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Sediment yield estimates from reservoir studies: an appraisal of variability in the southern Pennines of the UK

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Abstract A regional survey of sediment yields using reservoir re-survey has been undertaken in the southern Pennines, UK. This paper compares the data with those reported globally and discusses some of the controls on variability of measured sediment yields. These may reflect changes in sediment input or retention and may be natural or a product of management strategies, and may be to some extent a function of the measurement process. The organic fraction of the sediment yield was found to show stronger relationships with catchment parameters than did the total yield, reflecting the influence of eroding peat moorlands in the region.

INTRODUCTION

As a result of their size and relative permanence as river basin structures, reservoirs effectively act as long-term sediment sampling vessels. The use of reservoir re-survey as a means of deriving catchment sediment yield is a well established technique (e.g. Rausch & Heinemann, 1984) which overcomes many of the disadvantages inherent in short-term suspended sediment sampling (Walling & Webb, 1981). Many reservoir based studies have, however, tended to focus on individual or small groups of reservoirs examined outside their regional context, and thus the wider implications of the results are limited in scope. In areas where large numbers of reservoirs are found, the potential exists for a regional scale examination of sediment yield rates by investigating all of the sampling sites available. This paper will use such an approach in order to examine the variability in sediment yield of part of the uplands of northern England.

THE STUDY AREA

The Pennine region of the UK has been described as having one of the highest concentrations of small ($0.1\text{-}10 \times 10^6$ m^3) reservoirs in the world (Stott, 1985), with up to 300 earth embankments alone (Walters, 1971). The main construction phase for these reservoirs occurred in the late nineteenth century, providing the area with a large number of sample sites which have been in existence long enough to have experienced a wide range of storm events.

This study concentrates on those reservoirs which intercept tributaries to the River Ouse flowing eastward from the southern Pennines. The reservoirs have been constructed at elevations between 91.14 and 704.1 m AOD in an area dominated by

Millstone Grit on the higher ground, and overlain by Coal Measures to the south and east. The strata dip gently eastwards and are overlain by drift deposits on lower ground. Long-term average precipitation ranges from 755.5 to 1682 mm year^{-1}, with maximum values coinciding with higher altitudes to the south and west. Catchments range in area from 0.21 to 114.9 km^2, with a mean size of 7.44 km^2.

In total, 95 reservoirs were surveyed using EDM and echo-sounder between 1984 and 1992, representing 82% of impounded capacity in the study area. Because of uncertainties concerning the stated original capacity, data have been analysed in this paper for 77 of the reservoirs which originally impounded 115 346 $\times$ 10^6 m^3 and regulated flows from 572.88 km^2. A summary of the construction data for these reservoirs is given in Table 1. Reservoir sediment samples were taken using a Mackereth submersible corer and allowance made for the conversion from volumetric loss to a value equating to sediment mass. Annual area-specific sediment yields were then calculated using Brown's (1941) trap efficiency equation and adjustments after Trimble & Bube (1990). Summary data are presented in Table 2.

Table 1 Construction data for 77 southern Pennine reservoirs.

	Original capacity (m^3 $\times$ 10^6)	Year built	Maximum depth (m)
Total	190 055.9	-	-
Mean	1939.4	1891	19.62
Minimum	30.8	1796	5.49
Maximum	21772	1984	51.8
Standard deviation	2893.9	34.486	9.38

Table 2 Capacity loss and sediment yield values for 77 southern Pennine reservoirs.

	Revised capacity (m^3 $\times$ 10^6)	Capacity loss (m^3)	Capacity loss (%)	Annual loss (% year^{-1})	Annual loss (m^3 km^{-2} year^{-1})	Total sediment yield (t km^{-2} year^{-1})	Organic sediment yield (t km^{-2} year^{-1})
Mean	1 382	116.157	11.01	0.1076	205.90	124.50	20.53
Median	694	55.162	6.51	0.0738	157.50	86.10	14.18
Minimum	8	0.900	0.22	0.0020	6.53	3.70	0.84
Maximum	9 414	1 303.211	92.04	0.7514	1053.36	1111.50	122.26
Standard deviation	1 790	197.985	15.73	0.1272	198.80	59.60	22.07
Total	106 414	8 944.089	7.74	*	*	*	*

COMPARISON OF SOUTHERN PENNINE RESULTS WITH THOSE WORLDWIDE

Reservoir re-survey data are available from a large number of authors for over 300 impoundments world-wide, and are summarized in White (1993). The majority of these

Table 3 Comparison of mean southern Pennine sediment yields with other data.

Region	Sediment yield (t km^{-2} $year^{-1}$)
Southern Pennines	120
Other UK	125
UK OVERALL	100
Americas	1104
Africa	259
Asia	293
OUTSIDE UK	1004

data originate from the USA, with the remainder from India, Ecuador, China, Australia, Africa, together with 25 other results from the British Isles. These data have been broadly categorized on a continental basis (Table 3). Analysis of variance tests using this classification show that there is a significant difference ($p < 0.05$) in all expressions of capacity loss and sediment yield between the different continental groups. Capacity loss and sediment yield in the southern Pennines are lower than elsewhere, and these values conflated for the UK as a whole remain significantly lower than in the rest of the world.

Arriving at an explanation for this difference is problematic. The data are dominated by reservoirs from North America, with very poor representation from other parts of the world. Many of the data from outside the UK consist of individual studies in reservoirs where a severe sedimentation problem has been identified (e.g. Jahani, 1992), and these sediment yields may misrepresent the general situation for the region from which they originate. Reservoir type may also have an influence. Data from outside the UK tend to be collected from very large reservoirs (e.g. Gould, 1954) or from small lowland farm reservoirs with small catchments (e.g. Chakela, 1981). Further analysis of variance testing suggests that while southern Pennine reservoirs are no larger or smaller in capacity than elsewhere, their mean catchment size is significantly larger. This would imply that, while unit area sediment yields are on average lower in the southern Pennines, larger catchments act to deliver proportionately more sediment to the reservoirs. The age of the reservoirs under consideration also varies significantly between regions. Southern Pennine reservoirs are by far the oldest under consideration (most were over 100 years old at survey), and without these records there would be few sediment yield data covering more than 40 years.

The distinctiveness of southern Pennine data can be examined by producing correlations between reservoir capacity, catchment area and capacity loss/sediment yield data. If southern Pennine data, other UK data, and finally all UK data are progressively removed from the analysis of worldwide data, the coefficients change considerably (Table 4), with the direction of that change dependent on the predictor variable used. Removing southern Pennine data tends to increase correlations between expressions of capacity loss and catchment area or capacity, whilst correlations between age or capacity:watershed ratio tend to decrease. Correlations concerning log-transformed sediment yield values show a particularly marked increase when southern Pennine data are removed from the analysis.

Table 4 Significant correlation coefficients found between reservoir or catchment parameters and sediment yield with the progressive removal of UK data.

Variable *X*	Variable *Y*	All data	All data minus other UK data	All data minus southern Pennine data	All data minus all UK data
Log(catchment area)	Sediment yield	−0.210	−0.226	−0.321	−0.370
Log(catchment area)	Log(sediment yield)	n/s	n/s	−0.351	−0.615
Log(original capacity)	Sediment yield	−0.232	−0.252	−0.291	−0.334
Log(original capacity)	Log(sediment yield)	n/s	n/s	−0.273	−0.519
Age at survey	Sediment yield	−0.228	−0.220	n/s	n/s
Log(age at survey)	Sediment yield	−0.267	−0.266	−0.226	−0.197
Log(age at survey)	Log(sediment yield)	−0.585	−0.583	−0.540	−0.337
Log(capacity:watershed ratio)	Log(sediment yield)	n/s	n/s	0.224	0.334
Trap efficiency	Log(sediment yield)	n/s	n/s	0.303	0.421
Log(trap efficiency)	Log(sediment yield)	n/s	n/s	0.250	0.349

n/s = non significant correlation coefficient.

Possible reasons for these trends may be identified from examining Figs 1 and 2. These suggest that, when sediment yields are plotted against catchment area and original capacity, UK data form a distinct grouping apart from the main body of other results, in that while reservoir capacity and catchment areas are within the range found

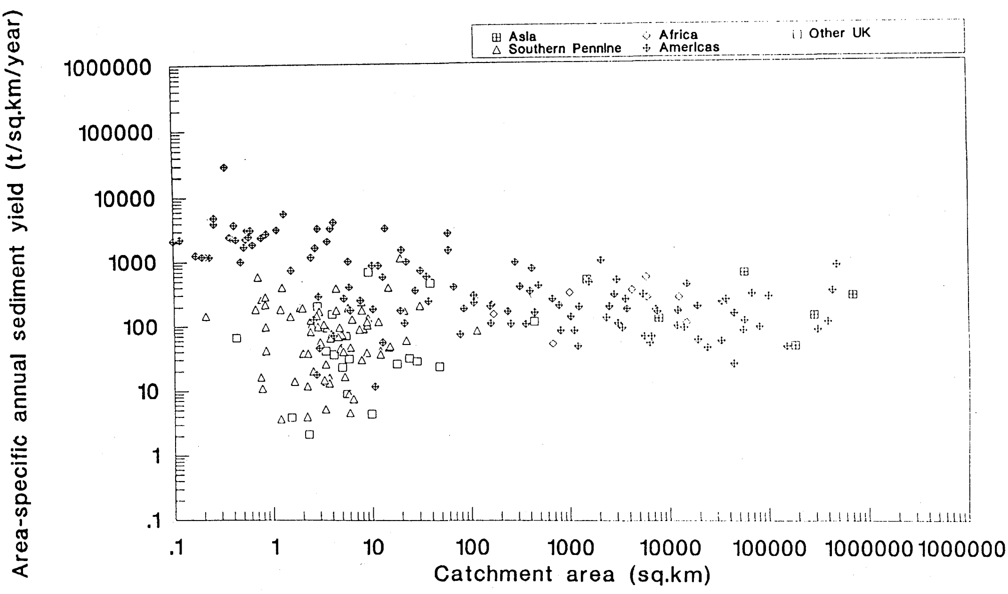

Fig. 1 Relationship between area-specific annual sediment yield and catchment area for reservoirs in this study and others reported in the literature (see White, 1993).

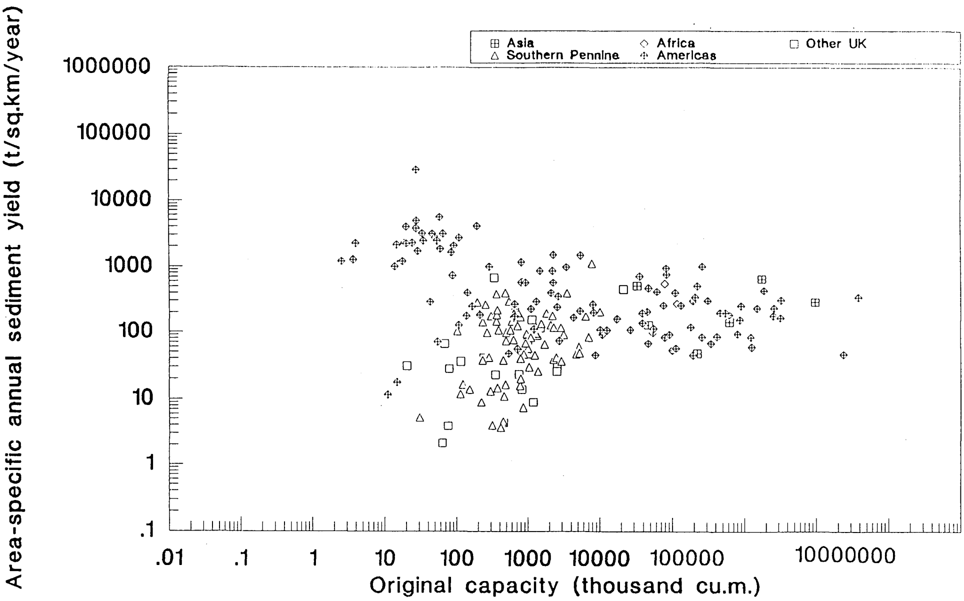

Fig. 2 Relationship between area-specific annual sediment yield and original capacity for reservoirs in this study and others reported in the literature (see White, 1993).

elsewhere, sediment yields are generally lower. Without UK data there is a clear trend towards decreasing sediment yield with increasing reservoir and catchment size, while the correlation coefficients given in Table 4 suggest that UK data show the opposite.

Further examination of the data reveals the influence of reservoir age on sediment yield. Figure 3 shows that the good correlation between sediment yield and reservoir age is largely a result of the presence of southern Pennine data. If the entire dataset is divided into 25 year age categories (Table 5), then there is an apparent decrease in sediment yields over time, with the exception of the oldest category, where all cases originate from the southern Pennines.

The above analysis suggests that sediment yield values from the southern Pennines behave somewhat differently from those in other surveys, but the question remains as to whether this is a product of genuine physiographic differences between study areas, or whether it can be explained in any other ways. Thus more detailed analysis of southern Pennine data is required.

REGIONAL VARIABILITY OF SEDIMENT YIELD RATES IN THE SOUTHERN PENNINES

The principal aim of the study was to identify any patterns in southern Pennine sediment yield data and to suggest possible causes for these patterns. Different approaches, involving either the examination of reservoirs individually or the division of the region as a whole into sub-components on the basis of locational or physiographic groupings, may be used to achieve this aim.

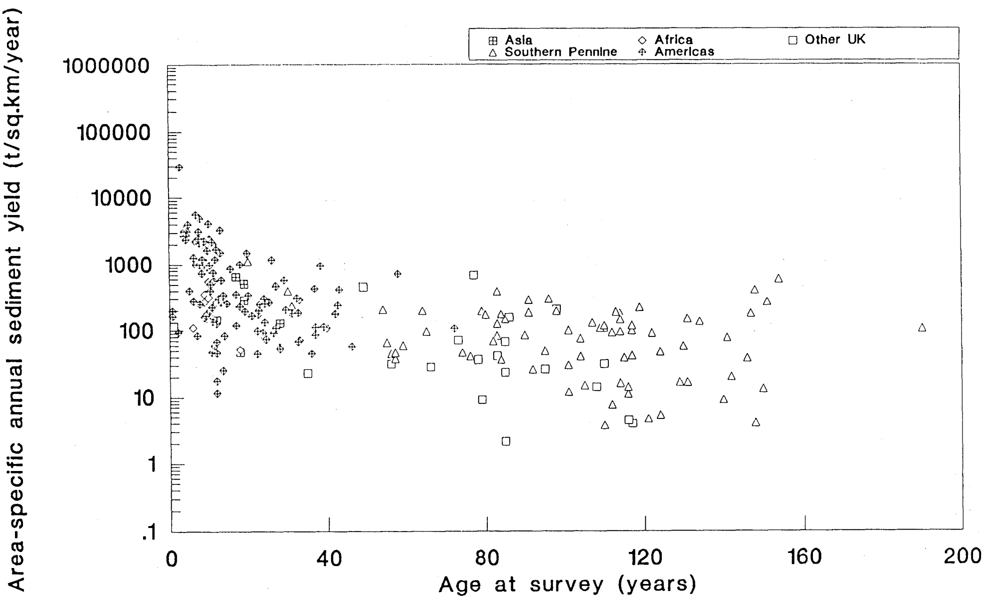

Fig. 3 Relationship between area-specific annual sediment yield and age at survey for reservoirs in this study and others reported in the literature (see White, 1993).

In the case of the former, there are a range of catchment and reservoir variables which have been identified in the literature as having a relationship with sediment yield. Summary statistics for the catchment parameters used in this study are given in White (1993). Many studies suggest that small, heavily dissected catchments at high altitude and with high relief ratio and high rainfall and dominated by peat soils, should experience the highest sediment yields. However, in the case of the southern Pennines, whilst expressions of capacity loss in percentage or volumetric terms do correlate significantly with some catchment parameters, no significant associations were found using sediment yield, and it is only when sediment yield is divided into its mineral and organic fractions that any significant relationships occur.

Organic sediment yield was found to correlate significantly with rainfall (r = 0.194), drainage density (r = 0.248), stream frequency (r = 0.304), relative

Table 5 Mean sediment yield data by age class.

Age at survey	Number of cases	Mean sediment yield (t km^{-2} year^{-1})
<25	109	775.9
25-49	32	247.5
50-74	14	181.9
75-99	27	174.9
100-124	33	138.5
>125	16	227.8

stream density ($r = -0.250$) percentage moorland ($r = 0.217$), maximum catchment altitude ($r = 0.250$), and relief ratio ($r = 0.235$). These relationships would suggest that larger organic yields occur in high altitude and predominantly moorland areas, and where steep gradients and relatively highly dissected catchments allow more efficient delivery of lighter organic matter to reservoirs. It must be noted, however, because of the size of the sample, the relatively weak correlations with catchment characteristics are significant statistically.

It was also anticipated that there would be some spatial pattern in the results, given that there is a decrease in altitude and rainfall with distance eastward from the Pennines and away from the peat soils of the moorlands. However, no significant relationships were found between sediment yield and the easting or northing of the reservoir grid reference. Furthermore, not only is there no apparent spatial trend, but the sediment yield data are frequently highly contradictory. Many reservoirs with relatively low sediment yields can be found adjacent to those with relatively high values. While this is often attributable to the occurrence of reservoirs in cascade systems, not all impoundments in lower positions in cascades have low sediment yields and adjacent catchments may also show markedly different sediment yields.

As reservoirs examined individually demonstrate little consistency in terms of sediment yield, it may be more informative to examine them as groups. The most obvious classification available in terms of spatial distribution is that of the component catchments of the Ouse. Six major sub-catchments can be identified, each running broadly from west to east. Major catchment and reservoir features of these rivers, together with associated sediment yields, are presented in order from north to south within Table 6.

The data strongly suggest that catchments in the southern half of the study area have higher total sediment yields and organic sediment yields. However, ANOVA indicates that while the different rivers exhibit significant differences in catchment area, reservoir size, maximum catchment elevation and mean first order stream length, there is no significant difference between total or organic sediment yield.

It is likely that the variation in these catchment parameters is not a product of geomorphology but of the development of these basins for water supply. Southern Pennine reservoirs tended to be developed not as part of a regional strategy but on a catchment-by-catchment basis by initially small water companies. Rapid use of optimum

Table 6 Distribution of catchment area and reservoir capacity for six major river systems in the southern Pennines.

River	No. of Reser-voirs	Mean age (years)	Total catchment area (km^2)	Mean catchment area (km^2)	Total reservoir capacity ($m^3 \times 10^6$)	Mean sediment yield ($t\ km^{-2}\ year^{-1}$)	Mean organic yield ($t\ km^{-2}\ year^{-1}$)
Nidd	7	87.4	178.87	25.54	25 193	71.1	10.04
Wharfe	5	110.8	62.20	12.44	12 330	70.3	13.28
Aire	17	99.9	67.32	3.96	9 843	86.1	11.73
Calder	16	88.9	82.72	5.17	25 584	152.9	28.93
Colne/Holme	13	123.9	52.52	4.04	9 061	145.5	29.18
Don	19	107.2	129.01	6.79	33 345	146.8	19.97

dam sites ultimately promoted programmes of intensive catchment development, so that many reservoirs exist as part of cascade systems developed over the years, thus reducing the effectiveness of catchment parameters as an analytical tool. This would suggest the need for broader catchment classification techniques.

As it is likely that within each river basin in the southern Pennines there is a range of soil types that are likely to influence sediment yields, a classification based on these parameters was also produced. The classification used was modified from that given by Jarvis *et al.* (1984), with reservoirs coded according to the soil association found over the majority of the catchment. The large number of associations present meant that catchments were classified in broad terms according to whether the dominant soil association was a brown earth, gley, podzolic or peat. Catchment parameters and sediment yields were then tested for significant variation between soil associations (Table 7).

The table indicates a westward progression with increasing altitude for the soil types and an associated increase in rainfall, catchment elevation and percentage moorland. It was anticipated that maximum organic sediment yields would be associated with peat soils, but in reality podzolic soils exhibit the highest organic yield. This apparent discrepancy may be explained in the soil association descriptions given by Jarvis *et al.* (1984). Maximum organic sediment yields occur in catchments dominated by Belmont soil associations. These soils have a marked organic horizon and are described as being subject to heavy erosion from trampling and after heavy rainfall on steep slopes. Table 7

Table 7 Mean values for parameters found to vary significantly ($p < 0.05$) between soil associations in the southern Pennines.

Variable	Soil type:			
	Brown earth: Rivington associations	Gleys: Wilcocks associations	Podzols: Belmont associations	Peat: Winter Hill associations
Easting	576.64	519.93	489.08	453.92
Annual rainfall (mm)	1041.1	1101.0	1276.2	1277.3
Reservoir overflow level (m AOD)	215.43	229.4	263.64	317.83
Maximum catchment elevation (m AOD)	389.21	386.57	468.98	477.08
Relief ratio	0.0431	0.0739	0.0965	0.0801
% moorland	50.63	58.02	65.36	91.12
% pasture	46.2	34.71	28.82	8.88
Organic sediment yield (t km^{-2} year^{-1})	16.13	14.13	37.15	21.18

above indicates that while rainfall receipt is very similar in Winter Hill and Belmont dominated catchments, the mean slope (as expressed by the relief ratio) is higher in the latter. Wilcocks associations, although frequently found with Winter Hill peats, are not normally found with a highly organic layer, and this may be reflected in the relatively low organic sediment yield.

RESERVOIR PARAMETERS AND SEDIMENT YIELD

The nature of a reservoir's catchment has some influence on the amount of sediment delivered to reservoirs in the southern Pennines, although the extent of this influence was considerably less than expected. Correlation coefficients, when significant, were relatively low and thus explain little of the variation in the data. Multiple regression based on combinations of catchment variables found to be significant by other workers (Ichim, 1990) also explained very little of the variability in the data. Furthermore, while the sediment yields reported for different soil associations are significantly different, there remains a high degree of variability within each association and the difference is for organic, rather than total yields.

Clearly, the expectation that catchment parameters would prove fundamental to explaining sediment yields in the study area has not been fulfilled, and alternative explanations were sought by examining the ability of the reservoir to trap sediment, rather than that of the catchment to supply it. A variety of parameters have been found to be significant by other workers and these variables have been calculated by White (1993). In contrast to many studies in the literature, this survey found significant positive correlations between size-related variables and sediment yields (Table 8).

The data suggest that as reservoir capacity increases, so does sediment yield and this contradicts many of the results reported elsewhere (e.g. Dendy *et al.*, 1973). One possible explanation may lie in the historical development of reservoir-based supply in the region. Large reservoirs tended to be constructed much more recently than small ones and were built at lower altitudes in much broader valleys with larger catchments. Improvements in correlation coefficients are achieved by using the natural catchment area of reservoirs (i.e. ignoring any catchment intercepted by impoundments upstream) in producing area-specific sediment yields but no new significant relationships are established.

It may be that southern Pennine reservoirs conform to Rausch & Heinemann's (1975) finding that larger reservoirs are better sediment traps, rather than larger reservoirs experiencing greater sediment yields. This would seem to be confirmed by many of the other relationships described in Table 8. The shape factor correlation suggests that reservoirs which are relatively long in comparison with their width tend to have higher sediment yields. The correlation with the Basin Permanence parameter

Table 8 Significant correlations between sediment yield and reservoir parameters in the southern Pennines.

Variable	Total sediment yield	Organic sediment yield
Original capacity	0.314	0.293
Maximum depth	0.448	0.398
Shape factor (length/width)	0.456	0.458
Reservoir age	−0.277	−0.234
Trap efficiency	0.193	0.207
Basin permanence (capacity:shorelength)	0.417	-

implies that as the volume of water per unit of shorelength increases, sediment yields increase, suggesting that those water bodies that are likely to act as good sediment traps are doing so. Reservoir age also appears to be a factor, with data in this study suggesting that the younger reservoirs are apparently experiencing greater sediment yields.

RESERVOIR CATCHMENT INTERACTIONS

Catchments and reservoirs do not exist in isolation but as part of single systems linked by channel flow from sediment production areas to sediment deposition sites. The rate at which the former contribute to the latter is a function of catchment features relative to reservoir features. While a number of parameters are suggested as being important in the literature, only the basin perimeter:shorelength ratio exhibits a significant relationship with sediment yield for reservoirs in the southern Pennines ($r = -0.218$). This would imply that the smaller the basin perimeter in relation to the shore, the higher the sediment yield.

Despite all the evidence presented above, the correlation coefficients, while significant, explain little of the variability between the variables tested. Furthermore, many of the patterns found in other studies are either not apparent in, or are contradicted by, southern Pennine sediment yield data. This paper has focused on sediment yield, rather than capacity loss data, and not only are there more significant correlations between capacity loss variables and reservoir or catchment variables, but these correlations are more significant than those for sediment yield. Regression analysis of combinations of reservoir and catchment parameters suggested by the literature also explain much more of the data variation, but the highest coefficient of variation obtained was 37.6%.

This would suggest that, in the case of southern Pennines, relative capacity loss data are more easily explained than sediment yields. There are a number of possible reasons for this. Firstly, it is likely that the assumptions made in determining sediment transfer rates between connected reservoirs may not be accurate, as this relies on trap efficiency equations often based on empirical work elsewhere and on sometimes inaccurate original capacity data (White, 1993). Secondly, assumptions have been made regarding sediment properties: namely that properties of sediment samples accurately reflect those found throughout the reservoir-catchment system, and that it is reasonable to apply sediment properties from the 44 sampled reservoirs to adjacent unsampled reservoirs.

CONCLUSIONS

Sediment yields obtained from southern Pennine reservoirs are generally lower than those reported elsewhere in the world, averaging 120 t km^{-2} year^{-1}. Individual reservoirs within the region produced values ranging from less than 5 to more than 1000 t m^{-2} year^{-1}, and relationships with catchment parameters are not always those expected from the literature. Important considerations in the use of reservoir surveys for the estimation of sediment yields are the extent to which the results reflect both the historical management of water and sediment within the catchment and the efficacy of the reservoir as a sampling vessel.

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REFERENCES

Brown, C. G. (1941) Factors in the control of reservoir silting. *J. Am. Wat. Wks Ass.* **33**(6), 1022-1040.

Chakela, Q. K. (1981) *Soil Erosion and Reservoir Sedimentation in Lesotho.* UNGI Rapport no. 54, Scandinavian Institute of African Studies.

Dendy, F. E., Champion, W. A. & Wilson, R. B. (1973) Reservoir sedimentation surveys in the United States. In: *Man-made Lakes: Their Problems and Environmental Effects* (ed. by W. C. Ackermann, G. F. White & E. B. Worthington), 349-357. American Geophysical Union, Geophysical Monograph no. 17. William Byrd Press, Richmond, Virginia.

Gould, H. R. (1954) Amount of sediment. In: *Comprehensive Survey of Sedimentation in Lake Mead, 1948-1949* (ed. by W. O. Smith, C. P. Vetter, G. B. Cummings *et al.*), 195-200. Geological Survey Professional Paper 295, US Government Printing Office.

Ichim, I. (1990) The relationship between sediment delivery ratio and stream order: a Romanian case study. In: *Erosion, Transport and Deposition Processes* (ed. by D. E. Walling, A. Yair & S. Berkowicz) (Proc. Jerusalem Workshop, March-April 1987), 79-86. IAHS Publ. no. 189.

Jahani, A. (1992) Calculating the sediment load of the Dez river. In: *Erosion and Sediment Transport Monitoring Programmes in River Basins* (ed. by J. Bogen, D. E. Walling & T. Day) (Proc. Oslo Symposium, August 1992), 225-232. IAHS Publ. no. 210.

Jarvis, R. A., Bendelow, V. C., Bradley, R. I., Carroll, D. M., Furness, R. R., Kilgour, I. N. L. & King, S. J. (1984) *Soils and Their Use in Northern England.* Soil Survey of England & Wales Bulletin no. 10. Harpenden.

Rausch, D. L. & Heinemann, H. G. (1975) Controlling reservoir trap efficiency. *Trans. Am. Soc. Agric. Engrs* **18**, 1105-1108 and 1113.

Rausch, D. L. & Heinemann, H. G. (1984) Measurement of reservoir sedimentation. In: *Erosion and Sediment Yield: Some Methods of Measurement and Modelling* (ed. by R. F. Hadley & D. E. Walling), 179-200. University Press, Cambridge.

Stott, A. P. (1985) Reservoir sedimentation and land-use change in NW England. Unpublished PhD thesis, Manchester University.

Trimble, S. W. & Bube, K. P. (1990) Improved reservoir trap efficiency prediction. *The Environmental Professional* **12**, 255-272.

Walling D. E. & Webb, B. W. (1981) The reliability of suspended sediment load data. In: *Erosion and Sediment Transport Assessment* (Proc. Florence Symp., June 1981), 177-194. IAHS Publ. no. 133.

Walters, R. C. S. (1971) *Dam Geology*, second edition. Butterworths, London.

White, P. (1993) The reliability of sediment yield estimates from reservoir studies: an appraisal of variability in the southern Pennines of the UK. Unpublished PhD thesis, the University of Huddersfield.