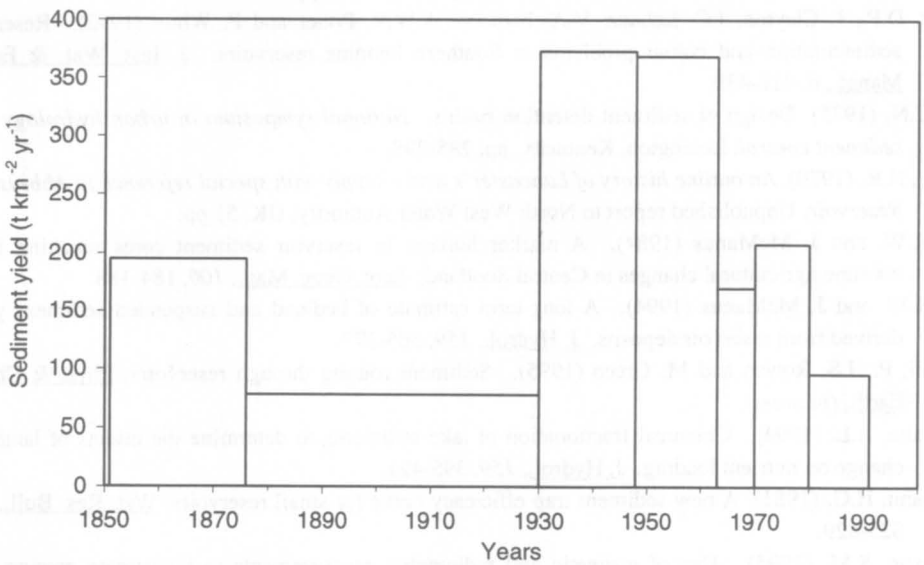


Fig. 5 Reconstructed sediment yields for the Upper Wyre basin

PERSPECTIVE

Sedimentation at Abbeystead reservoir has been a major problem throughout the history of the site due to periodically high erosion rates and a large catchment/lake ratio. This has culminated in it becoming functionally obsolete due to the near complete loss of original capacity. Because of the high sediment rates present (> 8 m in 140 years) the bathymetric approach was the only viable method to resolve the yield data for this study. Dating sediment cores by radiometric

assay, used successfully elsewhere, was inappropriate here because the stratigraphy extends beyond the age range of ^{137}Cs, and the high accretion rates effectively prohibit the use of ^{210}Pb due to dilution effects (c.f. Hutchinson, 1995).

The close coupling between subaerial delta growth and storage capacity losses permitted the development of a time-dependent relationship upon which to reconstruct the sediment yield history of the Upper Wyre. Application of widely applied trap-efficiency terms was shown to give a wide range of values and is the main area of uncertainty in the reconstruction. Nevertheless, significant variations in sediment yield were apparent, with peak values tentatively linked to construction work and agricultural land improvements. Elevated phases are superimposed on a long-term sediment yield of 70 - 200 t km^{-2} yr^{-1}, which is consistent with the findings of other research in the locality, and testifies to regionally high sediment production rates (Newson and Bathurst, 1990). These results are also in line with the growing body of evidence indicating sediment yields in the UK uplands to be higher than traditionally recognised (e.g. Labadz *et al.*, 1991). Future work on the site will attempt to model sediment routing from a hydrodynamic approach and to improve the confidence in the trap-efficiency terms used for yield estimation.

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