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Blanket peat erosion and sediment yield in an upland reservoir catchment in the southern Pennines, UK

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Abstract

This paper investigates temporal variations in fluxes of peat and other sediment in the catchment of March Haigh Reservoir, West Yorkshire. Long-term estimates of sediment yield were derived from a study of reservoir sediments. Magnetic properties were used to correlate ten cores to a master profile dated using ^{210}Pb and ^{137}Cs. A ^{14}C date suggests that most of the organic component of the sediment is allochthonous and derived from peat eroded from the catchment. Organic sediment yields suggest low catchment erosion rates between 1838 and 1963. Blanket peat erosion increased significantly after 1963, and peaked between 1976 and 1984. Estimates of total sediment yield range between 2 and 28 t km^{-2} a^{-1}. These yields are significantly lower than those from some previous studies examining reservoir sedimentation in other blanket peat-covered catchments. The low yield estimates may be due to relatively low rates of erosion in the basin, but may also be partly explained by maintenance of silt traps during the early life of the reservoir and removal of sediment by scouring. Sedimentation within the reservoir is spatially variable, and bathymetry and sediment source appear to be the dominant controls on sedimentation patterns within the reservoir. Copyright © 2005 John Wiley & Sons, Ltd.

Keywords: **blanket peat; erosion; sediment yield; reservoir sedimentation; South Pennines**

Introduction

Blanket peats occur in upland areas with high rainfall and an impermeable substrate. Literally, the bog lies like a blanket over flat or slightly sloping terrain (Taylor, 1983). The blanket mires of the British Isles cover an area of approximately 25 000 km^2, constituting 10 per cent of the world's total. This makes them of considerable international importance as only 3 per cent of the global land surface is covered by peat (Tallis, 1997). Unfortunately, blanket peats are vulnerable to degradation, and Tallis (1998) suggests that as much as 3500 km^2 of the blanket mires of the British Isles may be in an eroded state. The southern Pennine uplands is an area that is particularly affected by erosion; in the Peak District National Park, up to three-quarters of the moorland area has been subject to degradation and erosion (Anderson and Tallis, 1981). The denudation of blanket peat areas has been shown to have significant implications for habitat conservation (Yalden, 1981a), global climate change (Heathwaite, 1993), the loss of grazing land (Yalden, 1981b), the loss of reservoir capacity (Labadz *et al*., 1991) and discolouration of drinking water (Pattinson *et al*., 1994).

Management of blanket peat erosion into the future requires an understanding of its major causes in the past. Dating the onset (or increase in rate) of erosion has been an important component of studies examining the causes of the initiation of blanket peat erosion (Bradshaw and McGee, 1988; Mackay and Tallis, 1996). Several types of methodology have been applied in previous studies for this purpose including: observation of ground lowering by erosion pins (e.g. Imeson, 1974); analysis of aerial photographic series (e.g. Evans, 1989); palaeoecological studies of mires (e.g.

Table I. Estimates of sediment yield for catchments containing areas of upland peat, based on reservoir sedimentation

Author (s)	**Catchment**	**Sediment yield*** **(t km^{-2} a^{-1})**	**Method(s)†**
Young (1958)	Strines Reservoir, Pennines	39·4[a]	1
Kirkby (1967)	Water of Deugh, Ayrshire	16 m^3 km^{-2} a^{-1}[b]	1
Hall (1967)	Catcleugh Reservoir, Northumberland	43·1[c]	1
Ledger *et al.* (1974)	Southeast Scotland		1, 2
	North Esk Reservoir	25	
	Hopes Reservoir	26	
McManus and Duck (1985)	Glenfarg, Glenquey reservoirs, Scotland	26·3–31·3[d]	2
Labadz (1988)	Chew Reservoir, Lancashire	212·7	1
Duck and McManus (1990)	Scottish Midlands		2
	Earlsburn	68·2	
	North Third	205·4	
	Carron Valley	141·9	
Hoyle, civil engineer, (cited in Labadz *et al.*, 1991)	Abbeystead Reservoir, Lancashire	34·8[e]	1
Labadz *et al.* (1991)	Wessenden Valley Reservoirs	203·69 (organic fraction = 38·82)	1, 2
Labadz *et al.* (1995), White *et al.* (1996)	77 reservoirs in Yorkshire	mean 124·5, median 77	1
Hutchinson (1995)	Howden Reservoir, Derbyshire	126·7 (organic fraction = 31·3)	3
Rowan *et al.* (1995)	Abbeystead Reservoir, Lancashire	78–373	1

* Sediment yield: [a] no sediment density given, recalculated by McManus and Duck (1985); [b] no sediment density given; [c] no sediment density given, recalculated by Walling and Webb (1981); [d] inorganic component only; [e] no sediment density given, recalculated by Walling and Webb (1981).

† Method: 1, comparison of reservoir surveys since impoundment to calculate sediment volumes between survey dates; 2, comparison of modern reservoir survey with estimation of original capacity, based on augering of sediments; 3, estimation of sediment volume based on coring of lake sediments.

Tallis, 1987); use of sediment traps (e.g. Crisp, 1966); measurement of stream load (e.g. Francis, 1990); and examination of lake or reservoir sediments (e.g. Stevenson *et al.*, 1990). Estimates of dates for the inception of significant gully erosion in the south Pennines range from AD 1450 (Tallis, 1995) to AD 1850 (Tallis, 1965, 1973; Labadz *et al.*, 1991).

Catchment sediment yield can provide a measure of the rate of peat erosion of a basin that is comparable with other studies. Direct monitoring of outputs from eroding blanket peat catchments over a few seasons has produced sediment yield estimates of 0·7 to 122 t km^{-2} a^{-1} (Crisp, 1966; Imeson, 1974; Robinson and Blyth, 1982; McCahon *et al.*, 1987; Francis, 1990; Labadz *et al.*, 1991), whilst reservoir sedimentation studies have produced estimates ranging from 25 to 373 t km^{-2} a^{-1} (Table I). However, most of the reservoir sedimentation studies represent estimates of long-term average sediment yield over the life of the reservoir, and do not offer any clues as to the temporal variations in sediment flux occurring between survey dates.

Long-term estimates of sediment yield based on multiple cores taken from lakes or reservoirs have been used in several studies examining the effects of human disturbance and other factors on the environment (e.g. Dearing, 1992; Foster and Lees, 1999). Spatial variability in sedimentation is accounted for by correlating synchronous properties between cores, and sediments in a 'master' core are dated using isotopes such as ^{210}Pb or ^{137}Cs to indicate temporal variability in sediment accumulation.

This paper describes part of a research project designed to elucidate the causes of peat erosion in the catchment of March Haigh Reservoir, situated in the southern Pennines (Figure 1). In particular, this paper fulfils the following specific aims by conducting a multiple-core-based study of March Haigh: (1) to assess the temporal variations in sediment yield since the impoundment of March Haigh Reservoir, and identify changing fluxes of eroded peat and other sediment; and (2) to examine spatial variations in sedimentation patterns in March Haigh Reservoir.

March Haigh Reservoir and its Catchment

March Haigh Reservoir (SE 015 129) lies west of Huddersfield, in West Yorkshire (Figure 1). The reservoir was built as a canal-feeder, and has consequently not been subject to frequent drawdown of water level during the summer months or to the consequent reworking of sediments (Stott, 1984). It therefore should contain a relatively undisturbed sediment record. The reservoir provided water for the Huddersfield Narrow Canal, opened in 1811. The waterway was designed for the transportation of cargoes between the industrial towns adjacent to the Pennines. Examination of the

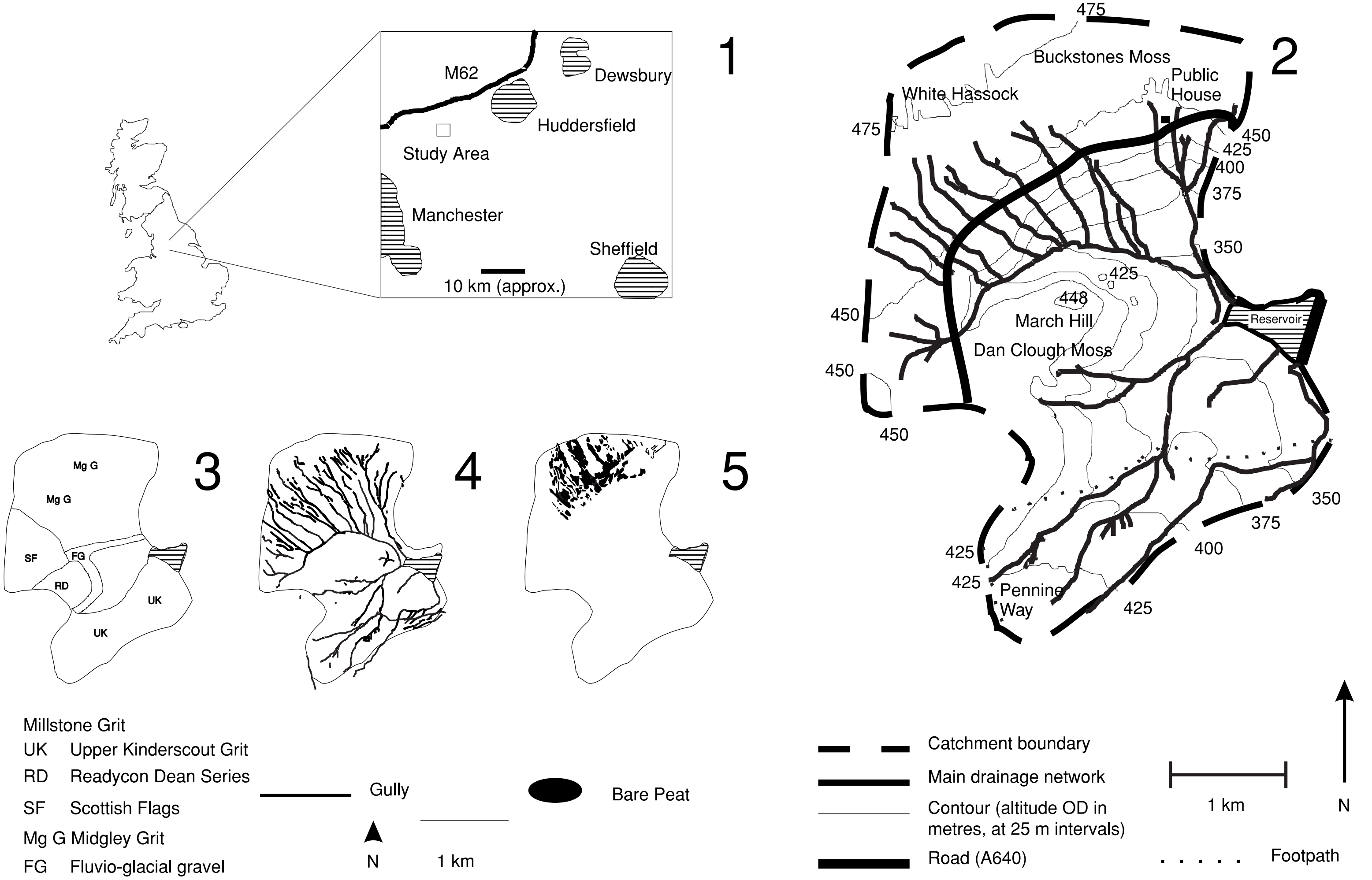

Figure 1. The March Haigh catchment: (1) location of the study area; (2) catchment features; (3) solid geology (Geological Survey of England and Wales, 1932); (4) 1995 gully systems; (5) 1995 areas of bare peat.

Table II. Features of March Haigh catchment. Based on information derived from 1995 aerial photography, Ordnance Survey maps (1:10 000 scale) and the 1999 reservoir survey

Catchment feature	
Reservoir altitude	*c.* 330 m OD
Maximum altitude of catchment	*c.* 482 m OD
Minimum altitude of catchment	*c.* 330 m OD
Catchment area (excludes reservoir surface area)	263·6 ha
Reservoir surface area	5·2 ha
Catchment: reservoir area ratio	51:1
Catchment drainage density	9·92 km km^{-2}

minutes of the Huddersfield Narrow Canal Committee by Binnie (1987) shows that the reservoir was completed *c*. 1838. Binnie also suggests two phases of engineering works designed to increase the capacity of the reservoir prior to June 1840, and one further raising of the dam, possibly completed in 1853. Decline of the textile industry in the area during the mid- to late 20th century, and previously the replacement of the canal by the railway as the main means of freight transport, meant that demand for water in the area decreased significantly. It has been suggested that, as a result of this decrease, silt traps positioned at the inflows to the reservoir may have been left to fall into disrepair within the last 30 years (D. Dutton, British Waterways, 1999, pers. comm.).

The catchment of March Haigh (Figure 1) drains into the River Colne, which runs adjacent to the Huddersfield Narrow Canal. March Hill (SE 007 131, 448 m OD) dominates the area. The north slopes of March Hill show remnants of past landslides which are a common feature of the upper Colne valley. Further information concerning the reservoir and its catchment is given in Table II. Namurian Millstone Grits dominate the solid geology that underlies the catchment (Figure 1). The majority of the upper slopes of the catchment are covered in blanket peat, whilst the low relief area around the reservoir has podzolic soils. Aerial photos taken in 1995 were obtained from the National Trust, and from these the detail of gully systems and areas of bare peat has been derived (Figure 1). The 1995 drainage density was estimated at 9·92 km km^{-2}. It can be seen from Figure 1 that the denuded areas in the March Haigh catchment are concentrated around Buckstones Moss, which forms a small proportion of the catchment area. Anderson *et al*. (1989) examined aerial photographs of the area taken between 1948 and 1988, which suggested that the gully system had already been initiated by 1948. A significant increase in areas of bare peat and extent of the gully system had occurred by the time the second photographic set was taken in 1964. The last set of photographs, taken in 1988, shows a further extension of the gully system.

Anderson *et al*. (1989) carried out a vegetation survey of the area. At the time of the survey, the upper slopes were dominated by a mixture of sedges (*Eriophorum* spp.) and grasses (including *Nardus*, *Molinia* spp.). These were interspersed with patches of *Empetrum nigrum*. The steep slopes between the reservoir and Buckstones Moss were covered in a mixture of *Pteridium aquilinum* and *Cladonia* lichens. *P. aquilinum* also occurred on the gentler slopes of March Hill Carr. In wetter areas, *Rubus chamaemorus* bordered gullies, whilst *Sphagnum recurvum* was encountered on the sides of gullies.

The March Haigh catchment currently forms part of the Marsden Moor Estate, run by the National Trust. Due to the high variety and abundance of moorland birds that breed in the area, much of the estate has been designated both a Site of Special Scientific Interest, and a Special Area of Conservation under the European Habitats Directive. The land is mainly used for water supply and for the grazing of sheep and cattle as an ‘urban common’ moorland, with some grouse shooting taking place during the season.

Methods

The process of estimating sediment yields based on the sampling of multiple cores required three steps. Firstly, the reservoir was surveyed and sediment samples collected. Secondly, the organic content, dry density and mineral magnetic properties of the samples were measured. Downcore variations in mineral magnetic signatures are often synchronous between cores, and have been shown to be a reliable sediment property for core correlation (Thompson and Oldfield, 1986). Samples from a ‘master’ core were dated using ^{210}Pb and ^{137}Cs, to establish a sediment chronology. Thirdly, correlations were made between samples from the different cores using mineral magnetic properties, and total volumes of sediment between mineral magnetic horizons were calculated. Not all sediment output from the catchment will be retained by the water body, and sediment yield estimates were adjusted for variations in the trap efficiency of the reservoir (following the method of Brown, 1944).

As sediment yield estimates were to be used as a measure of peat erosion rate, it was necessary to identify the proportion of the sediment that was composed of allochthonous organic matter (eroded peat), in comparison to organic matter derived from internal (autochthonous) production within the reservoir. In sediments with a high proportion of allochthonous input, the sediments can become contaminated by older carbon, affecting age estimates (Olsson, 1991). Where the influx of older carbon exceeds that which is autochthonously derived, a reversal in the age–depth relationship of the sediments may occur, such that the ^{14}C date of the 'contaminated' sediments may be measured 'older' than that of the material further down the stratigraphy. Edwards and Whittington (2001) suggest that radiocarbon reversals can be viewed as a positive indicator of erosion and reworking of organic material.

Field methods

Field work at March Haigh Reservoir was aided by British Waterways conducting engineering work on the dam during the spring and summer of 1999. This meant that the reservoir was almost entirely drained and the sediments could be surveyed on foot. The topographic survey was conducted using a Nikon A20 Total Station electronic distance measuring instrument. A total of 488 points around the dam and sediment surface were surveyed to produce the map shown in Figure 2. The contours in Figure 2 are the altitude of the drained sediments relative to that of the spillway (top water level). The minimum altitude was −11·06 m. The south-facing slopes of March Haigh have a relatively shallow gradient, and appeared to have minimal sediment deposited. Opposite is a very steep north-facing rock wall, also with minimal sedimentation. At the bottom of this valley, the majority of sediment appeared to be deposited in a flat area which extended up to the sides of the embankment. The soft sediment here was overlain by a thin, dry crust, cracked in a polygonal pattern and coated with patches of green algae. There were signs of a scour channel starting to develop with a band of coarse gravel traversing the flat area. Sixteen points along regularly spaced transects in the

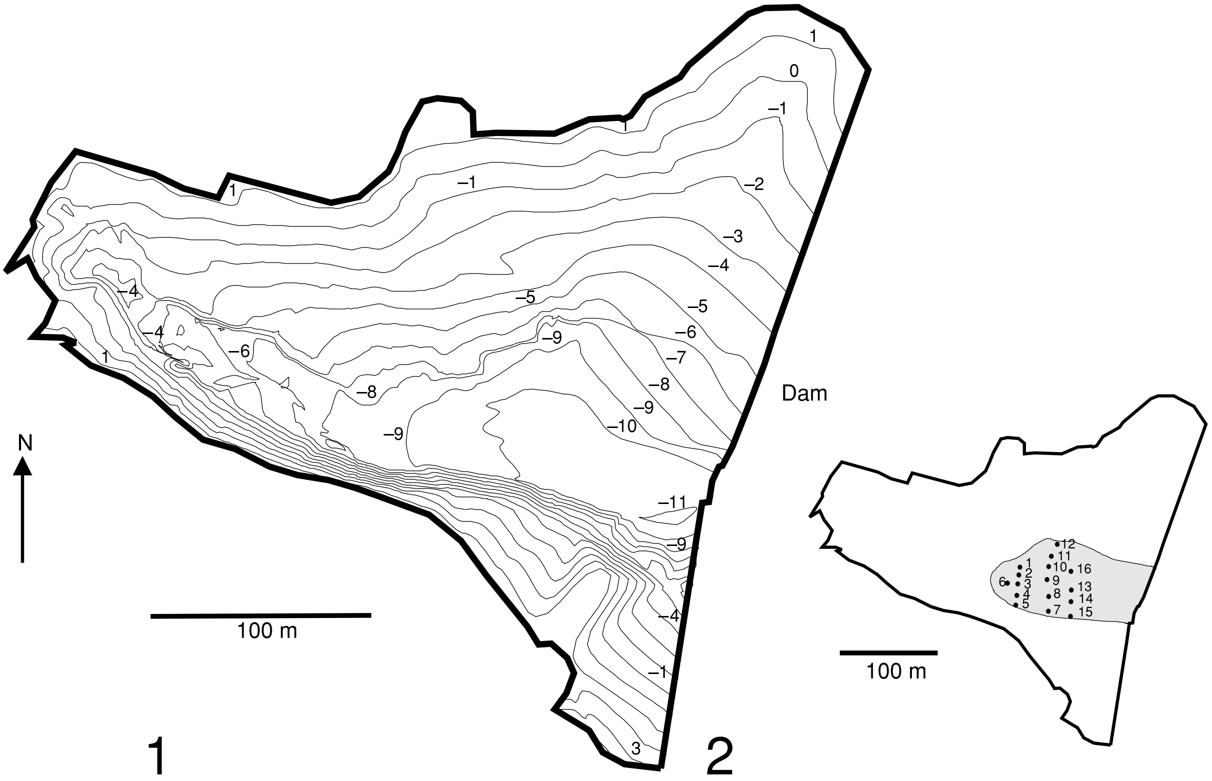

Figure 2. March Haigh Reservoir: (1) topography of the drained reservoir, August 1999. Contours are depths (m) relative to the overflow crest. (2) Sediment sampling positions; numbered points indicate boreholes; shading indicates area of thick sediment.

area of soft sediment were surveyed and marked by wooden posts; these were intended for sediment sampling (Figure 2). Coring sites were not positioned close to the dam because the sediment in this area was still very soft, and deemed too dangerous to walk on. The upstream area of the reservoir contained little soft sediment, and was composed of gravel and large rocks. Sediment cores (labelled MAR1–MAR16) were taken using a 4 cm diameter piston corer, or, where the surface of the sediment was too hard and dry for this, a 6 cm diameter Dutch auger was used.

Laboratory analysis

All cores were sampled at *c*. 3 cm intervals using a slicing plate. This produced sample volumes of *c*. 38 cm^3 and 85 cm^3 for cores bored with the piston corer and Dutch auger respectively. The lithology of each sample was described in terms of an arbitrary classification of the four types of sediment encountered: organic gytjja (detritus mud), coarse inorganic deposits (sand and gravel), fine inorganic deposits (silt) and peat. Colour(s) was recorded using a Munsell® soil colour chart. Each sample was then deposited in a foil tray and allowed to air-dry. Air-dried samples were gently disaggregated using a pestle and mortar, sieved to select the <2 mm diameter particle size fraction, and packed into 10 cm^3 plastic pots. Mass-specific magnetic susceptibility was measured at low frequency (χ_{lf}) using a Bartington MS2 meter calibrated with a $MnCO_3$ standard (Gale and Hoare, 1991).

Core MAR13 was selected as the 'master' core as it reached the base of the sediments, was the deepest (370 cm), and contained much of the variation in lithology shown to a lesser extent in the other cores. Sub-samples from MAR13 were analysed for organic content, dry bulk density and radionuclide activity. Samples were dried at 105 °C for determination of dry bulk density. Organic matter content was determined by measuring the loss-on-ignition at 430 °C for 24 hours. Activity of the radionuclides ^{210}Pb and ^{137}Cs was assayed in selected sub-samples of MAR13 at the University of Durham, using an EG & G Ortec well detector. Samples selected were centred on correlated mass susceptibility horizons. Sample masses were typically 1–3 g. Samples were placed in non-porous tubes, sealed with a rubber cap, and assayed for 48 hours. A sub-sample of sediment from 139·5 to 130·5 cm depth in core MAR16 was assayed for ^{14}C, at the Beta Analytic laboratory, Miami, USA (reference number 156829). This core was selected as it still contained enough material for ^{14}C dating after the other analyses had been completed.

Results

Sediment properties and core correlation

Mass-specific magnetic susceptibility, dry bulk density and loss-on-ignition profiles for MAR13 are shown in Figure 3 and summary statistics in Table III. The lithology of the deposits varies between four types of sediment: organic gytjja (detritus mud), coarse inorganic deposits (sand and gravel grade clasts), fine inorganic deposits (silt grade) and peat. The majority of the sediment in MAR13 is composed of organic gytjja, interspersed with thin horizons composed of the other lithologies. Magnetic susceptibility and lithology profiles of the sixteen cores taken around March Haigh are shown in Figure 4. The pattern of the magnetic susceptibility profiles relates to the lithology of the sediment. This is especially evident for MAR4, 5, 6, 7, 8, 14 and 15, where the sediment profiles are interspersed with significant thicknesses of coarse inorganic deposits and peat inwash, which produce relatively low magnetic susceptibility values. These results are not surprising since the Millstone Grit lithology is of a magnetically impoverished nature (Hutchinson, 1995). This influence of lithology on magnetic susceptibility profiles makes the identification of time-synchronous horizons in the March Haigh sediments difficult. To aid the interpretation of the data, measurements from samples with lithology other than organic gytjja were eliminated from the analysis, producing a set of compressed magnetic susceptibility profiles for 14 of the cores (Figure 5). Three synchronous magnetic susceptibility horizons (labelled A–

Table III. Sediment properties of core MAR13

	Mass-specific magnetic susceptibility (10^{-6} m^3 kg^{-1})	Dry bulk density (g cm^{-3})	Loss-on-ignition (%)
Minimum	0·56	0·09	2
Mean	1·37	0·25	25
Maximum	4·79	0·76	38

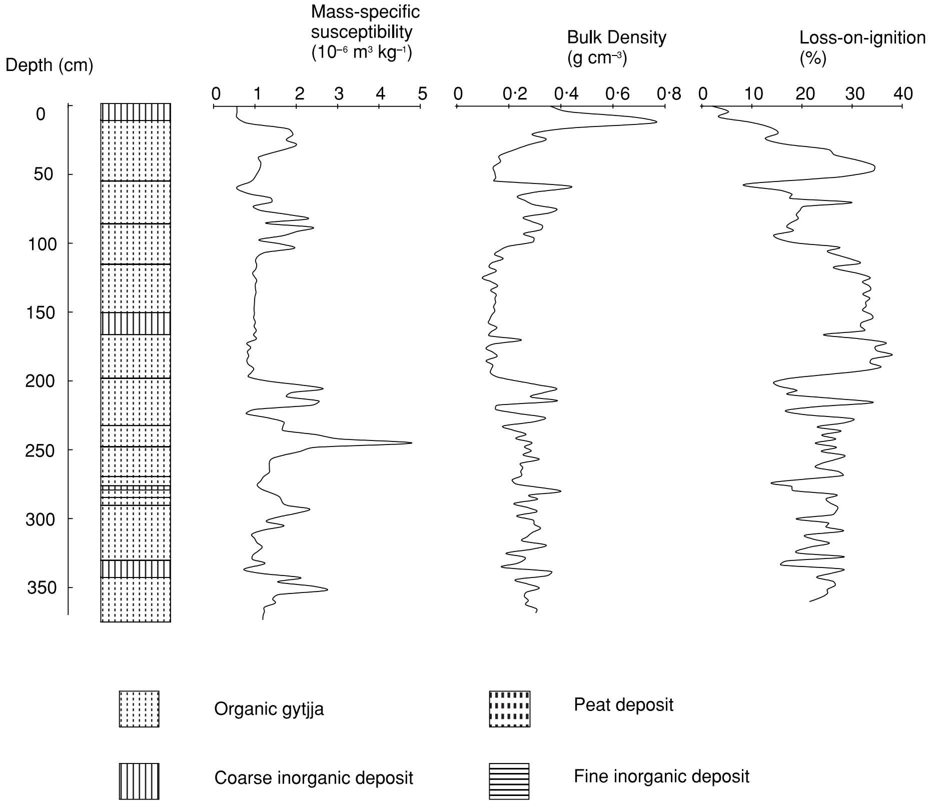

Figure 3. Sediment stratigraphy of core MAR13. Mass-specific magnetic susceptibility expressed as 10^{-6} m^3 kg^{-1}.

C) could be identified from visual inspection of ten of the compressed profiles. The magnetic susceptibility characteristics and 'relative' depths of each horizon (based on the top depths of each sub-sample) are given in Table IV. Profiles of MAR4 and MAR7 are not shown in Figure 5, as these were composed almost entirely of mineral and peat deposits with no organic gytjja. Cores MAR5, 8, 14 and 15 do not exhibit any correlation features with the remaining cores.

Radioisotope chronology

The sediments of March Haigh are clearly not homogenous in terms of lithology, porosity or bulk density. The constant rate of supply (CRS) ^{210}Pb dating calculation (Appleby and Oldfield, 1978) assumes that sediments are heterogeneous and that the sedimentation rate is variable, and may thus be applicable to March Haigh. Due to

Table IV. Relative depths below top water level (cm) of magnetic susceptibility horizons

		Borehole (MAR)															
Horizon	**Description**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
A	Lower limit of susceptibility plateau	51·2	9·2	34·7	–	–	112·0	–	–	39·0	51·0	51·0	42·0	107·2	–	–	45·0
B	Susceptibility peak	90·2	39·2	–	–	–	–	–	–	73·0	63·0	85·1	93·1	240·1	–	–	130·5
C	Susceptibility peak	148·6	–	–	–	–	–	–	–	108·3	104·2	124·1	153·1	345·2	–	–	176·9
Base of sediment	–	169·3	77·3	136·3	–	94·6	181·0	15·1	–	116·1	122·4	132·3	161·8	369·7	–	–	–

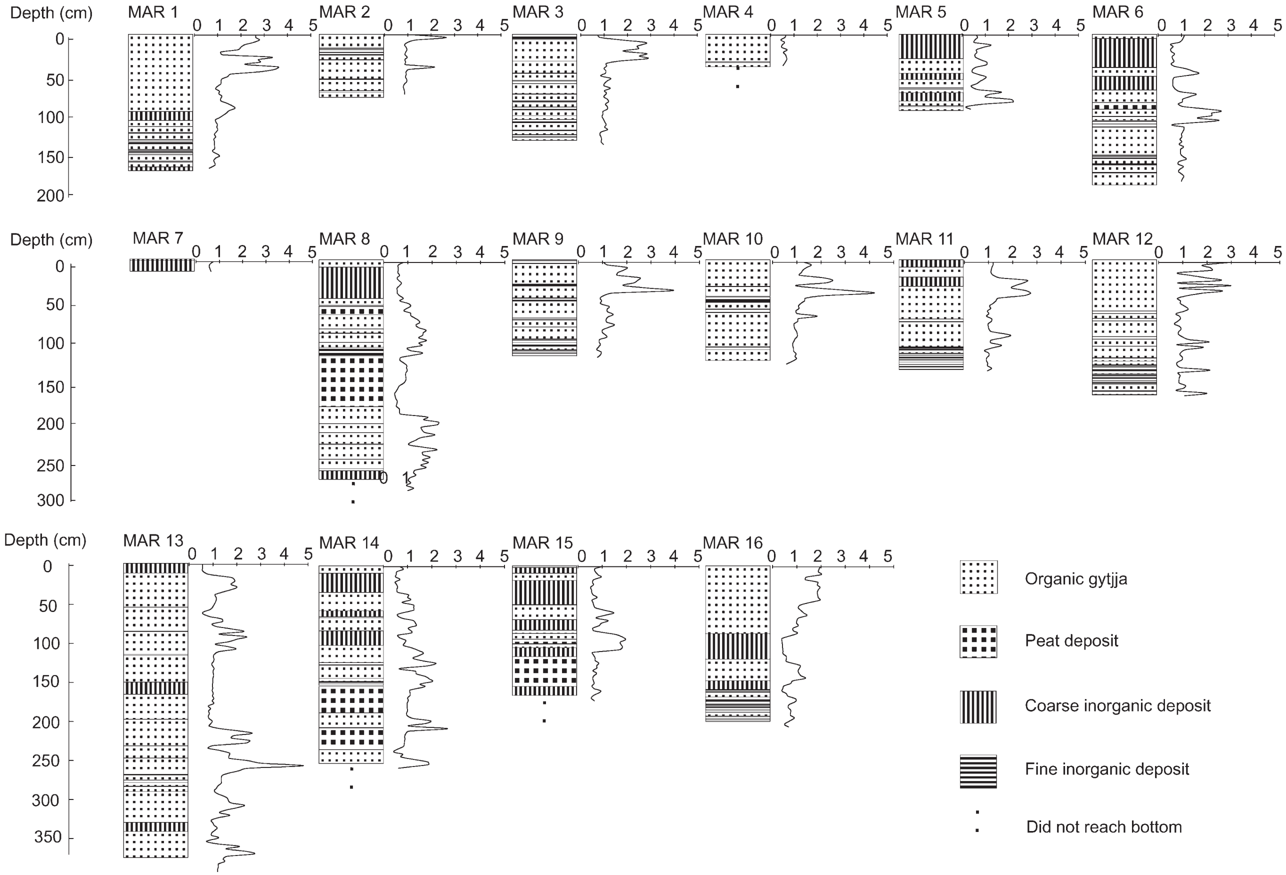

Figure 4. Magnetic susceptibility profiles and sediment types. Mass-specific magnetic susceptibility expressed as 10^{-6} m^3 kg^{-1}.

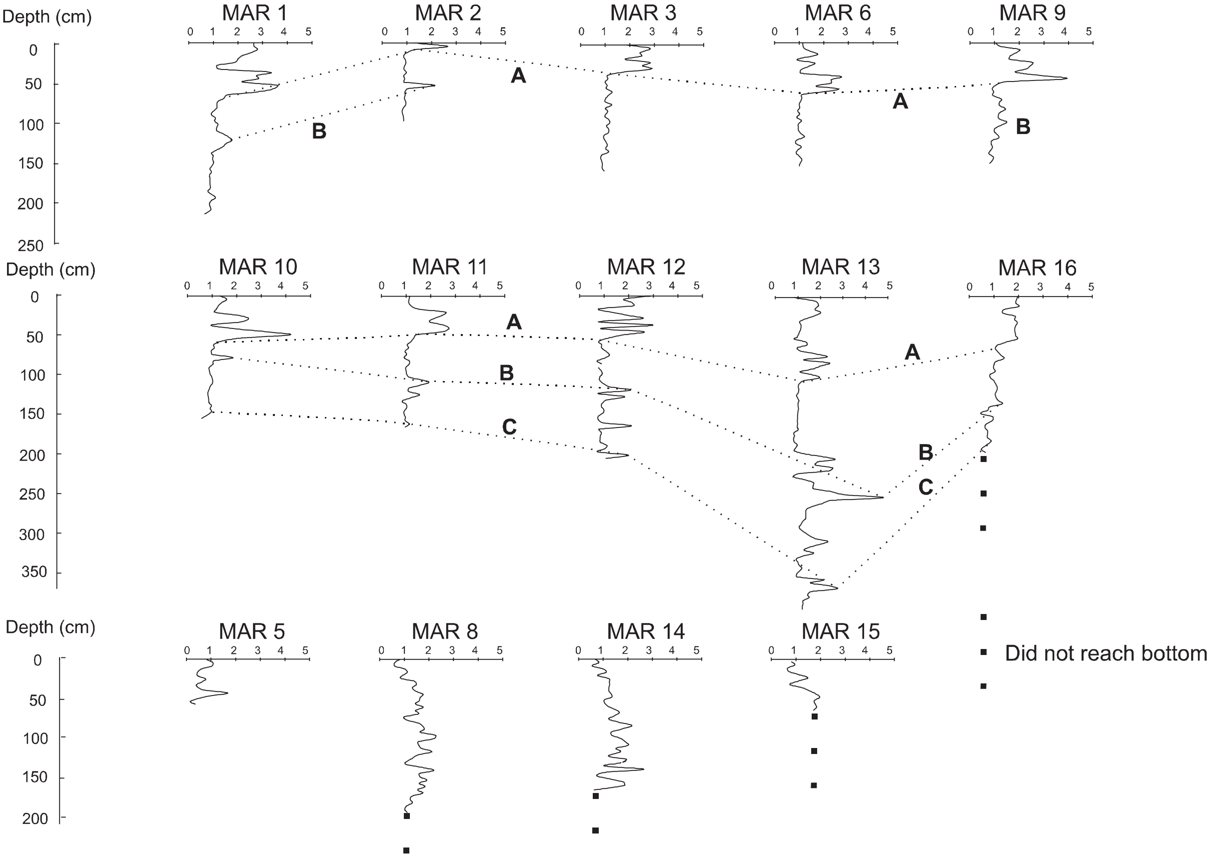

Figure 5. Transformed magnetic susceptibility profiles, showing location of synchronous magnetic susceptibility horizons. Mass-specific magnetic susceptibility expressed as 10^{-6} m^3 kg^{-1}. Measurements represented are from samples composed of organic gytjja sediment type only.

equipment problems, only five and nine sub-samples were successfully measured for ^{210}Pb and ^{137}Cs respectively from the MAR13 core. The activity of supported ^{210}Pb (from the activity of ^{226}Ra at the sediment–water interface) was subtracted to provide an estimate of unsupported ^{210}Pb activities. These are reported as activities of the granddaughter of ^{210}Pb, ^{210}Po. The ^{210}Pb age calculations using CRS are shown in Table V. ^{137}Cs measurements of MAR13 are shown in Figure 6. Peak activity of ^{137}Cs occurs at *c*. 287 cm depth, although the low sampling resolution would suggest the peak lies between the two adjacent sub-samples at 345 and 237 cm depth. This peak is probably due to the 1963 fallout maximum, and an inventory of 12·72 ± 0·35 mBeq g^{-1} is slightly lower than 1963 inventories from the nearby River Ouse area ranging from *c*. 18 to 22 mBeq g^{-1} (Walling *et al.*, 1997). The low inventory may be due to gully erosion diluting the reservoir sediments with old material of zero ^{137}Cs concentration (Walling and He, 1992). There is a small peak at *c*. 207 cm, which may be due to the input of contaminated material from Chernobyl in 1986. However, the low sampling resolution, and high catchment erosion at this time (see below) may be obscuring any real Chernobyl peak.

Figure 6 shows the age–depth plot for MAR13, based on a combination of ^{210}Pb and ^{137}Cs age estimates and the date of 1838 for reservoir impoundment (Binnie, 1987). The ^{137}Cs (1963) and the 1838 (reservoir impoundment) dates appear to corroborate the ages derived from ^{210}Pb dating. The data demonstrate a sharp rise in sedimentation rate during the 1960s, with increased deposition sustained up to the time of the survey in August 1999. The single sub-sample from MAR16 has been ^{14}C dated at 2860 ± 50 yr BP (Beta Analytic reference number 156829). The date was calibrated using the database of Stuiver *et al.* (1998), which provided an age estimate of 2960 cal yr BP, with a 68 per cent probability of occurring between 3050 and 2890 cal yr BP. This date is clearly 'older' than the known age of the reservoir, and the age estimates derived from the ^{210}Pb and ^{137}Cs chronology, and is indicative of the transport of old allochthonous peats within the catchment rather than autochthonous organic matter.

Table V. ^{210}Pb age calculations for core MAR13

Depth (cm)	Unsupported ^{210}Pb activity (Bq g^{-1})	Layer thickness (cm)	Mean dry bulk density (g cm^{-3})	^{210}Pb Inventory below depth (Bq g^{-1})	Age (yrs before 1999)	Error (± yr)
12·0	0·031	12·0	0·49	1·977	0	0
24·0	0·027	83·2	0·26	1·794	3	0
107·2	0·009	132·9	0·18	1·220	15	2
237·1	0·029	126·9	0·27	1·004	22	2
366·2	0·019	3·5	0·30	0·020	147	10
Total inventory				1·977		

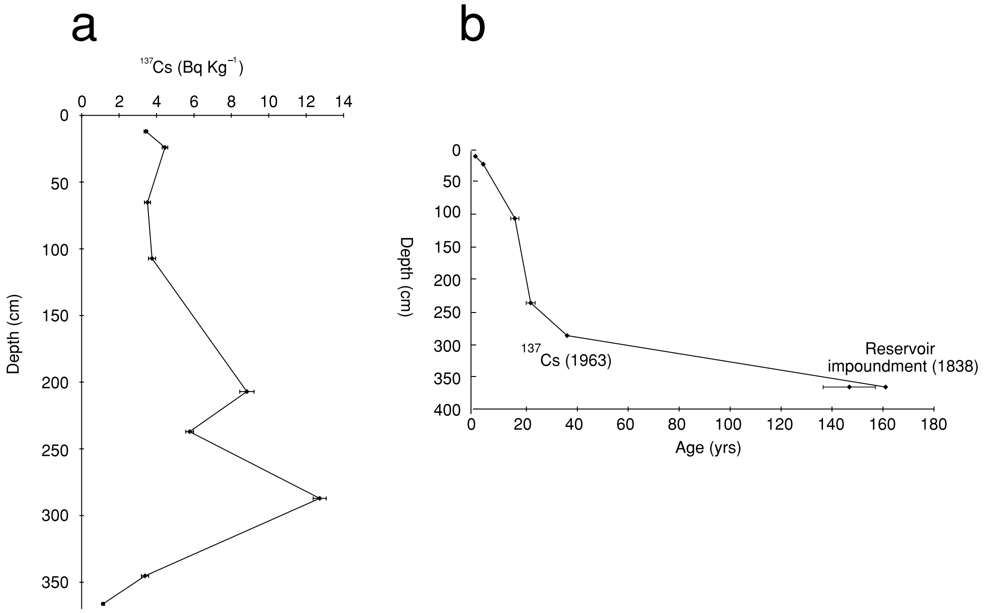

Figure 6. (a) Distribution of ^{137}Cs. (b) Age–depth plot. Horizontal bars indicate error in ^{210}Pb age estimates; this is the uncertainty in estimating the area of the net peak in gamma emissions for ^{210}Pb (at an energy of 45 keV).

Catchment sediment yields and sedimentation patterns within March Haigh Reservoir

The volume of sediment between mineral magnetic horizons was calculated using the Intsurveyor software package. Digital terrain models (DTM) at each magnetic susceptibility horizon were produced by combining the field survey points with sediment depths estimated using core correlation (Figure 5). These points were then linked together to form a mesh of linked, non-overlapping plane triangular facets. The capacity of the reservoir was calculated by estimating the volume beneath the top water level (TWL) of the reservoir, i.e. the altitude of the spillway. The capacity of the reservoir was calculated by projecting the triangular facets up to the plane surface of the TWL. The average depth of the three triangle apices below the surface was then used with the estimate of the plan area of the reservoir to calculate the volume of the triangular prism. The volume of all the prisms was then summed to produce an overall estimate of the reservoir volume. It should be noted that the DTMs produced for March Haigh Reservoir do not take into account the variation in sediment horizons in the area closest to the dam, which were not sampled because of the safety-related problems encountered in surveying this area.

The volume of each sediment layer was calculated by subtracting the reservoir capacity of the top horizon of the layer from that of the bottom (Table VI). The total mass of each layer was calculated by multiplying sediment volume by the average bulk density estimate, based on measurements of sub-samples from core MAR13. Table VI shows that the bottom two sediment layers have reasonably uniform bulk density profiles, but that the upper layers show

Table VI. Sediment yield calculations

Layer	Time period	Reservoir capacity at bottom horizon ($m^3 \times 10^3$)	Reservoir capacity at top horizon ($m^3 \times 10^3$)	Volume of layer (m^3)	Average bulk density ($g\ cm^{-3}$)	Mass of sediment (t)	Average LOI of sediment (%)	Mass of organic fraction (t)	Total sediment yield ($t\ km^{-2}\ a^{-1}$)	Organic sediment yield ($t\ km^{-2}\ a^{-1}$)	Volumetric Total sediment yield ($m^3\ km^{-2}\ a^{-1}$)
A–Top of sediment	1984–2000	186	185	1321	0·30 ± 0·28	398	18·60 ± 16·44	74	9·64	1·79	31·71
B–A	1976–1984	189	186	2849	0·18 ± 0·15	515	29·13 ± 12·39	150	27·71	8·07	152·24
C–B	1871–1976	191	189	1777	0·27 ± 0·10	483	23·89 ± 7·89	115	1·76	0·42	6·41
Base of sediment–C	1838–1871	193	191	2252	0·28 ± 0·04	637	24·64 ± 3·48	157	7·40	1·82	25·97

large downcore variations in bulk density. The mass of the organic fraction of each sediment layer was estimated by multiplying the average loss-on-ignition (LOI) estimate by the calculated mass of sediment.

The age of each magnetic susceptibility horizon has been derived from the age–depth model of Figure 6. Horizon A has been directly dated by ^{210}Pb, and has a date of 1984 ± 2. Horizon B has been estimated by linear interpolation between dates derived directly from ^{210}Pb (1978 ± 2) and ^{137}Cs measurements (1963). Caution must be advised with respect to Horizon C, which has been assigned a rough date of 1871 by linear interpolation. This date is based on an assumption of constant sedimentation between the inception of the reservoir in 1838 and the ^{137}Cs peak of 1963, a period of 125 years. It is probable that sedimentation rates will have varied during this period, and the date of 1871 may be inaccurate.

Estimates of catchment sediment yield are given in Table VI. Gravimetric estimates for total sediment yield and the organic sediment yield of each layer have been expressed in units of tonnes per square kilometre per year ($\mathrm{t\,km^{-2}\,a^{-1}}$), whilst volumetric estimates for total sediment yield have units of cubic metres per square kilometre per year ($\mathrm{m^3\,km^{-2}\,a^{-1}}$). The trap efficiency (TE) of the reservoir was predicted using the equation of Brown (1944). Butcher *et al.* (1992) suggest that Brown's equation, based on the ratio of reservoir capacity to watershed area, may be appropriate for Pennine reservoirs such as March Haigh. TE is close to 99 per cent in all cases, and there is negligible change during the life of the reservoir. The variation in sediment yield with time is plotted in Figure 7, and is expressed both gravimetrically (total and organic component) and volumetrically (total sediment). Total sediment yield varied between 2 and 28 $\mathrm{t\,km^{-2}\,a^{-1}}$. The 33 years after reservoir construction (1838–1871) have a total sediment yield of 8 $\mathrm{t\,km^{-2}\,a^{-1}}$. Sediment yield then falls to a minimum (total sediment yield = 2 $\mathrm{t\,km^{-2}\,a^{-1}}$) for the majority of the life of the reservoir during the years 1871–1976. The years 1976–1984 witness a significant rise in the sediment yield of the basin (total sediment yield = 28 $\mathrm{t\,km^{-2}\,a^{-1}}$), which then declines during the period 1984–1999 (total sediment yield = 10 $\mathrm{t\,km^{-2}\,a^{-1}}$). Sediment accumulation rates for MAR13 are shown in Figure 7. Sediment accumulation rates show a similar temporal pattern to catchment sediment yield. However, the relatively high sediment yield estimated for the period 1838–1871 is not reflected by the sedimentation rate at MAR13. Sediment accumulation rates at MAR13 start to increase noticeably *c*. 1963 (based on ^{137}Cs date), which compares with 1976 for the sediment yield estimates (based on ^{210}Pb dates).

Dry sedimentation rates for correlated cores have been calculated by multiplying the change in depth of sediment by the average dry bulk density of the zone (based on measurements made on MAR13), and then dividing this product by the time period in years (expressed in $\mathrm{g\,cm^{-2}\,a^{-1}}$). These have been contour-mapped using the Intsurveyor package (Figure 8). During the early life of the reservoir (1838–1871), sedimentation was concentrated around a small depression in the centre of the reservoir, with slower, more uniform deposition near the dam. The area by the dam then filled relatively uniformly with material at a slow rate (1871–1976). During the increased inwash of 1976–1984, sedimentation was focused around two points: in the centre of the reservoir and near the dam. In the more recently deposited sediments (1984–1999), sedimentation is less uniform and more fragmented around the infilling area of the reservoir.

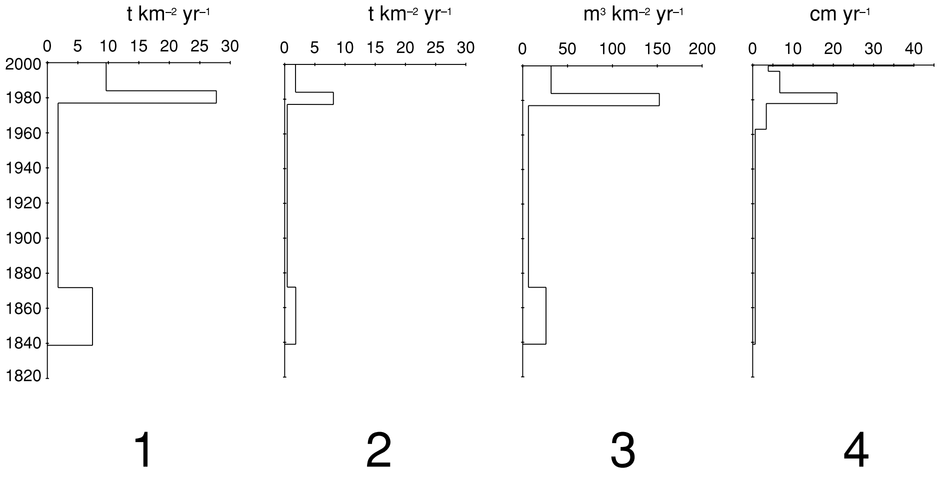

Figure 7. Variation in sediment input to March Haigh Reservoir catchment over time: (1) total sediment yield expressed gravimetrically; (2) organic sediment yield expressed gravimetrically; (3) total sediment yield expressed volumetrically; (4) sediment accumulation rate (MAR 13).

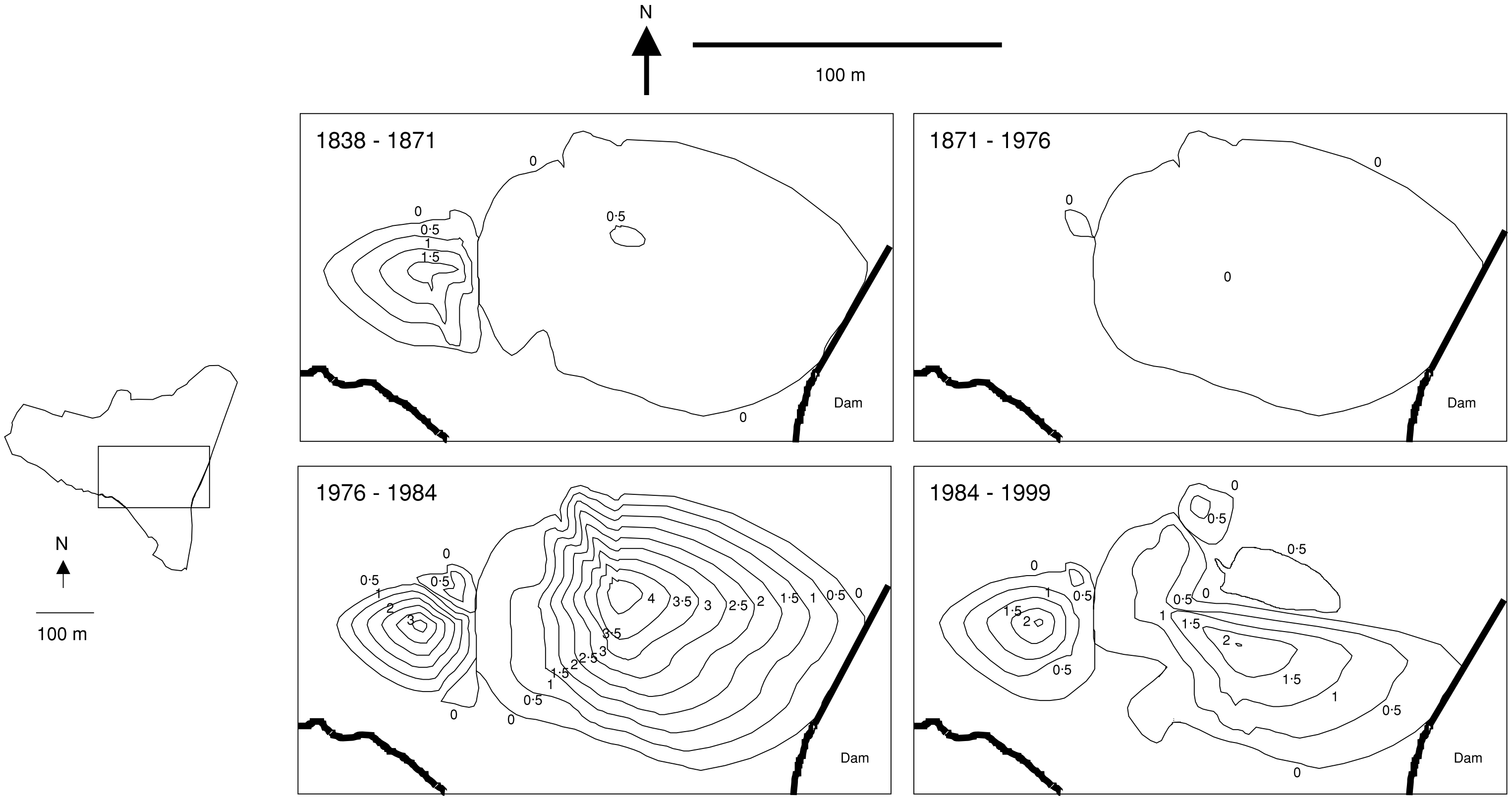

Figure 8. Dry sedimentation rate patterns for March Haigh Reservoir. Contour interval is 0·5 g cm^{-2} a^{-1}.

Discussion

Blanket peat erosion and sediment flux in the March Haigh catchment

Radiocarbon dating has produced a date of 2960 cal yr BP for a sample from core MAR16. This is clearly 'older' than estimates from the ^{210}Pb-^{137}Cs based chronology which suggests a date between AD 1976 and 1984. The ^{14}C technique dates the formation of the organic fraction of the sediment; the 'older' date may therefore be due to the significant contribution of older allochthonous carbon to the sediments. This suggests that the organic component of the March Haigh sediments is composed mostly of eroded blanket peat.

The relatively high sediment yields estimated for the early period of the reservoir (1838–1871) may be the result of erosion of vulnerable sediments after the construction of the dam. Wave erosion of soils on the new reservoir's shoreline may have also contributed some sediment. Additionally, a small depression in the centre of the reservoir had focused deposition, and the high accumulation rates of sediment at borehole MAR6, which is situated in the depression, may have exaggerated the overall estimate of sediment yield. Estimates of organic sediment yield after this time represent catchment erosion rates, which for 1871 to 1963 were relatively low. Sediment accumulation rates in core MAR13 increased around 1963, and the period 1963 to 1999 represents a time of increased peat denudation. Estimates of organic sediment yield show that erosion rates increased by an order of magnitude during the period 1976 to 1984. These results concur with the analysis of aerial photography taken over the period 1948 to 1988 by Anderson *et al.* (1989). The examination of aerial photographs suggested that there was significant peat erosion, in terms of extensive areas of bare peat and the increase in length and complexity of the gully system on Buckstones Moss (currently the most denuded area of the catchment), between 1948 and 1964. These erosion features had increased in severity by 1988, with the western part of the Moss most affected. The proportion of Buckstones Moss covered by bare peat patches had increased from 22·5 to 42·5 per cent during the 24-year interval. Compared with other studies from the south Pennines, which date the initiation of gully erosion to between 1450 and 1850 (Tallis, 1965, 1973, 1995; Labadz *et al.*, 1991), the estimate of *c.* 1963 for the March Haigh catchment is relatively recent, and deserves further attention. Research is currently underway with the aim of assessing the factors influencing the initiation of erosion in the March Haigh catchment, during the period 1963–1999.

Catchment sediment yield (gravimetric inorganic + organic fractions) varies between 2 and 28 t km^{-2} a^{-1}. This is a significantly lower estimate than from previous studies, where sediment yields from peat-dominated catchments range from 25 t km^{-2} a^{-1} for North Esk Reservoir in Scotland (Ledger *et al.*, 1974), to 373 t km^{-2} a^{-1} for Abbeystead Reservoir in Lancashire (Rowan *et al.*, 1995) (Table I). March Haigh, in comparison, has a significantly lower estimate.

There are features of the methodology used in this study which were designed to increase accuracy in the sediment yield estimates. The current sediment surface of March Haigh was surveyed when the reservoir was drained, and there is evidence to suggest that surveys of drained reservoirs are accurate (Butcher *et al.*, 1993). Studies utilizing suites of correlated cores have been shown to provide a far more reliable assessment of sediment volume than studies based on single cores. Dearing and Foster (1993) compared the estimation of sediment yield for the Llyn Geirionydd catchment in Wales based on a suite of cores, with the accumulation rate calculated from a single core. The single core estimate was in error by over 200 per cent when compared with the mean result based on a number of cores. Evans and Church (2000) used data from multiple cores to calculate sediment yields for the catchments of four alpine lakes in British Columbia. The error of sediment yield estimates was calculated using a regression technique, and ranged between 7 and 21 per cent; this error was sufficiently low to allow detection of temporal variability in sediment yield.

The difference between the estimates of sediment yield for the March Haigh catchment and those from other studies of blanket peat-covered catchments may be explained by one or more of the reasons discussed below.

First, the rate of peat erosion in the March Haigh catchment may be relatively low compared to other blanket peat areas. Drainage density is estimated at 9·92 km km^{-2}, and is less than, for instance, the Shiny Brook catchment (SE 062 072) which lies to the south. Shiny Brook comprises dissected blanket peat moorland and has an estimated drainage density of 20·18 km km^{-2}, of which the main stream network accounts for 11·15 km km^{-2} (Burt and Gardiner, 1982). This suggests that gully systems in the March Haigh catchment are relatively undeveloped compared with Shiny Brook. Labadz (1988) observed that most erosion in the Shiny Brook catchment takes place within the gullies. Assuming that the gully systems of the March Haigh catchment are the major suppliers of eroded peat, this suggest that sediment yields would be low compared with Shiny Brook. Shiny Brook contributes a proportion of the sediment deposited in the Wessenden valley chain of reservoirs, which gave an estimated sediment yield of 204 t km^{-2} a^{-1} for the period 1836 to 1986 (Labadz *et al.*, 1991), far greater than the maximum of 28 t km^{-2} a^{-1} estimated for the March Haigh catchment.

However, the Shiny Brook catchment (maximum 520 m OD) and many other eroded sites in the south Pennines are of higher altitude than the March Haigh catchment (maximum 482 m OD). Erosion in the south Pennines has been documented as most significant above an altitude of *c.* 500 m (Anderson and Tallis, 1981), due to the increased effects of climatic factors such as frost and drought on the peat surface. The gullies on the upper slopes of Shiny Brook accord with the Type II classification of Bower (1960), and have peat of 1·5–4 m depth (Labadz *et al*., 1991). Further surveys may be required to determine whether the depth of peat and type of gully erosion occurring on the March Haigh catchment have also been factors limiting the severity of blanket peat erosion.

Second, British Waterways (D. Dutton, 1999, pers. comm.) have suggested that silt traps positioned at the inflows to the reservoir may have been maintained prior to the last quarter of the 20th century. Sedimentation estimates between 1871 and 1963 are very low, and it is possible that a significant proportion of the deposited sediment may have been removed during regular maintenance of the silt traps. Unfortunately, reliable maintenance records are not available for March Haigh Reservoir, and there is no clear indication of management practices such as sediment removal.

Third, during the reservoir survey it was observed that the river channel was scouring the sediment bed, and had laid down coarse gravels. Blatt *et al*. (1972) suggest that the removal of non-cohesive sediments by scour frequently leads to the accumulation of layers of coarse fractions. The sediment profile of March Haigh is interspersed with bands of sand and gravel grade clasts. Although turbidity flows resulting from storm events may be responsible for most of the inorganic deposition, some of these layers may be the result of a scour channel. Scouring by the impounded river channel may have been active throughout the life of the reservoir, and responsible for erosion of an unknown quantity of sediment.

Fourth, not all sediment may be deposited before leaving the drainage basin, so an estimate of sediment yield may underestimate the real extent of catchment erosion. The natural situation of the reservoir may also have an influence on sediment delivery. In addition to the unknown quantity of sediments stored on the catchment slopes, factors such as shape and volume of the water body, hydrodynamic flow pattern and delta development can all have an effect on sediment delivery (Håkanson and Jansson, 1983, pp. 148–176).

Fifth, the sediment yield estimates derived in previous surveys of reservoirs in peat-covered catchments may be inaccurate. A number of these studies use a comparison with previous surveys to calculate changes in sediment volume. Butcher *et al*. (1992, 1993) note two types of common error involved with this method. Although estimates of changes in sediment volume between surveys may be accurate, the absolute datum levels used for each survey of the reservoir may be inconsistent, and Butcher *et al*. (1992) noted this source of error when comparing four surveys of Strines Reservoir, South Yorkshire. Butcher *et al*. (1993) also suggest that past records of water companies may refer to the usable capacity of the reservoir (more relevant to the concerns of the water company), which may be different from the true capacity of the reservoir as measured in surveys.

Spatial patterns of sediment deposition within March Haigh Reservoir

During the early stages of infilling (1838–1871), deposition was variable. A small depression lies to the west of the sedimenting area and this appears to be responsible for a proportion of the spatial variation. The sediments deposited around this point are composed mainly of coarse gravels and sands. Sediment deposition was concentrated in the deepest part of the basin, during the middle life of the reservoir (1871–1976). By the later stage of infilling (1976–1999), sediment accumulation had become more fragmented, and deposition had shifted to the south of the sedimenting area by the period 1984–1999. These deposits contain a proportion of coarse clasts. These coarse deposits may be accounted for by the presence of the steep rock slope to the south of these sediments. During the life of the reservoir, material may have been eroded from the slope and deposited on to the soft sediments below, or passed down the slope from the shoreface above.

There are several sources of sediment influx to the reservoir, and suspended material may enter the basin at different locations: two cloughs (streams) input material at the west end of the reservoir, and a small catchment channel enters the reservoir near the south end of the dam (Figure 1). Weathering and erosion of the steep rock shelf on the south edge of the reservoir may have produced an input of mineral material as noted earlier. An unknown proportion of the sediment influx to the reservoir may be from overland flow over the surface of the moorland.

The main controls on sediment distribution in March Haigh appear to be bathymetry and the variation in sediment inputs. Sedimentation in March Haigh does not conform to the classic morphometric model, which suggests that sediment types are distributed according to water depth (Håkanson, 1981) and basin slope (Blais and Kalff, 1995). This concurs with the study of Abraham *et al*. (1999) who argued that the morphometric model is based on studies of natural lakes, and reservoirs are different from natural lakes: reservoirs are impounded rivers, and will have an extra riverine hydrodynamic component that many natural lakes do not possess. Abraham *et al*. (1999) examined Texan reservoirs and showed that reservoirs with multiple inputs had a heterogeneous sediment type distribution, suggesting that morphometry was not the dominant influence on sediment distribution.

The heterogeneous spatial distribution of sediments in March Haigh suggests that estimates of catchment sediment yields based on a single dated core would probably be subject to large errors. Emphasis in future reservoir-based studies of catchment erosion and sediment flux should be on the sampling of multiple cores, to account for the significant spatial variations in sedimentation within the reservoir itself.

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