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Assessment of catchment erosion in the southern Pennines, United Kingdom, using reservoir sedimentation monitoring

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ABSTRACT Over 100 reservoirs and artificial lakes have been surveyed in the Southern Pennines of the United Kingdom using standard techniques. The loss of capacity since construction is calculated and sediment yields are estimated. Sediment yields between 3.4 and 398 $t.km^{-2}yr.^{-1}$ are recorded, with the highest yields in areas of blanket peat moorland. A review of the accuracy of the techniques used is undertaken.

INTRODUCTION

The use of reservoir surveys for measuring catchment sediment yields has been described as an "excellent method" by Rausch and Heinemann (1984). The results of reservoir surveys provide estimates of erosion rates complementary to those of erosion plots and stream sediment loads, yet they offer a longer timescale and the integration of yield from a wider catchment area. Furthermore Stott et al (1988) have argued that because measurements of sediment deposits do not involve generalised statistical models of sediment erosion and transport or spatial extrapolations of point and plot measurements they are inherently more useful and representative. The relative simplicity of data collection in reservoir surveys is a further attraction: in contrast to stream sampling or plot and pin measurements only a short field survey is necessary. Few authors, however, have considered the difficulties inherent in any estimation of sediment yield from reservoir surveys: Stott et al considered the difficulties involved in the definition of the reservoir-catchment system and of sediment losses from the reservoir, and other authors have described the errors involved in the estimation of trap efficiency. There has been little work on the problems of the calculation of sediment density or of sediment sampling procedures (Dearing and Foster, 1992). Furthermore recent work by Butcher et al (1992a) and Duck and McManus (1992) has emphasized the problems of assessment where reservoir management has resulted in the diversion of sediment which would otherwise have been captured by the reservoir.

THE RESERVOIR CATCHMENT SYSTEM

For a reservoir survey of the type described by Rausch and Heinemann (1984) to give an accurate representation of catchment sediment yield, one of two preconditions must be met: either the reservoir should act as the final store for all sediment detached on the catchment, or some quantitative measure of the movements of sediment through the reservoir must be obtained. Results from a number of workers have suggested that sediment movement through the reservoir is a significant factor, but extremely difficult to quantify. It is also apparent that a detailed examination of a large number of catchments will reveal a complexity of sediment storage and transfer systems (Butcher et al, 1992b). This is illustrated in Figure 1. Only in a minority of cases is it possible to recognise a defined catchment area that is contributing sediment directly to one single reservoir.

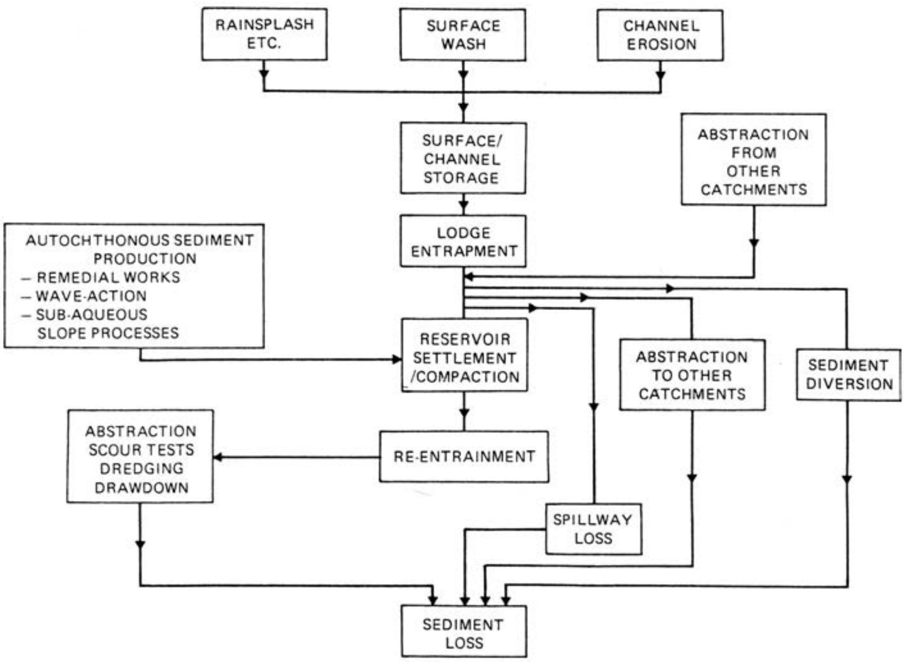

FIG. 1 Sediment movement through the reservoir/catchment system.

The principal criticism of the reservoir sedimentation technique made by Stott et al (1988) was that catchment boundaries are extremely difficult to define in reservoired catchments and that water company records of catchment areas are highly erroneous. Furthermore an underlying principle in the construction of many reservoirs has been the desire to prevent sediment entering the reservoir, particularly at high flows.

Figure 2 shows the proportions of 69 reservoirs in the southern Pennines of the United Kingdom that have structures liable to influence the deposition of sediment into that reservoir.

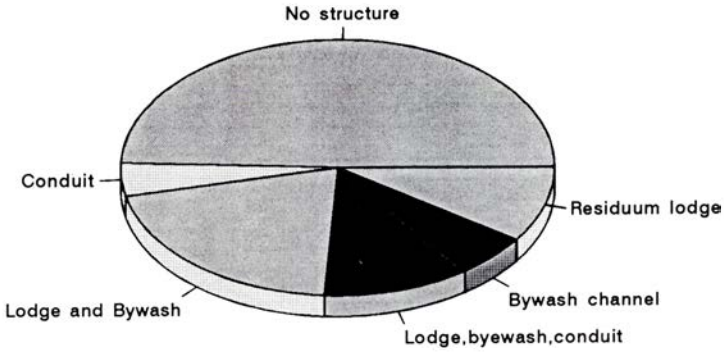

FIG. 2 Types of reservoir control structure.

i) Residuum lodges are sediment traps constructed immediately upstream of reservoirs. They are often quite large in size (up to 3% of reservoir capacity) and in the UK were often emptied on a regular basis. There are very few records however, one exception being the lodges on the Longdendale reservoirs near to Manchester. Records here of sediment removed from 5 lodges on 7 reservoirs over the period 1941-72 total 164,000m^3. Over the period 1884 - 1962 the total capacity of the 7 reservoirs was reduced by 1,400 Mgl. Tallis (1980) estimates that some 23% of the incoming sediment was trapped by the lodges.

ii) Bywash channels are constructed, usually around the perimeter of the reservoir, to divert high flows. This is usually achieved through weir systems although in some cases flows may be diverted manually or through automatic gates. These channels are often extremely effective in diverting sediment-laden flows away from the reservoir. Duck and McManus (1990) describe the effects of a breach in one such bywash channel of Lambieletham Reservoir in southern Scotland. During the 21st-23rd September 1985 a significant storm event breached a culvert and deposited 104t of sediment into an empty reservoir basin. This volume is equivalent to 27% of the deposits accumulated during the previous 84 years.

iii) Conduit systems are usually designed to enlarge the effective catchment area of the reservoir by the diversion of flow into the reservoir. They frequently occur as stone structures closely following a contour line. In the southern Pennines of the UK they are commonly constructed so that high flows pass over the conduit. This is achieved by such structures as "leaping weirs". This type of structure represents a significant problem because their effect is to create a variable catchment area for the reservoir: at low flows the catchment area is significantly higher than at high flows. It is almost impossible, without detailed flow and sub-catchment area measurements to calculate the percentage of sediment that is diverted out of the

THE STUDY AREA

The study area, in the southern Pennine region of the UK, is an upland arc 20-30 km wide and 100 km long extending from Sheffield in the south to Ripon in the north. Geologically the region is dominated by Upper Carboniferous sandstones and shales which are sometimes mantled by glacial drift or post-glacial peat deposits. The strata are largely tilted into a gentle easterly dipping sequence of rocks, which produce upland plateaux in the west dropping gradually to lower, more urbanised and industrialised, areas in the east. The drainage systems, which also generally flow from east to west across this area, have been deeply incised leading to relatively narrow, steep-sided valleys suitable for damming.

Soils are typically acid and the high rainfall and low evapotranspiration rates, particularly in the upland areas, often lead to waterlogging which has helped to promote the development of peat on the flatter slow-draining slopes.

Over 120 reservoirs can be identified in the study area, draining at least 770 km^2, and with a total original capacity of 188000 Mgl. Individual capacities range from as little as 31 Mgl to over 10000 Mgl, although the numbers involved in the latter size range are much smaller. The majority of reservoirs have earth dams across a river valley, but some of the larger constructions are either masonry or concrete gravity dams. Unusual valley morphology has forced some reservoirs to be constructed using earth dams with inflexions of up to 90 degrees. Integration of local water companies into a unitary governing body, combined with numerous piecemeal responses to supply problems promoted the development of multiple reservoir systems managed by conduits, bywash channels, residuum lodges and inter-basin transfers, as described in section 2. Catchment sizes range from less than 0.5 km^2 to over 100 km^2.

Recent concerns over erosion problems on the moorland gathering grounds and the consequent impact on reservoir capacity through sedimentation have prompted a comprehensive survey of the region's direct supply reservoirs. This has allowed the examination of capacity loss rates and sediment yields on a regional basis for the first time.

RESULTS

To date over 100 reservoirs have been surveyed by Huddersfield Polytechnic. Of these, revised capacity data is discussed here for 69 impoundments. For these reservoirs, the total original capacity amounts to 87412 Mgl supplied by 385.0 km^2. The current capacity of these reservoirs amounts to 80563.7 Mgl, a total loss of supply of 6846 Mgl, or 7.8%. To place this in perspective, one of the most recent reservoir constructions, Scammonden, built at an estimated cost of 8 million pounds sterling, had an original capacity of 7873 Mgl.

There are numerous problems with the data. There is a need to rely on the accuracy of the original capacity figures given by Yorkshire Water Services plc, which in turn should rely on good original surveys. Also, operational requirements occasionally result in such figures being given for capacity minus dead storage. This can result reservoir system.

As may be seen from Figure 2 it is common for reservoirs to have one or more of these structures. Butcher <u>et al</u> (1992b) have suggested a protocol for the selection of reservoirs for sedimentation surveys, in which reservoirs with these types of structure are omitted at an early stage. Figure 3 shows the percentage loss of capacity for the 69 reservoirs. It is clear that those reservoirs with no structure have significantly higher capacity loss than those with one or more structures. These reservoirs form part of a regional data base of sedimentation rates constructed by workers at Huddersfield Polytechnic since 1984. The vast majority of the surveys were undertaken as part of a research contract with Yorkshire Water Services plc, in an effort to quantify the current capacity of surface water supply in the region. A few of the reservoirs take the form of single impoundments within a discrete catchment but, as has been shown, a more complex system of physical water management is the rule rather than the exception.

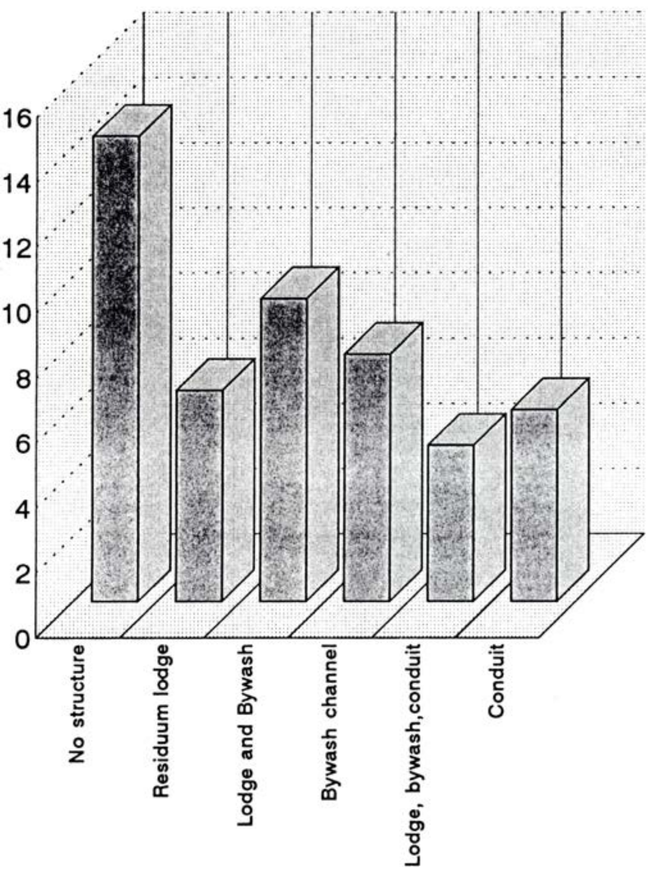

FIG. 3 Reservoir loss of capacity (% per century).

in an apparent increase in capacity if the rate of infilling to a particular basin is slow. These problems can only be overcome by careful archive searches and good relationships with the company operating the impoundment.

Area-specific annual capacity loss rates average 203.5 m^3 km^{-2} yr^{-1} Using data from sediment cores and adjusting for trap efficiency losses and scour valve tests, this represents a mean sediment yield of 112.3 $t.km^{-2}.yr^{-1}$,of which 20.4 t. $km^{-2}.yr^{-1}$ is organic matter. These figures are low compared to other parts of the world, eg. Thompson (1984) gives a figure of 1710 t. $km^{-2}.yr^{-1}$ for Beni Armane reservoir (Algeria). However, they are relatively high in comparison with other parts of the UK. Francis (1990), for example, finds a sediment yield of 62.3-66.2 $t.km^{-2}.yr^{-1}$ for the Plynlymon catchment in Wales, Lovell et al (1973) a capacity loss rate of only 12 $m^3.km^{-2}.yr^{-1}$ for a Scottish reservoir, and Ledger et al (1980) a sediment yield of 41 $t.km^{-2}.yr^{-1}$. The relatively high yields are all the more significant due to the difficulties of planning and constructing new reservoirs.

However, in common with many other reservoir sedimentation surveys, regional means disguise an enormous variation in individual results. Percentage losses, for example, range from 0.22% to 92.04%, and sediment yields range from as low as 3.4 $t.km^{-2}.yr^{-1}$ to a maximum of 397.8 $t.km^{-2}.yr^{-1}$. Absolute capacity losses increase with reservoir and catchment size, as do annual capacity loss rates. Annual area-specific capacity loss and sedimentation rates show much poorer relationships and fail to match results found in the literature. The exception to this is a link between area-specific annual capacity loss and stream frequency, with more dissected catchments having higher capacity loss.

As was mentioned in section 2, the majority of reservoir catchments differ from natural lake catchments in the intensity of their management for water supply. The influence of management practice on capacity loss is evidenced by the fact that reservoirs with no inflow control structures have much higher capacity loss rates than those with residuum lodges and bye-wash channels. A possible explanation for the lack of any consistent relationships regarding catchment data and sediment yields may stem from the fact that, while capacity loss rates are representations of an actual process, the extrapolation from these to catchment sediment yield ignores any material trapped upstream or passed around the reservoir. If the mean capacity loss rates for reservoirs with no inflow control structure are representative, and are applied to those reservoirs which do have such features, then it is suggested that sediment control structures may have kept a further 1.3 million tonnes of sediment from entering Yorkshire Water's reservoirs.

Results for the major river systems

As has been said, consideration of the entire data base produced few significant relationships between catchment characteristics and sediment yields. However, reducing the general database to its six main river system components, as defined by Yorkshire Water, (Table 1)

TABLE 1 Reservoir sedimentation in the major river systems.

i) Average values

	A	B	C	D	E	F	G	H	I	J	K
Nidd	4	86	12.21	3768	3578	190.06	3.4	3381	130.7	68.8	12.26
Wharfe	5	111	12.44	2466	2372	94.27	4.43	848	100.4	70.7	13.63
Aire	16	103	3.69	553	495	57.19	12.05	552	186.4	87.1	12.11
Calder	15	94	4.21	1181	1124	57.41	5.05	976	182.1	88.2	22.54
Colne	13	124	4.04	697	596	100.25	27.06	875	248.4	139.6	29.46
Don	16	112	6.24	1525	1366	158.44	9.7	1671	254.6	156.8	21.11
All	69	106	5.59	1267	1168	99.22	11.76	1150	203.5	112.3	20.04

ii) Percentage of total

	A	B	C	D	E	F	G	H	D/C	F/C	H/C
Nidd	5.8	*	12.67	17.24	17.77	11.10	*	17.04	1.36	0.87	1.34
Wharfe	7.2	*	16.13	14.11	14.72	6.88	*	5.34	0.87	0.43	0.33
Aire	23.2	*	15.31	10.11	9.84	13.37	*	11.13	0.66	0.87	0.73
Calder	21.7	*	16.38	20.27	20.92	12.58	*	18.44	1.24	0.77	1.13
Colne	18.8	*	13.62	10.36	9.62	19.04	*	14.34	0.76	1.40	1.05
Don	23.2	*	25.89	27.91	27.13	37.03	*	33.70	1.08	1.43	1.30

iii) Total values

	B	C	D	E	F	G	H
Nidd	345	48.84	15072.9	14312.7	760.24	5.04	13524.1
Wharfe	554	62.21	12329.9	11858.6	471.34	3.8	4240.3
Aire	1641	58.99	8840.5	7925.2	915.09	10.35	8831.8
Calder	1403	63.17	17715.6	16854.4	861.16	4.86	14633.0
Colne	1610	52.55	9057.0	7753.8	1303.20	14.39	11380.0
Don	1794	99.86	24396.2	21859.0	2534.99	10.39	26741.1
Total	7347	385.62	87412.1	80563.7	6846.04	7.83	79350.3

Column Headings:

A = Number of reservoirs
B = Age of reservoirs (years) at time of resurvey
C = Catchment area (km^2)
D = Original capacity (Mgl)
E = Resurveyed capacity (Mgl)
F = Capacity loss (Mgl) between surveys
G = Loss of capacity (%) between surveys
H = Annual loss of capacity (m^3)
I = Annual area-specific capacity loss ($m^3.km^{-2}.yr^{-1}$)
J = Annual area-specific sediment yield ($t.km^{-2}.yr^{-1}$)
K = Annual area-specific organic-only yield ($t.km^{-2}.yr^{-1}$)

TABLE 2 Reservoir sedimentation in the Thornton Moor Chain.

	Hewenden	Doe Park	Stubden	Thornton Moor	Mean
i) Original data					
Date Constructed	1843	1862	1868	1885	*
Overfl. altitude (mAOD)	205.7	244.9	313.9	377.9	285.6
Catchment area (Km^2)	11.7	7.74	10.21	5.12	8.69
Capacity (Mgl)	298.0	486.0	451.0	795.0	507.5
Percentage capacity	14.68	23.94	22.22	39.16	*
Basin Order	3	3	3	4	*
Drainage dens ($km.km^{-2}$)	1.25	1.57	2.018	3.214	8.052
Max. altitude (mAOD)	365.8	430	430	441.01	416.7
Relief (m)	167.4	185.1	116.1	63.12	132.93
Relief Ratio	0.036	0.078	0.022	0.013	0.037
C:W ($Mgl.km^{-2}$)	25.47	62.79	44.17	155.27	71.93
C:S ($km^2.km^{-2}$)	197.44	99.5	232.64	27.67	139.31
ii) Current data					
Date applicable	1862	1868	1885	1885	*
Catchment area (km^2)	3.69	5.28	5.09	5.12	4.8
Percentage catchment	19.24	27.53	26.54	26.69	*
Capacity (Mgl)	230.87	408.34	406.00	710.6	438.953
Percentage capacity	13.15	23.26	23.12	40.47	*
Basin Order	2	2	3	4	*
Drainage density	1.467	0.86	1.15	3.214	1.673
Max altitude (mAOD)	365.8	385	416.34	441.01	402.04
Relief (m)	167.4	135.1	102.44	63.12	117.015
Relief Ratio	0.064	0.057	0.019	0.013	0.038
C:W ($Mgl.km^{-2}$)	62.56	77.34	232.47	138.79	127.79
C:S ($km^2.km^{-2}$)	62.27	67.88	44.20	27.67	50.51
iii) Loss data					
Age at survey (yr)	150	129	121	104	126
Cap'y loss (m^3)	67129	77661	45000	84400	68547.5
% of total loss	24.48	28.32	16.42	30.78	*
% loss per reservoir	22.5	15.9	9.9	10.6	14.73
% loss per century	15.02	12.39	8.25	10.21	11.47
Annual loss (m^3)	447.53	602.02	447.53	811.54	577.16
% of total ann loss	19.39	26.08	19.39	35.15	*
Capacity loss ($m^3 km^{-2} yr^{-1}$)	121.3	114.1	191.7	158.5	146.3
Sed Yield ($t.km^{-2}.yr^{-1}$)	17.59	16.54	27.78	38.72	25.16
Adjusted sed. yield ($t.km^{-2}.yr^{-1}$)	13.098	16.41	4.59	39.97	18.517

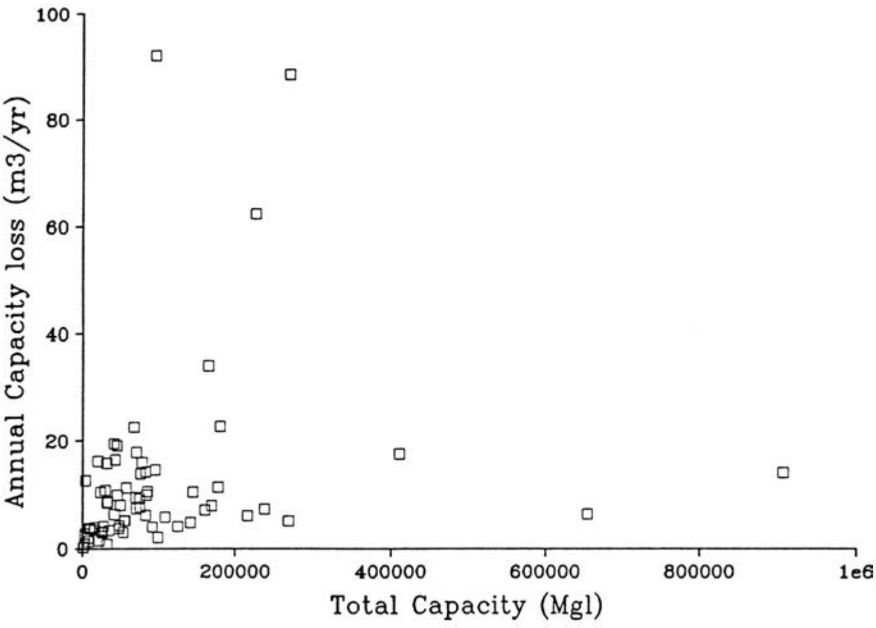

FIG. 4a Reservoir capacity loss.

does allow the identification of some trends. Figure 4a illustrates the relationship between total capacity and annual capacity loss. It may be seen that some of the highest annual losses occur in the smaller reservoirs. Figure 4b shows absolute capacity lost against

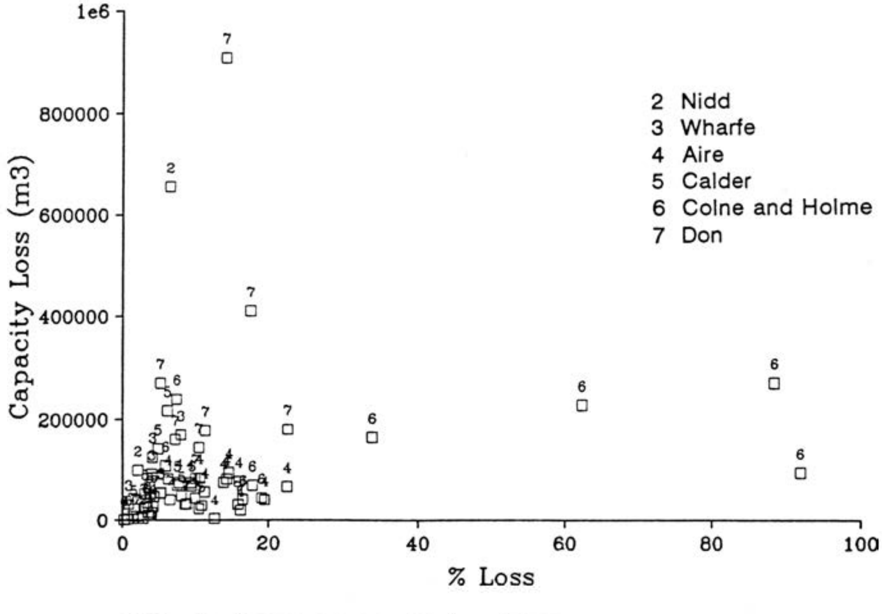

FIG. 4b Reservoir capacity loss.

the percentage of original capacity lost. Again the smaller reservoirs tend to have the greatest relative losses, and these are particularly found on the rivers Colne and Holme. Even so, there remain some inconsistencies in the trends that are only explicable in terms of the catchment histories of individual reservoirs.

River Don reservoirs have the highest capacity loss and sediment yield rates in the study area. 37% of the total capacity loss has taken place in 27% of the total capacity, with the capacity of a small reservoir lost every year across the system. In terms of the reservoirs themselves, however, the actual % loss is relatively small,as there are a large number of reservoirs, some of a considerable size. The individual histories of specific reservoir systems affect results. In one complex, water yield is distributed via catchwaters, diversionary structures and cascades between five reservoirs. The network is further complicated by pumped inflows into the oldest reservoir from the neighbouring valley operated by a different water company and not part of the study area. It has been shown that the complex nature of the reservoir system varies within the region. It is therefore not surprising that sediment yields calculated from sedimentation surveys cannot be linked to catchment characteristics in a straightforward fashion. However, it is also true that the widespread nature of management practices would severely limit opportunities for study if only "simple" systems are considered. The current research is therefore attempting to concentrate on understanding of one reservoir chain.

The rivers Colne & Holme, two major tributaries to the Calder, also have sedimentation problems, with 20% of total capacity loss occurring from 13% of total catchment and in only 10% of the total original capacity. In contrast to all other catchments, the Colne & Holme contain a large number of relatively small reservoirs with a low capacity: watershed ratio. Thus a sediment yield comparable to the Wharfe's would have a significant impact despite the low trap efficiency implied. When this is combined with the largest concentration of peat soil in the study area, the impact on supply is enormous, as a mass of organic matter will occupy a greater volume than an equivalent mass of mineral matter. Organic matter contents of sediments in Colne/Holme reservoirs were found to be much higher than other reservoirs. The other river networks have relatively fewer problems of sedimentation; whilst the absolute capacity losses for the Aire are small, the relative supply loss is high. This is a product of under reservoired catchments on the whole.

A CASE STUDY OF A RESERVOIR CHAIN

Reservoirs regulating a sub-catchment of the river Aire are currently under study by the authors and are used here to illustrate the problems of using average rates of loss over time in complex catchments. Hewenden, Doe Park, Stubden and Thornton Moor were built in ascending order on Harden Beck during the first half of the 19th century , and are shown diagrammatically in Figure 5 . Thornton Moor reservoir is built along a contour, and but for a 5km conduit, regulated by numerous check dams, residuum lodges and sluice gates, would have a natural catchment of only a few hundred metres square. Flow can be diverted over any of its conduit residuum lodge structures

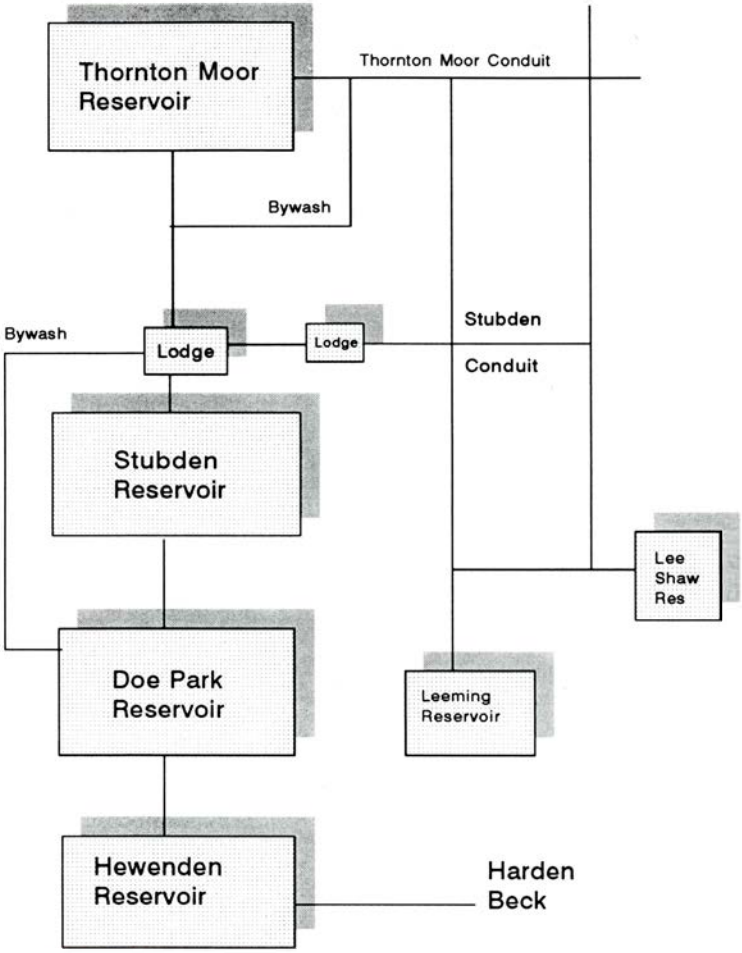

FIG. 5 The Harden Beck reservoir chain.

and at the reservoir itself. In the case of the lodges, water passes downslope to a second catchwater supplying Stubden reservoir. All or any portion of water reaching this second conduit may, in turn, be diverted into a third catchwater supplying Leeshaw reservoir in an adjacent valley. This third conduit also intercepts flow which would otherwise reach Leeming reservoir. Water diverted past Thornton Moor is passed to Stubden via a tunnel.

In addition to the smaller lodges along its length, Stubden catchwater passes through two major residuum lodges: one upstream of the reservoir, and another at the reservoir itself shared by Thornton Moor overflow. This second lodge is also part of a diversionary structure which can pass flow around Stubden reservoir to one arm of Doe Park. A final catchwater intercepts flow which would otherwise pass into the second of Doe Park's arms. Overflow from Doe Park continues downstream to Hewenden.

Construction data and survey results are given in Table 2.

Absolute sediment yields are straightforward conversions of annual area specific capacity loss using mean dry bulk density values. Adjusted sediment yields are calculated by separating out the contributions from different catchment components, using ergodic substitution and adjusting for trap efficiency losses. The data revealed that, if current sediment yields are correct, Hewenden had acquired 29% of its sediment total in the years before the upstream impoundment of Doe Park (14% of lifespan). Doe Park acquired 7.2% of its sediment total in 6.6% of its lifespan, and Stubden 59% of sediment total in 14% of lifespan.

The hypothetical nature of the data, combined with the intensive management of this reservoir network, means that the true picture may be far removed from that presented above. The data give an indication of the impact of upstream impoundment on sedimentation, with much of the sediment seemingly acquired in the early stages in the lifespan of reservoirs lower down in a cascade. These results have implications for reservoir managers when assessing the need for new sediment control measures, and illustrate again the inadequacy of attempting to assess simple catchment-average sediment yields in realistic situations.

CONCLUSIONS

1. The relative simplicity of collection of data on reservoir sedimentation has promoted the widespread use of this method for estimating catchment-wide sediment yields. There are, however, many factors influencing the movement of sediment through a reservoir/catchment system, and these must not be neglected in the search for easy answers.
2. Investigations on 69 reservoirs in the southern Pennine region of the UK have shown a link between the existence of sediment trapping or diversionary structures and the percentage loss of capacity per century. Rates of infilling are not a product of catchment characteristics alone.
3. Capacity loss rates and the sediment yields derived from them in Southern Pennine reservoirs are highly variable. When losses over the spillway are accounted for, catchment-wide sediment yields range from 3.4 to 397.8 $t.km^{-2}.yr^{-1}$. Values are at a maximum in reservoirs supplied by large catchments in relation to reservoir size (high capacity:watershed ratio), in heavily dissected catchments, and those dominated by blanket peat soils.
4. Rates of loss and yield are highly influenced by the catchment and reservoir management histories of individual reservoirs. Current research is now concentrating on elucidating the rates and processes of sediment transport within one particularly complex reservoir system.

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