Department of the Environment Transport and the Regions

Sedimentation in Storage Reservoirs

Final Report

February 2001

Halcrow Water

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The web version of the report was assembled by Tony Green, links have been included for Figures and bookmarks to enable better navigation. To keep file size to a minimum figures have been saved in a low resolution, please contact greenap@halcrow.com if a clearer version is needed or you have further comments.

Department of the Environment Transport and the Regions

Sedimentation in Storage Reservoirs
Final Report

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Contents

1 Summary and Conclusions

This report describes research carried out on aspects of reservoir sedimentation in British reservoirs with the emphasis on those used for water supply. The topics covered include a review of the available data, the development and use of a classification method for determining sedimentation rates, the analysis of sediment movement under dam failure conditions and a review of methods of reducing sedimentation. This is the first time that such a study has been carried out for British conditions and a number of potential areas of further research are suggested.

It is found that for British conditions the data available suggests that a reasonably simple method of classification can be used as a predictive tool for estimating sedimentation rates which, though generally not high by global standards, are significant in some locations.

The behaviour of sediment in small reservoirs under dam failure conditions has been found to be strongly dependent on the rate of flow into the reservoir. If the dam fails under 'sunny day' conditions when the flow into the reservoir is small, then only a small proportion of even the very low strength deposits found in small reservoirs can be expected to 'flow' with the escaping contents of the reservoir. If there is a large flow into the reservoir when a breach occurs then more sediment is entrained although in the case studied the proportion of sediment moved is small compared with the total sediment deposit within the reservoir. It would be expected that more sediment would subsequently be suspended by the action of the stream which may have environmental impacts on the river system but would not constitute part of the 'escapable contents' of the reservoir under dam failure conditions.

The sediment control measures in place in a number of British reservoirs such as residuum lodges (silt traps) and bypass channels are shown to be effective in prolonging the life of a reservoir although improvements to allow mechanical removal of the sediment may be required. Disposal of accumulated material may pose difficulties but an encouraging development was found in the Pennine area where a private company has developed a potting compost that successfully utilises the sediment collected in residuum lodges.

A range of environmental benefits and impacts of reservoir sedimentation have been identified. On the positive side, moderate rates of siltation in a number of reservoirs have allowed the development of valuable wetland environments. However, for reservoir safety it is necessary to regularly operate bottom outlet valves and data is presented showing that this can adversely affect the downstream river unless carefully managed.

For the future there are concerns that changes in the climate may increase sedimentation rates due to more intense rainfall and more frequent storms but this has not as yet become apparent from reservoir surveys.

2 Introduction

2.1 Background

The accumulation of sediments in reservoirs in Britain can lead to a range of problems, including the following:

- Increased flood risk on influent streams, loss of flood storage for downstream channels and increased spillway flows;

- Loss of storage capacity with associated loss of reservoir yield and difficulties in storage recovery;

- Severe blockage of scour / drawoff works resulting in periodic reservoir drawdown to excavate sediment or abandonment of bottom outlet facilities;

- Build up of sediment against the upstream face of dams, adversely affecting the stability of certain dam structures;

- Sediment accumulations near power intakes, increasing the sediment load of the water passing through turbines, thereby accentuating turbine wear.

The research described in this report aims to review reservoir sedimentation in the Britain and to provide guidance on the prediction of storage loss and the measures that can be taken to mitigate the associated problems.

This study has been carried out as a research contract in response to a specification set by the Department of the Environment, Transport and the Regions in February 1999. The contract was awarded through competitive tender to Halcrow Water and their sub-consultants, Professor David Butcher and Dr Jillian Labadz of Nottingham Trent University in April 1999. A copy of the contract specification is included in Appendix C of this report. The study commenced on 1 May 1999 with a completion date of 29 December 2000.

2.2 *Scope of report*

This report describes the results of the work carried out for the seven specific project Milestones as follows:

Milestone 1 - Classification of British reservoirs;

Milestone 2 - Reservoir surveys;

Milestone 3 - Extrapolation of data to reservoir classes;

Milestone 4 - Behaviour of sediments under dam failure;

Milestone 5 - Effectiveness of sediment exclusion measures;

Milestone 6 - Options for sediment removal;

Milestone 7 - Consequences of sedimentation in the past and in the future.

2.3 *Data collection*

As part of this study the major owners of reservoirs in England, Wales and Scotland were approached in order to obtain any available information on reservoir sedimentation and to obtain additional characteristics of reservoirs that are kept in the Prescribed Form of Record for each reservoir. This has been a successful exercise and much data has been obtained. The information has been entered into a study database based on the Building Research Establishment's (BRE) database of British dams which covers all known reservoirs within the Reservoirs Act (see Figure 2.1). The database is also geographically linked through the use of National Grid co-ordinates and can thus be used for geographical analysis of sedimentation rates.

3 Review of existing information

3.1 Sedimentation in British reservoirs

The rate at which reservoir capacity is lost by sedimentation in Britain is low by global standards. It is reported that the global average for the useful life of a reservoir is less than 25 years (Mahmood, 1987) whereas the average useful life of British reservoirs is considerably longer and in a number of cases already exceeds 100 years as shown in Figure 3.1.

The operational life of the reservoir is normally determined by the point in time at which sediment accumulations reduce the reservoir yield below supply requirements. This 'useful' life of a reservoir is often defined as the time taken for 90% of the live reservoir storage to be depleted, although in practice measures normally have to be taken well before this occurs to ensure reliability of supply. This is dependent not only on the magnitude and nature of the incoming sediment yield but also on any physical or operational measures that are in place to reduce the rate at which the remaining storage is depleted. Such measures might include upstream sediment traps (residuum lodges) and managed diversion of water around the reservoir by means of by-wash channels. In Britain, many reservoirs which have surpassed their useful life have been supplemented by larger reservoirs downstream and then effectively act as gravel traps. However, even when the useful life has been reached, the reservoir will often continue to provide supplementary benefits such as recreational usage or wetland development. Provided that such benefits outweigh the operational costs involved in maintaining the reservoir, the life of the reservoir can be extended at least until such time as the reservoir is completely filled with sediment. However, with the increasing problems associated with the location of suitable sites for replacement reservoirs, it is expected that reservoir owners will increasingly consider extending their life through the removal of sediment from reservoirs, for example by dredging.

The mechanics of how sediment becomes deposited in reservoirs is covered in technical literature (Mahmood, 1987) and is only described briefly here in general terms. As flow enters a newly-formed reservoir, the channel cross-sectional area increases and this is accompanied by a decrease in flow velocity and a dampening of water turbulence such that particles begin to deposit. The pattern of sediment distribution is dependent on many factors including the size and texture of the sediment particles, the physical characteristics of the reservoir and reservoir operation. Generally, deposition commences with the coarser particles, creating a delta formation at the reservoir headwaters. These form the 'topset' beds and the point at which coarse sediments are deposited moves gradually towards the reservoir in time, forming 'foreset' beds that slope down into the reservoir. Fine sediment particles are carried further into the reservoir and settle on the floor of the reservoir area forming 'bottomset' beds. Empirical and mathematical modelling techniques have been used to estimate the distribution of the sediment within reservoirs. As the sediment distribution affects the stage-storage relationship of a reservoir, the distribution can be important in determining the effect of sedimentation on reservoir operation. It is a common misconception that reservoir sedimentation acts to deplete all of the 'dead' storage (i.e. the storage below the lowest drawoff level) before live storage is affected. Sedimentation patterns are such that the usable capacity starts to diminish before the entire non-usable component is filled with sediment.

3.2 *Sediment yields in British rivers*

Reservoirs tend to trap both coarse and fine sediment particles. In consideration of reservoir sedimentation, 'sediment yield' is defined as the sediment transport comprising both a bedload component (typically sands and gravels transported along the bed of a river) and a suspended sediment component typically comprising finer particles of silt and clay. Suspended sediment transport is generally easier to measure than bedload transport and consequently there is much more data available for suspended sediment yield than for 'total' sediment yield. Estimates of total sediment yield are often derived from reservoir surveys, whereby the total sediment deposited over a specific time is measured with allowances made for the proportion of sediment which is not trapped by the reservoir.

Sediment yield in the Britain is known to be low by global standards. Mahmood (1987) gives the global average total sediment yield as 190 t/km^2/yr. In Britain there is considerable spatial variation in average suspended sediment yields. Walling (1987) gives 50 t/km^2/yr as a typical value of suspended sediment yield for Britain and cites site specific yield measurements between 1 and 488 t/km^2/yr. Suspended sediment yields from a recent study of sites within the Humber catchment gave figures of suspended sediment yield between 3.4 and 92.1 t/km^2/yr with a mean value of 26 t/km^2/yr (Waas and Leeks, 1999). The site with the highest mean suspended sediment yield (58 t/km^2/yr) was a steep upland catchment. As well as there being considerable spatial variation, the sediment load can vary considerably with flow conditions at a site over time. Suspended sediment concentrations in British rivers have been recorded to vary by up to three magnitudes within a year.

Newson (1986) pooled British data for suspended and bedload measurements and found that bedload can exceed 50% of the total yield in small upland catchments whereas suspended sediment dominates in the larger lowland rivers where it typically represents over 85% of the total yield.

A number of reservoir surveys have been carried out in recent years to estimate total sediment yield. White et al (1996) studied Yorkshire's peat-dominated upland reservoirs and determined an average sediment yield of 124.5 t/km^2/yr. Duck and McManus (1990) studied many reservoirs in the Midland Valley of Scotland and found that a range of 20 - 60 t/km^2/yr is typical here of small well-vegetated upland catchments. Data from reservoir studies are covered more fully in Section 3.4.

Given that there has been an absence of a national sediment monitoring programme in Britain, no definitive estimate for the average total sediment yield can be made. From the information available however, it appears likely that this lies in the range of 50 - 75 t/km^2/yr.

Outside Britain, reservoir re-survey data are available from a large number of authors for over 300 impoundments world-wide (White, 1993) and serve as a useful guide to global sediment yield figures. The majority of these data originate from the USA, with the remainder from India, Ecuador, China, Australia, Africa. These data have been broadly categorised on a continental basis in Table 3.1.

Table 3.1 Sediment Yield Data from Reservoir Surveys outside Britain (White, 1993)

Region	Sediment Yield (t/km2/yr)
Americas	1104
Africa	259
Asia	293

Care is required in interpreting the data in Table 3.1, which are all higher than the figure given by Mahmood (190 t/km^2/yr). The data are dominated by reservoirs from North America, with very poor representation from other parts of the world. Many of the data consist of individual studies in reservoirs where a severe sedimentation problem has been identified and these sediment yield data may misrepresent the general situation for the region from which they originate. In the same manner, care is needed when using British reservoir studies as a guide to national sediment yield.

3.3 Factors affecting catchment sediment yield in Britain

Given that the tendency of a reservoir to trap sediment is in part dependent on the nature of the sediment influx, it is important to consider the characteristics of the influent streams in the light of the deposition characteristics of the river at the reservoir site.

Much of the west and north of Britain comprises the third of Britain that can be considered as uplands. This area gives source to many of the major British rivers. Some of these streams reach the sea as gravel bed rivers while others (principally those draining to the south and east) flow to lowland areas. River channels in the upland areas are generally controlled by bedrock or coarse glacial deposits and the river sediment in sourced mainly from neighbouring hillsides. Rivers which do not reach the sea with a gravel bed tend to make an abrupt transition to silt-clay channels (the Severn is an example). Sand-bed rivers are generally confined to Scotland whereas the upland mudstones in England and Wales tend to shatter to gravel but weather to clay (Newson and Leeks, 1987). Where the channel slope decreases more rapidly than the stream discharge increases, deposition of coarse material occurs in Piedmont river reaches. The proportion of bed load to the total sediment load therefore decreases from upland to lowland regions.

Sediment yield can be considered as the portion of the gross erosion within a catchment area that is not deposited before being transported from the area. Given that erosion is a two-stage process comprising both the detachment and the transport of material (by water or wind), two distinct conditions can be recognised (Morgan, 1995):

(i) Supply limited conditions whereby less material is detached than can be transported.

(ii) Transport limited conditions whereby more material is available than can be transported.

Britain is generally considered to display supply limited conditions (DoE, 1995). Nevertheless, the main river draining a catchment will only transport a fraction of the total material detached, the remaining material going into storage on hillslopes, floodplains or within the river channel itself. Much of this material might be mobilised in the course of high runoff events. The variation in the sediment load of a river is largely flow-dependent. However, the relationship is complex - sediment loads in a flood following a period of low flow will tend to scour the river channel and the sediment load associated with a similar flood a short time later may be much lower. Long-term monitoring of sediment loads is therefore important in the understanding of sediment regimes.

The factors which determine the sediment transport in a watercourse are well reported in general terms for Britain (DoE, 1995). The literature confirms that controls such as land use, management practices, vegetation cover, grazing intensity, soil type, channel steepness and length, flow convergence/divergence and surface roughness are all important. However it is only recently that a large-scale (regional) study of the processes has been undertaken in the Britain. The Land-Ocean Interaction Study (LOIS) was launched by the Natural Environmental Research Council in 1992 and was completed in 1998. The 'river component' of LOIS focused on the Yorkshire Ouse and other principal rivers draining to the Humber Estuary, and on the River Tweed. In view of the general lack of information on suspended sediment transport by British rivers, particular attention was given to investigating the suspended sediment dynamics of the study rivers. It is important to note however that as LOIS aimed at a better understanding of the interaction between suspended sediments and nutrients and contaminants; bed load transport was not covered by the study.

The research found a positive relationship between suspended sediment yield and catchment area with the rate of increase tending to decrease with large catchments. It was considered that larger catchments are subject to lower erosion and depositions of sediment on the floodplains during overbank flood events.

The analysis of reservoir and lake sediments carried out within the LOIS studies (Foster and Lees 1999) provide a significant new data set of significance to reservoir sedimentation. The results of the work consider land use and sediment yields as shown in Table 3.2.

Table 3.2 LOIS Results on Sediment Yield (Foster & Lees 1999)

Catchment Land Use	Reservoir	Trap Efficiency % Calculated	Catchment Area (km^2)	Reservoir Area(km^2)	Sediment Yield ($t/km^2/yr$)
Pasture	Silsden	91	8.15	0.1036	18
	Elleron Lake	63	2.56	0.0299	8
Mixed	Newburgh Priory Pond	46	5.88	0.0396	52
Arable	Fillingham Lake	87	2.90	0.0699	16
	Yetholm Loch	63	12.21	0.144	25
Forested	Boltby Reservoir	83	3.25	0.0224	16
	Fontburn Reservoir	91	27.74	0.32	9
Moorland	Barnes Loch	80	1.78	0.058	23
	March Ghyll	85	4.04	0.057	34

Other recent reservoir studies have also shown that area-specific sediment yield is inversely correlated with catchment area, as found by Dearing and Foster (1993) and also by many earlier studies which have also reported decreases in sediment yield with increasing catchment area. The temporal variation in yield was also found to be significant from the LOIS research - a six-fold variation in yield at a station on the River Trent was observed over successive years. Wide geographic variations were also observed and attributed to the effects of geology, climate, land use, catchment scale, channel bank and floodplain deposition, and reservoir entrapment. The application of LOIS research and the influence of catchment land use and management on reservoir sedimentation rates will be further discussed in Sections 4 and 7.

3.4 *Previous British reservoir studies*

Measurements of sediment yield in Britain have predominantly been carried out by short term monitoring programmes on inflow streams (e.g. Moore and Newson, 1986), surveys of reservoir sediment that estimate the rate of infilling since construction (e.g. Duck and McManus, 1994) and sediment coring strategies that seek to reconstruct past erosion histories (e.g. Foster and Lees, 1999a and b). All three of these approaches have difficulties in fully characterising the temporal and spatial variability in the sediment delivery process. Short term river sampling, in particular, may not account for the highly variable nature of sediment delivery. Wiebe and Brennan (1973), for example, noted that the John Martin reservoir (Colorado, USA) lost 7.5% of its capacity in its first 15 years but that half of this loss was the product of two extreme storms. The resurvey of reservoirs overcomes this problem by taking a longer term view, but suffers from potentially important yet unquantifiable errors in the accuracy of the original capacity of the reservoir (Foster and Walling, 1994; White et al, 1996). Palaeolimnological methods which use dated reservoir bottom methods have been used more recently to provide long term measures of sediment yield (e.g. Foster and Lees, 1999a) but these rely on the sediments within the reservoir being relatively undisturbed. The effects of variable trap efficiency, sediment redistribution during reservoir drawdown and scour events make it particularly important that the management history of any reservoir used in such a study is thoroughly researched.

Table 3.3 outlines British studies on reservoirs reported in the literature. These data were collected only from studies using methods of reservoir resurvey, so that capacity losses in reservoirs estimated from stream sediment concentrations or estimated using models have been excluded. Some studies have reported sediment yields in terms of cubic metres of sediment, and unless it is explicitly stated that this represents cubic metres of dry mass, these data should be regarded as capacity loss rates rather than sediment yields.

Table 3.3a Reservoir Capacity Loss Rates in British Studies

Location	Capacity Loss Volume/Mass of sediment deposition	Percentage loss of capacity		Author(s)
		Total	Per annum	
Cropston	25.6 t/km²/yr = 200 m³/yr	0.7	0.007	Cummins & Potter (1967)
Lambieletham Haperleas Drumain	2.1 t/km²/yr 13.8 " 3.9 "	0.6 1.5 1.4	0.007 0.014 0.012	Duck & McManus (1987)
Cullaloe N Cullaloe S	36.0 t/km²/yr 30.8 "	10.2 6.0	0.131 0.055	Duck & McManus (1987)
Hopes Pinmacher Holl Earlsburn #1 North Third Carron Valley	23.1 t/km²/yr 66.4 " 153.9 " 203.0 " 676.6 " 451.9 "	3.0 3.1 4.6 8.7 14.3 4.0	0.086 0.037 0.054 0.089 0.186 0.082	Duck & McManus (1990)
Catcleugh	114 m³/km²/yr	*	*	Hall (1967)
Abbeystead	161.5 m³/km²/yr	45.2	0.532	Hoyle (1985)
Howden	127.71 t/km²/yr	*	*	Hutchinson (1995)
Kelly Res.	18 m³km²/yr = 41 t/km²/yr	11.0	0.13	Ledger et al (1980)
Hopes	25.0 t/km²/yr	*	*	Ledger et al (1974)
North Esk Res.	12 m³/km²/yr	10.0	0.08	Lovell et al (1973)
Glenfarg Glenquey Glenfarg Glenquey	108.33 m³/km²/yr 29.85 " 31.3 t/km²/yr 9.0 "	2.5 1.1	0.05 0.01	Duck & McManus (1985)
Trentabank	34.5-49.3 t/km²/yr	*	*	Stott (1985)
Grassholme Blackton Hury	* * *	8.1 9.2 1.1	0.23 0.17 0.02	Winter (1950)
Strines	113.4 m³/km²/yr	4.6	0.05	Young (1958)
South Pennine Reservoirs (95 no.)	206m³/km²/yr	10	0.11	White/Labadz/ Butcher (1996)

Table 3.3b Reservoir Capacity Loss Rates in Studies for Anglian Water (Pumped Reservoirs)

Location	Reservoir Volume (000s m^3)		% loss of capacity		Catchment Area km^2	
	Volume Lost	Total Volume	Total	per annum	Pumped	Natural
Grafham Water	2270	57760	4	0.125	2570	0.9
Rutland Water	7420	124000	6	0.27	2064	6.4
Pitsford	1805l	17545	10	0.23	312	45
Hollowell	138	2064	7	0.12	0	1.2
Ravensthorpe	138	1884	13	0.12	0	1.1
Foxcote	42	613	7	0.17	389	0
Covenham	621	11370	6	0.19	29.2	29.2
Ardleigh	185	2370	8	0.3	22.8	1.1
Alton Water	0	9090	0	0	32.6	1.8

The single largest set of reservoir sedimentation data is from the recent study of the southern Pennines. The data in Table 3.3a shows that, although some reservoirs have very high rates of infilling, southern Pennine percentage capacity loss rates are very similar in range to other reservoirs in the British Isles. However annual area-specific capacity losses are apparently higher.

In terms of capacity loss, part of the difference between southern Pennine reservoirs and other studies may result from differences in the method used to derive gravimetric values for sedimentation rates. For example, Ledger et al (1980) calculated an annual percentage capacity loss of 0.13% from a capacity loss rate of just 18 $m^3/km^2/yr$, compared with southern Pennine means of 0.108% per year and 205.9 $m^3/km^2/yr$ so that similar relative loss values are not matched by similar rates of capacity loss. Ledger et al's area-specific loss figures, however, were expressed in cubic metres of dry mass accumulated (based on known sediment moisture and density properties), whereas others have used a direct conversion of the volume of wet sediment mass. This means that while the relative loss figures express the same feature, the absolute figure quoted by Ledger et al refers to a different property of the sediment body. The absolute capacity loss figures are most readily understood if percentage values are calculated in terms of 'real' cubic metres of volume lost to sediment. If the Ledger et al data are re-calculated in this way, then a 27,000 m^3 loss over 83 years in a catchment of 3.4 km^2 converts to 95 $m^3/km^2/yr$. This value is still much lower than the southern Pennine mean, but well within the range of data. Similarly, the data given by Lovell et al (1973) (again with a similar annual percentage loss) can be converted from 12 $m^3/km^2/yr$ of dry mass to 71.43 $m^3/km^2/yr$.

Differences in sediment yields are less easily explained. The data suggests that the volumes of accumulated material are comparable to southern Pennine reservoirs, and Table 3.4 suggests that dry bulk densities and organic contents (where available) are also markedly similar.

Table 3.4 Sediment Characteristics in Reservoir Studies

Reservoir	**Dry Bulk Density (g/cm^3)**	**Organic Content (%)**	**Authors (s)**
Strines	*	29.95	Young (1958)
Kelly	0.341	10.0	Ledger et al (1980)
North Esk	0.333	10.0	Lovell et al (1973)
Glenfarg	0.430	25.34	Duck & McManus (1985)
Glenquey	0.430	25.50	" " "
Lambieletham	0.830	14.29	Duck & McManus (1987)
Harperleas	0.360	16.67	" " "
Drumain	0.500	15.38	" " "
Cullaloe	0.435	14.94	" " "
Hopes	0.400	*	Duck & McManus (1990)
Pinmacher	0.742	10.41	" " "
Holl	0.449	14.66	" " "
Earlsburn No. #1	0.305	*	" " "
North Third	0.289	*	" " "
Cameron	0.528	22.0	" " "
Carron Valley	0.282	*	" " "
Southern Pennine Data	0.36	31	White/Labadz/Butcher
Mean	0.444	17.39	

Sediment yields given for the southern Pennines have been adjusted to allow for theoretical trap efficiency losses between reservoirs, whereas data in other surveys are not (e.g. Lovell et al, 1973). If the data from other surveys are treated in the same way as data from the southern Pennines (i.e. sediment yields are adjusted by a trap efficiency value from Brown, 1943) then there ceases to be any significant difference between the two data sets. The reason for this change is the significantly lower trap efficiency values in most other parts of Britain, which is in turn a product of the lower C:W (reservoir capacity to watershed or catchment area) ratio used in estimating trap efficiency.

There is a general decline in percentage and annual percentage loss with increasing C:W ratio. Whilst southern Pennine reservoirs are concentrated in the high C:W range, other British studies are more evenly distributed across the C:W spectrum. This may reflect the differences between larger lowland catchments, such as Cropston in Leicestershire (Cummins & Potter, 1967) and those of eastern and central Scotland (e.g. Ledger et al, 1980; Lovell et al, 1973), and the upland reservoirs found where steep valley sides give a relatively large water storage volume for a given catchment size.

There is a general downward trend both in capacity and catchment area as the period of record lengthens. As with catchment area, young reservoirs divide the loss of capacity by a smaller amount than older ones in generating annual percentage and area-specific losses. Table 3.5a illustrates the impact of this feature on percentage and annual percentage losses.

Table 3.5a Average percentage and annual percentage losses for reservoirs in the British Isles (excludes pumped reservoirs)

Age at survey (years)	No. of cases	Capacity Loss	
		%	% per year
<50	6	6.93	0.2268
50-75	15	5.82	0.0950
75-100	29	10.34	0.1213
100-125	34	7.59	0.0673
>125	17	21.25	0.1379

By classifying reservoirs into age groups and subjecting the mean values per age group to analysis of variance, the variation in mean percentage loss and annual percentage loss between age classes is significant at 5%, with the figures showing an apparent upward trend in percentage loss in older reservoirs. The literature suggests that, because of the decrease in trap efficiency as reservoirs fill with sediment, much of a reservoir's capacity loss occurs in the early part of the reservoir lifespan. This would suggest that, if the incremental loss in percentage capacity becomes progressively smaller in older reservoirs, the division of that loss by time has an increasingly large impact on the annual loss rate produced, and thus it might be expected that the annual loss rate in Table 3.5a declines as older reservoirs are examined. Although there is some support for this hypothesis there is also significant scatter in the data possibly due to natural variation and the relatively limited siltation that occurred in the bulk of cases.

A similar pattern can be observed with annual area-specific capacity loss and sediment yields in Table 3.5b. There is significant variation in both variables between reservoir age groupings, and there is a general downward trend in yield/loss rate as older reservoirs are considered. This could suggest that actual sediment yield or sediment delivery is decreasing with time or that there is a decrease in the amount of sediment trapped by the reservoir. The significant difference reported earlier between the two populations of sediment yields may, therefore, be as much a product of the relatively long sampling period of southern Pennine reservoirs, rather than actual differences between the amounts of sediment being delivered to sampling points.

Table 3.5b Average Annual Area-Specific Capacity Loss and Sediment Yield Rates for Reservoirs in Britain

Age at Survey	Sediment Yield		Capacity Loss	
	No. of Cases	($t/km^2/yr$)	No. of Cases	($m^3/km^2/yr$)
<50	5	442.2	6	391.1
50-75	12	76.9	16	161.5
75-100	27	139.4	29	174.9
100-125	33	65.3	34	138.5
>125	16	128.3	17	226.1

In terms of the southern Pennines, if the population of reservoirs is classed as those upland reservoirs draining eastward into the Ouse catchment, then the sample of 95 reservoirs represents almost all the population available. The question arises, then, as to whether the data given in other studies represents an equivalent population of other regions. The majority of other British Isles data consists of surveys in the midlands of Scotland (Duck & McManus, 1987, 1990;

Ledger et al, 1980; Lovell et al, 1973; Duck & McManus, 1985). Although the total number of reservoirs for this region is smaller, coverage of the total number of reservoirs for the region is near complete, as the density of impoundment is considerably less than in the southern Pennines.

Reservoir studies outside of the southern Pennine study area have a smaller range in age and catchment area because of the lower number of reservoir studies available. Only the studies in Scotland and the southern Pennines can be regarded as truly representative of their regions. It is clearly questionable as to whether, given the large numbers of water bodies involved, single or small groups of reservoirs in Tyneside, Teesside and Leicestershire can adequately represent the remainder of Britain. This point is underlined when it is considered that the heavily impounded areas of South Wales and the western draining portion of the southern Pennines are almost absent from the database.

Table 3.6 summarises the reservoir data collected, including reservoir survey data, data available from the BRE database of dams and information provided by reservoir owners by the beginning of December 1999. Note that the sample of British reservoirs for which data is available is different for each column.

Table 3.6 Percentage Annual Capacity Loss in British Reservoirs

	Reservoir Capacity (m^3)	**Reservoir surface area (m^2)**	**Average Rainfall (mm)**	**Annual % capacity loss**
Mean	38,126	702	1,120	0.11
Max.	12,728,800	74,677	2,500	0.75
Min.	25,000	0.01	450	0.00
Sample number (n)	2,366	1,644	156	73

The trap efficiency of a reservoir can be defined as the ratio of the quantity of deposited material to the total sediment inflow. There are a number of ways of estimating trap efficiency including simple empirical relationships and use of modelling techniques for specific studies. One method commonly used is that of Brune's curves (1953) which provide a guide to reservoir trap efficiency. These curves relate the ratio of mean reservoir capacity to the mean volume of annual inflow against the percentage by weight of sediment retained. One study

(Pemberton, 1987) has shown that Brown's method (1943), which relates trap efficiency to the ratio of reservoir capacity to catchment (watershed) area (i.e. the C:W ratio), is a more accurate predictor than Brune's method for upland reservoirs. While it is considered that Brune's method generally provides a better indicator of sediment retention than Brown's method, the latter is likely to more convenient in analysing a large sample of British reservoirs from the information available. This is because of the uncertainties involved in transforming mean annual rainfall to mean annual runoff without detailed study of the catchment processes and the influence of catchwater.

3.5 Analysis of South Pennine data

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 British data, and finally all British data are progressively removed from the analysis of world-wide data, the coefficients change considerably (Table 3.7), 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 3.7 Significant correlation coefficients found between reservoir or catchment parameters and sediment yield with the progressive removal of British data

Variable X	Variable Y	All data	All data Minus other British data	All data Minus Southern Pennine Data	All data minus all British 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 plotting sediment yields against catchment area and original capacity. British 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 elsewhere, sediment yields are generally lower. Without British data there is a clear trend towards decreasing sediment yield with increasing reservoir and catchment size, while the correlation coefficients given in Table 3.7 suggest that British data show the opposite.

The above analysis suggests that sediment yield values from the southern Pennines behave somewhat differently from the rest of Britain, 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.

The significantly smaller catchments supplying equivalent capacities give much higher C:W values for the southern Pennines, reflecting the development of water supply in the region. The cascade nature of many southern Pennine impoundments effectively eliminates the bulk of a reservoirs natural catchment in the lower parts of the cascade. Most of the reservoirs recorded elsewhere exist in isolation, or with upstream reservoirs isolating a smaller fraction of the natural catchment. Low C:W values suggest a large catchment supplying a small water body, so that even where sediment yields between basins are the same, the impact in percentage terms on a low C:W reservoir is greater than in a high C:W reservoir.

In comparing southern Pennine data with other British studies, a number of assumptions have been made. Initially, in comparing mean values for different data sets, it was assumed that the two sets of samples were from distinct populations of reservoirs, separated in spatial terms, and in terms of their dimensions and age. Closer examination revealed, however, that for most expressions of capacity loss available, no significant differences existed between the two data series, or that the differences could at least partially by explained by the treatment given to the data.

4 Reservoir sedimentation rates

4.1 *Introduction*

The susceptibility of a reservoir to sedimentation depends on the sediment delivery of the source watercourse, the retention characteristics of the reservoir and the manner in which the flow is delivered from the natural source to the reservoir. A classification of reservoirs is therefore needed which combines these major influences. The data available for British reservoirs that could be widely used without site specific studies are:

1. Reservoir Area and Volume(BRE database);
2. Dam height and length (BRE database);
3. Year of impoundment (BRE database);
4. Catchment Area (Obtained from Prescribed Form of Record);
5. SAAR (Standard annual rainfall from Prescribed Form of Record);
6. Grid Reference (BRE database).

The data available on existing measurements of siltation and catchment sediment yield were discussed in Section 3 of this report.

A literature review was undertaken to investigate how reservoirs are classified in terms of sedimentation in other parts of the world. The review was unable to yield any classification system covering both reservoir characteristics and catchment sediment yield delivery. The factors typically considered in siltation studies are:

- Catchment/Reservoir area (Brown);
- Capacity Inflow Ratio (Brune);
- Nature of Sediment (Fine/Coarse) ;
- Lake/Floodplain/Foothill/Gorge (Types I-IV) (USBR);
- Land Use and Catchment Sediment Yield;
- Reservoir Management.

These factors are taken into account in the development of the proposed classification system for British reservoirs described below.

In comparison with sedimentation studies in other countries, a large proportion of the British reservoir stock comprises small reservoirs (<100,000 m^3) and the bulk of reservoirs have capacities less than 1 million m^3 as shown in Figure 4.1. Correspondingly, catchment sizes are also small with most being less than 25 km^2 (Figure 4.2). In Scotland there are a proportionately greater number of larger reservoirs reflecting the geography of that area (see also Figure 3.1 showing the greater storage volume in Scotland).

There are a number of important chains of reservoirs with complex arrangements of bypass channels and sediment traps (residuum lodges) in Yorkshire, the North West and Northumbria. In Wales there are also a number of significant upland reservoirs and chains of reservoirs supplying major urban centres. In the Thames and Anglian region there is a large dependence on bunded reservoirs with pumped inflows.

4.2 Data available for British reservoirs

As part of this study an up to date database has been established which incorporates all of the available evidence to date on rates of reservoir sedimentation in England, Wales and Scotland. This database was initially based upon the information in the BRE dams database (Tedd et al, 1992) and was supplemented with information derived from published literature sources, from unpublished research by Butcher and Labadz and others, and responses received from various reservoir undertakers.

The BRE dams database contains over 2500 reservoirs but information on sedimentation is available for very few of these. Where water companies did respond to the request for information it was most frequently to supply details of rainfall, land use and catchment areas of reservoir gathering grounds.

Tables 4.1 and 4.2 below indicate the variables included in the new database and the range of information obtained. Where available, other details have also been included to describe any factor which may influence the rate of sedimentation in a particular reservoir. This may include knowledge that there is another reservoir basin upstream, existence of any structure for managing sediment movement such as a bywash channel, or that there has been removal of sediment from the basin in the past.

In many cases the rates of sedimentation calculated are dependent upon the accuracy not only of a recent survey but also of the original survey at the time of dam construction and on comparability between two surveys. White et al (1996) have discussed some of the difficulties of this approach. Some of the information (such as that from He et al, 1996) uses isotope dating of sediments rather than direct volumetric differences between two surveys. This may be a preferable approach if a detailed study is undertaken and the sediments are relatively undisturbed but it has its own attendant difficulties, particularly if the number of sediment cores is limited and values obtained may therefore not be representative of the entire reservoir.

The following variables regarding the reservoirs and rates of sedimentation were defined:

Table 4.1 Variables used in reservoirs database

BRECAP	capacity of reservoir in BRE database (Ml)
DATEORIG	date of construction
ORIGCAP	original capacity (Ml)
DATEREV	date of revised capacity
REVCAP	revised capacity (Ml)
SAREA	surface area of reservoir (m^2 x 10^3)
HEIGHT	height of dam (m)
LENGTH	length of dam (m)
CATCHMNT	catchment area (km^2)
INDIRECT	indirect catchment area (km^2)
CARATIO	capacity:catchment ratio ($Ml.km^{-2}$)
RAIN	annual average rainfall (mm)
M3YEAR	capacity loss ($m^3.yr^{-1}$)
M3KM2YR	capacity loss ($m^3.km^{-2}.yr^{-1}$.)
ANNPERC	annual loss of capacity (% of original)
MEANDBD	mean dry bulk density of sediment ($t.m^{-3}$)
SY	sediment yield to reservoir ($t.km^{-2}.\ yr^{-1}$)
RISKCAT	sedimentation susceptibility category (definition follows)

The table below summarises the extent of the information available for reservoirs in the study database which have at least some direct catchment area (i.e. excluding service reservoirs and those entirely used for pumped storage).

Table 4.2 Descriptive statistics for British Reservoirs

Variable	Mean	Std Dev	Minimum	Maximum	No of cases	Median
BRECAP	8115.02	31907.63	25.00	382800.0	524	718.5
DATEORIG	1896.73	55.76	1725.00	1993.00	528	1901
ORIGCAP	3007.96	11259.61	.00	121020.0	209	551
DATEREV	1989.30	5.38	1967.00	2000.00	161	1990
REVCAP	3037.47	10454.03	8.20	116580.0	163	722.69
SAREA	1056.46	4207.72	2.00	74677.00	510	165.5
HEIGHT	16.17	12.99	.60	91.00	519	13.0
LENGTH	367.95	413.54	2.00	4420.00	419	266.0
CATCHMNT	33.42	124.96	.00	1810.00	473	4.69
INDIRECT	32.61	107.21	.00	989.81	209	1.78
CARATIO	579.72	3727.51	3.00	48286.00	177	183.0
RAIN	1114.81	408.64	450.00	2500.00	316	1003
M3YEAR	4530.98	18694.44	.00	185000.0	124	606.0
M3KM2YR	366.76	1021.10	.00	9339.50	100	139.1
ANNPERC	.13	.16	.00	1.01	123	.088
MEANDBD	.45	.19	.05	.93	75	.435
SY	84.29	78.36	3.69	389.11	107	48.11

It can be seen that the information available is relatively sparse - 163 reservoirs actually have revised capacities available, the majority of which were surveyed by Butcher and Labadz (see White, Labadz and Butcher, 1996 etc) for either Yorkshire Water or North West Water. Other clusters of reservoirs have been surveyed by Duck and McManus (1985, 1990 etc) for various water undertakings in Scotland, and by Foster and Lees (1999) as part of the NERC LOIS project. The remaining information is mostly for single reservoirs which have been the subject of an individual research project, or where sedimentation was of particular concern to the undertaker.

From the available data it has been possible to determine the gross rates of infilling ($m^3.yr^{-1}$) for 124 reservoirs and sediment yields per unit catchment area ($t.km^{-2}.yr^{-1}$) for 107 reservoirs. The mean sediment yield to British reservoirs for which information is currently available (107 reservoirs) is 84 $t. km^{-2}.yr^{-1}$.

The average loss of capacity from British reservoirs is perhaps best expressed by the annual percentage loss. The mean value here, derived from 123 reservoirs, equates to a loss of 13% of original capacity per century. As has been previously noted, this is a relatively low value compared to losses experienced elsewhere in the world but it may be of increasing significance as water resources in Britain come under increasing pressure.

The volumetric measure of capacity loss has a mean value of 4531 $m^3.yr^{-1}$ and a median of 600 $m^3.yr^{-1}$ but the distribution is very skewed. A more meaningful parameter is the volumetric measure of capacity loss per unit catchment area. This is also skewed, the mean of 366.76 $m^3.km^{-2}.yr^{-1}$ being less "typical" than the median value of 139 $m^3.km^{-2}.yr^{-1}$.

The median value for sediment yield for a sample of 107 British reservoirs of 48 $t.km^{-2}.yr^{-1}$ is close to the value proposed as typical for sediment yields from British catchments by Walling and Webb (1981). The mean sediment yield obtained is 84 $t.km^{-2}.yr^{-1}$, but with a standard deviation approximately equivalent to this value (78 $t.km^{-2}.yr^{-1}$) which again indicates a great deal of variability amongst the group.

4.3 Classification of British Reservoirs

4.3.1 Proposed classification system

Given the wide range of sediment yield rates assembled in the database, it was considered instructive to try to divide the information according to anything known about the land use of each catchment and the presence or absence of structures controlling sediment transport into the reservoir. The full results of this preliminary classification are given in Table B1, Appendix B and are summarised in Table 4.3 below.

Table 4.3 Sedimentation rates observed in British Lakes and Reservoirs

Land use	Impounding reservoirs	
	WITH sediment control or upstream reservoir ($t.km^{-2}.yr^{-1}$)	WITHOUT sediment control or upstream reservoir ($t.km^{-2}.yr^{-1}$)
Lowland pasture		Minimum = 8.0 Maximum = 141.3 Median = 29.3 Mean = 44.5
Mixed arable, channels <1:1000		Minimum = 6.4 Maximum = 16.0 Median = 11.2 Mean = 11.2
Upland less erodible soils or established forest		Minimum = 7.0 Maximum = 28.5 Median = 12.5 Mean = 15.4
Lowland intensive agriculture or upland poor vegetation	One case 72.3 $t.km^{-2}.yr^{-1}$	Minimum = 3.9 Maximum = 93.0 Median = 39.0 Mean = 36.8
Upland peat / Moorland	Typical rate of 80 $t.km^{-2}.yr^{-1}$ from survey of 77 reservoirs	Minimum = 35.7 Maximum = 212.7 Median = 167.0 Mean = 148.0

There is a general trend of increasing sedimentation rate with land use category down the table as would be expected but it must be noted that individual reservoirs sometimes produce anomalous results which bias the mean values for a category group.

For example, Chew Valley Reservoir (Bristol Water) seems to have a relatively high sedimentation rate given that its catchment is described as “mainly grass covered farmland”, which would be expected to have a low value. It may well be that the sediment yield here would be of the order of 100-150 $t.km^{-2}.yr^{-1}$, assuming that the dry bulk densities of the sediment are close to the average for the entire data set.

Further investigation of the individual situation would be necessary in order to understand the relatively high sedimentation rate experienced.

Rates for Stourton Lake (Somerset) and Wadhurst Park(Kent) given by He et al (1996) are also higher than were generally expected for lowland pasture, although the precise nature of the land use in these catchments is not clear from the paper. It may be that relatively steep slopes or soil types are conducive to catchment erosion in these cases.

The largest number of individual previous studies can be categorised as concerning reservoirs at "medium susceptibility" to sedimentation, by virtue of their being set within catchments dominated either by lowland intensive agriculture or by poor vegetation in the uplands. The mean value for the 23 studies listed here is 37.7 $t.km^{-2}.yr^{-1}$ with a standard deviation of around 20 $t.km^{-2}.yr^{-1}$. It is suggested that this average figure is a good "first approximation" for reservoirs in these types of catchments.

The final land use class in the table is for those reservoirs set in upland peat moorlands. The majority of data here derive from studies by Butcher and Labadz (White et al, 1996, Labadz et al , 1991 and 1995 etc) in the southern Pennines or from the work of Duck and McManus (1990, 1994) in Scotland. These are two areas where a perception of abundant rainfall on the hills led to development of water supply reservoirs in the 19th century to support industrial and urban developments further down valley. In Scotland there has also been development of reservoirs for hydroelectric power generation. In both cases, sediment yields in excess of 100 $t. km^{-2}.yr^{-1}$ are commonly experienced.

It must be noted that these rates are particularly important because the dry bulk densities of peat sediments can be very low, giving rapid capacity loss in volumetric terms. For example, the authors found that Wessenden Old Reservoir contains sediment at least 7 m deep (Labadz et al, 1991) and both Strines and March Haigh reservoirs have been rodded and shown to hold at least 4 m of sediment in places (White et al, 1997). Direct measurement of sediment depths at most other sites has been hampered by the inundation of the basin, with samples from corers only including the top metre of deposit.

The impact of sediment control structures upon the measured rates of sedimentation is summarised in the Table B1, Appendix B, and is discussed in more detail by Labadz et al (1995) and White et al (1996). Residuum lodges and bywash channels do seem to be effective measures for reducing sedimentation, but variance within the samples was high. These measures were often deployed in situations where the original engineers anticipated very high sedimentation rates, meaning that direct comparison with other reservoirs lacking such structures may not be strictly appropriate.

The combined effect of relative sediment delivery and reservoir retention characteristics is illustrated in Table 4.4a below. The susceptibility of a reservoir to sedimentation is governed by its position in the table. The definitions of the resulting nine ‘susceptibility categories’ are given in Table 4.4b.

The column on the left-hand side of Table 4.4a represents the total sediment delivery of the contributing watercourse multiplied by the trap efficiency of the reservoir. Both the rate of sediment delivery to a reservoir and the efficiency of the reservoir in trapping the sediment will vary over the lifetime of the reservoir. Hence a reservoir might start its life in Category 9 and finish its life in Category 3. Changes in catchment land use or management might also influence changes in reservoir category with time.

Reservoir types are represented across the columns of Table 4.4a. The first column represents reservoirs with pumped inflows where the sediment delivery will generally be restricted to suspended sediments and where the inflow can be controlled. These might be impounding reservoirs but are more likely to be represented by off-line, fully-bunded reservoirs. The design of the intake will normally prevent the bedload sediment from being transferred but high suspended sediment loads during flood events would impact on the receiving reservoir. Reservoirs falling into Category 7 are considered to be too rare in Britain to justify full inclusion in the classification.

The final two columns generally cover impounding reservoirs where, unless artificial controls are put in place, all of the bedload and suspended load enter the reservoir without restriction. Approximately 80% of all large-raised British reservoirs falling within the ambit of the Reservoirs Act 1975 are impounding reservoirs.

Table 4.4a Classification of reservoir susceptibility to sedimentation

Relative sediment delivery		Off-line reservoir with pumped inflows	Impounding reservoir with reservoir(s) upstream or other management practise	Impounding reservoir with no reservoir upstream or other management practise
	Low	Category 1	Category 2	Category 3
	Medium	Category 4	Category 5	Category 6
	High	Category 7	Category 8	Category 9

Increasing susceptibility to sedimentation

Table 4.4b Definition of susceptibility categories

Category	Description
1	Lowland pasture/mixed agriculture, predominantly pumped storage
2	Lowland pasture/mixed agriculture, some sediment control or reservoir upstream
3	Lowland pasture/mixed agriculture, no sediment control or reservoir upstream
4	Upland less erodible/lowland intensive agriculture, predominantly pumped storage
5	Upland less erodible/lowland intensive agriculture, some sediment control or reservoir upstream
6	Upland less erodible/lowland intensive agriculture, no sediment control or reservoir upstream
7	Upland peat/moorland, predominantly pumped storage
8	Upland peat/moorland, some sediment control or reservoir upstream
9	Upland peat/moorland, no sediment control or reservoir upstream

In general, reservoirs with one or more upstream reservoirs will clearly be less susceptible to sedimentation as much of the natural sediment delivery is normally intercepted. However, there are exceptions such as Tunnel End reservoir in Yorkshire that is completely filled with sediment despite having much of its catchment area draining through upstream reservoirs. Such a reservoir would have originally fallen into Category 8. Where an impounding reservoir includes the use of a bywash channel, this will have a similar effect to those with upstream reservoirs and such reservoirs would normally fall within the second column of Table 4.4a.

4.3.2 Testing of proposed classification system

The broad classification method proposed above was tested using the reservoirs in the study database for which sufficient information existed. Table 4.5 below indicates the various measures of sedimentation rate by susceptibility category for these reservoirs.

Table 4.5 Observed sedimentation rates in British reservoirs by susceptibility category:

SUSCEPTIBILITY CATEGORY	**No. of reservoirs identifiable in category**	**Mean Sedimentation ($m^3.yr^{-1}$)**	**Mean sedimentation ($m^3.km^2.yr^{-1}$)**	**Mean Sedimentation ($t.km^2.yr^{-1}$)**	**Mean loss (annual % of original capacity)**
1	2	3195.2 (2)	120.7 (1)	-	.04 (1)
2	0	-	-	-	-
3	7	1369 (1)	14.7 (1)	25.72 (7)	.33 (1)
4	7	37843.67 (3)	4962.65 (2)	-	.1 (4)
5	16	814.02 (9)	161.59 (7)	35.6 (5)	.06 (9)
6	45	1102.9 (24)	87.63 (25)	31.86 (27)	.08 (22)
7	0	-	-	-	-
8	37	2893.78 (26)	235.13 (15)	92.66 (21)	.1 (27)
9	60	1866.71 (39)	325.02 (33)	132.89 (36)	.39 (39)
Significance of F for main effect in analysis of variance		.000	.000	.000	.174

The figures in brackets indicate the number of reservoirs for which data are available on a particular variable where this is less than the total for that category.

The analysis of variance between the susceptibility categories suggests that significant differences exist between data for the defined groups and thus that the categorisation suggested is a valid method for dividing susceptibility.

It is recognised that many reservoirs will not fall neatly into one particular category. In these cases, it is necessary to consider the dominant influences affecting the sediment delivery and retention. One of the aims of this research is to attempt to quantify and verify, as far as possible, deposition rates distinguishing the categories defined.

It can be seen that not all the measures of sedimentation were available for each reservoir, since the data depend upon the methods used and the source of the information. The analysis of variance is significant for the first three measures of sedimentation rate, but it must be noted that the highly variable number of cases in each category (including at least two empty categories) makes this result less meaningful than might otherwise be the case.

Figure 4.3 shows the actual sedimentation yield rates against the assigned reservoir susceptibility category for the available data set. It can be seen that although there is generally an increase in mean sedimentation rate with susceptibility category there is still significant variation in actual rates for each susceptibility category. This variation reflects the relatively broad classes of susceptibility category defined, the importance of detailed local factors, possible errors in the measurement and the typically wide bands of variation in sediment supply and transport found in the field. It would seem that the data available suggest a “first approximation” for sedimentation rates, but that more detailed work would be needed to predict the sediment yield rate in a particular reservoir with any degree of accuracy.

4.3.3 Sediment yield table

Table 4.6 below summarises the nine susceptibility categories defined and the corresponding indicative reservoir sediment yield rates suggested by the available data for British reservoirs. The sedimentation rates in pumped storage reservoirs will clearly depend on the relative quantity of water abstracted from the river. This will vary from case to case and thus only nominal rates are indicated for categories 1 and 4.

Table 4.6 Sediment yield table

Susceptibility Category	Reservoir/Catchment Description	Typical range of sediment yield rates in Category (t/km²/year)	Indicative Category sediment yield rate (t/km²/year)
1	Lowland pasture/mixed agriculture, predominantly pumped storage	0 – 10	5
2	Lowland pasture/mixed agriculture, some sediment control or reservoir upstream	0 – 25	15
3	Lowland pasture/mixed agriculture, no sediment control or reservoir upstream	10 – 30	25
4	Upland less erodible/lowland intensive agriculture, predominantly pumped storage	10 – 25	10
5	Upland less erodible/lowland intensive agriculture, some sediment control or reservoir upstream	25 – 75	35
6	Upland less erodible/lowland intensive agriculture, no sediment control or reservoir upstream	25 – 100	35
7	Upland peat/moorland, predominantly pumped storage	N/A	N/A
8	Upland peat/moorland, some sediment control or reservoir upstream	50 – 200	100
9	Upland peat/moorland, no sediment control or reservoir upstream	50 – 300	135

4.4 *Regression analysis of sedimentation rates*

Prior to attempting any prediction of sedimentation rates for “unknown” sites it was important to establish whether any of the available variables has a strong relationship with sedimentation rates for the “known” reservoirs. Statistical analysis was undertaken using SPSS software. Correlation coefficients between the variables tested from Table 4.1 are presented in Table B2, Appendix B.

Correlations significant at the 5% level or better have been highlighted in bold face. It can be seen that each of the predictive variables has a significant relationship with at least one of the measures of sedimentation rate, but that RAIN is the only variable with four significant relationships. It would traditionally be expected that high annual rainfall would be associated with greater catchment erosion and therefore with greater supply of sediment to the reservoir. Here, however, the correlations are all relatively weak and in fact the two volumetric measures ($m^3.yr^{-1}$ and $m^3.km^{-2}.yr^{-1}$) actually seem to decrease as rainfall increases. One issue is that rainfall intensity rather than total may be important for detachment of soil particles (Morgan, 1995), but such information is not included in the database at present.

The highest individual correlations are those between capacity:catchment ratio and annual volumetric loss per unit catchment area (0.6949, significant at 0%) and between dam length and annual volumetric loss per unit catchment area (0.5947, significant at 0%). The capacity:catchment ratio was significantly related with three of the four measures of sedimentation. This is thought to be an indicator of the trap efficiency of the reservoir basin (Brown, 1944).

Simple regression models were produced as a first step towards more detailed prediction of sedimentation rates for reservoirs where no measurements are available.

Linear regression and curve fitting of various types were applied to the measures of sedimentation in order to find the best predictive equations possible using only a single independent variable at any one time. Results are presented in Table B3, Appendix B.

None of these relationships is particularly satisfactory, although those highlighted in bold face demonstrate some predictive ability.

Using the information in the database, stepwise regressions were then requested using independent variables to produce multivariate relationships using:

a) *physical features of the reservoir* - date of origin, original capacity, surface area, length and height of the dam;

b) *catchment inputs* - average annual rainfall and catchment area;

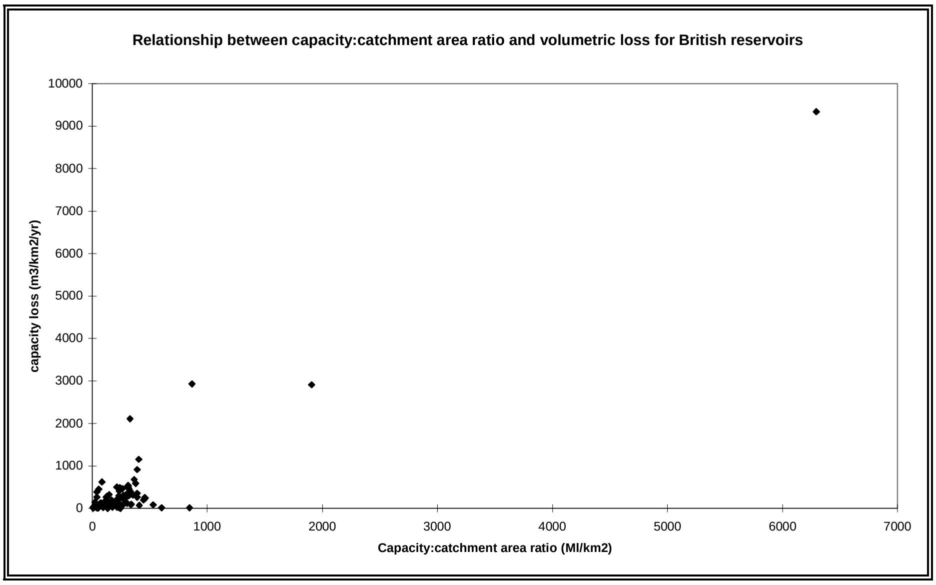
c) *relationship between reservoir and catchment* - capacity to catchment area ratio.

These variables were selected on the basis of likely supply of sediment and the physical behaviour of the incoming sediment, such that a greater reduction in velocity will encourage more efficient settling and deposition (Mahmood, 1987). They were also selected as being those variables for which most information was available in practice. Brown (1944) used the ratio of capacity to catchment area as an empirical predictor of reservoir trap efficiency, and these data are more widely available than those for Brune's (1953) capacity:inflow ratio. Other variables such as land use, altitude and presence of sediment structures would have been informative but would have reduced the sample here to a very small size and so were not included.

The regression for the annual volumetric sedimentation rate per unit catchment area ($m^3.km^{-2}.yr^{-1}$) uses the capacity:catchment area ratio as the only significant independent variable. Results are shown in the graph below and in Table B4, Appendix B.

The coefficient of determination (R^2) is 89%, suggesting a very good fit. However, this regression has only 52 degrees of freedom (because other reservoirs have incomplete data for the selected variables) and inspection of the chart indicates that two reservoirs are having an undue influence on the relationship. These are Diddington (Grafham Water) and Empingham (Rutland Water) reservoirs, both operated by Anglian Water and reported to have very high rates of volumetric loss relative to the size of their direct catchment areas. It is not entirely clear, however, whether these are really the result of sedimentation or whether differences in survey details might be contributory to some extent (Eastern Hydrology Ltd, 1998). Further, the likely sediment inputs from a pumped supply to the reservoirs are not taken into account in the catchment:capacity ratio. If these two reservoirs are omitted from the data the coefficient of determination (R^2) falls to 0.22.

Graph to illustrate relationship between capacity:catchment area ratio and annual volumetric sedimentation per unit catchment area for British Reservoirs:



A similar regression was produced for annual percentage loss of capacity. This time the variables selected as most informative were surface area, original capacity and rainfall. The information for the third step of this model is included in Table B5, Appendix B.

It can be seen that the rate of capacity loss is predicted with coefficient of determination 44% and 62 degrees of freedom. Whilst far from ideal, this may offer some potential for estimation of capacity loss in other British reservoirs since the variables included are readily available.

Results of the regression for sediment yield are presented in Table B6, Appendix B. It can be seen that the two variables entered into this equation are rainfall and the height of the dam (perhaps a measure of trap efficiency of the basin). The coefficient of determination, however, is poor at 21%. Closer inspection also reveals that this equation also has only 52 degrees of freedom. Many of the reservoirs have been omitted from the analysis because they are missing data for at least one variable.

If the exercise to predict sediment yield is repeated using only RAIN and HEIGHT as independents, the coefficient of determination obtained is still only 21% although the degrees of freedom have now increased to 66.

In summary, the following variables have been shown to be of some significance in predicting sedimentation in British reservoirs:

DATEORIG	**date of construction**
ORIGCAP	**original capacity (Ml)**
REVCAP	**revised capacity (Ml)**
SAREA	**surface area of reservoir (m^2 x 10^3)**
HEIGHT	**height of dam (m)**
LENGTH	**length of dam (m)**
CATCHMNT	**catchment area (km^2)**
CARATIO	**capacity:catchment ratio (Ml.km^{-2})**
RAIN	**annual average rainfall (mm)**
RISKCAT	**sedimentation susceptibility category based on land use and sediment control structures (as definition previously)**

Some of these parameters are clearly related and add little as additional variables in a prediction technique, for example a measure of capacity effect is given in five of the variables and not all could be justified for use in a prediction method.

4.5 Calculation method for reservoir sedimentation rates

The multiple regression analyses carried out shows that there are no overwhelming correlations between sediment yield or capacity loss and the descriptive parameters identified above based on the current data set. This data set represents the majority of available information for British reservoirs.

A simpler method to provide a first hand estimate of the likely loss in capacity to sedimentation on a rational basis based on the classification method presented above was therefore sought.

For the British reservoir sites the effect of catchment size and rainfall is relatively weak and masked by the effects of soil types and land use and thus a simple predictor of sediment yield at the site can be used based on the sediment susceptibility category. The proportion of this sediment actually deposited within the reservoir must be amended using the calculated trapping efficiency and the percentage loss in volumetric capacity of a reservoir can then be calculated as follows:

$$ANNPERC = \left(\frac{SY * CATCHMNT \ * \ TRAP}{MEANDBD \ *.\left(1000 * ORIGCAP\right)} \right)$$

Equation 1

where the variables are as defined in Table 4.1, i.e.

	ANNPERC	= annual loss of capacity (%/year)
	SY	= sediment yield to reservoir (t/km^2/year)
	CATCHMNT	= catchment area (km^2)
	MEANDBD	= mean dry bulk density of sediment (t/m^3)
	ORIGCAP	= original reservoir capacity (Ml)
and	TRAP	= reservoir trapping efficiency (%)

The trapping efficiency of a reservoir may be determined from an empirical relationship and the reservoir characteristics. Brown's (1958) trap efficiency curves relate trapping efficiency to the ratio of reservoir storage capacity to catchment area. The ratio of storage capacity to catchment area for the current data, with the exception of a few cases, exceeds the range where Brown's curves suggest that trapping efficiency is less than 100%. A comparison with Brune's (1953) trap efficiency curves, which relate trapping efficiency to the ratio of storage capacity to mean annual inflow, also suggests that most of the reservoirs in the data set lie in the range where trapping efficiency is close to 100%.

The catchment area and original reservoir capacity should be readily available for most reservoirs. The principal unknown variables in the above expression are therefore the sediment yield and the mean dry bulk density.

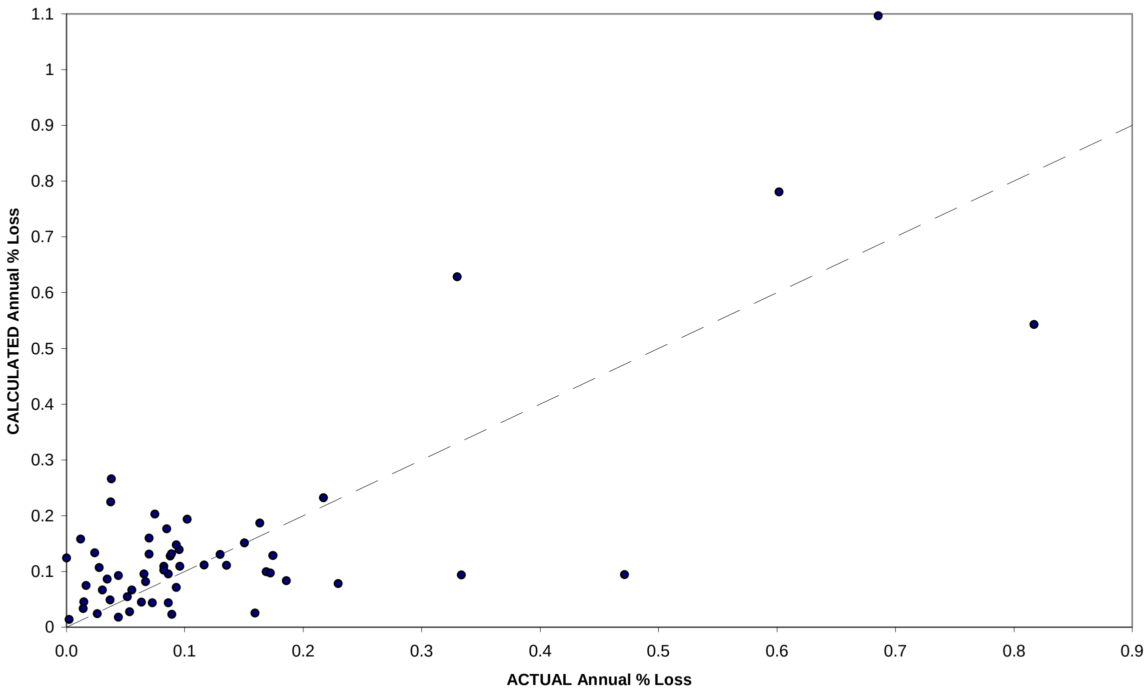
The sediment yield for a given type of reservoir and catchment can be estimated from the tables of sedimentation susceptibility category and indicative sedimentation rates proposed in Section 4.3 (see Table 4.6).

The other significant factor in estimating capacity loss due to sedimentation is the dry bulk density of the sediment. Figure 4.4 shows the actual mean dry bulk density against reservoir susceptibility category for the same data set. It can be seen that there is significant variation in the recorded densities for each class. The minimum density of the sample is 0.05 t/m^3, the maximum density is 0.93 t/m^3, the mean density is 0.45 t/m^3 and the median density is 0.44 t/m^3. These bulk densities are lower than would be expected from values given in textbooks (for example Morris & Fan 1998) which suggest a range of 1.04 to 1.36 t/m3 for silt-clay mixtures that are aerated (i.e. the reservoir is periodically drawn down) or 0.64t/m3-1.04t/m3 where sediment is always submerged. Allowances for compaction of the sediment with time also appear inappropriate for a simple predictor although there is clearly an increase in bulk density with time as shown by the core samples obtained in this study (see data for Reservoir A in Section 5.5).

When looking at specific sites, the mean dry bulk density of the sediment in a reservoir will generally be an unknown but very important factor in the prediction of loss of reservoir volume.

4.6 Testing of the proposed calculation method for reservoir sedimentation rates

The chart below shows the results of calculating the annual percentage loss in capacity using Equation 1 as compared to the actual loss rates for reservoirs in the current data set. The sediment yield rates for each reservoir have been determined from the indicative values in Table 4.6 and a mean dry bulk density of 0.45 t/m^3 has been assumed in each case.



The use of measured dry density in each case was also tested but this had a negligible impact on the performance of the predictor. Trapping efficiency has been determined through use of Brown's curves which results in an efficiency of 100% for all but two cases, Thoresby Lake (Upper) and Abbeystead for which the estimated trapping efficiencies are 50% and 80% respectively.

It can be seen that Equation 1 provides a reasonable estimate of the annual percentage capacity loss for the current limited data set. There is a significant amount of scatter which is mostly attributable to uncertainty in the estimated sediment yield rate deduced from Table 4.6. The coefficient of determination is 59%. Use of the actual mean dry bulk density instead of the assumed value of 0.45 t/m^3 makes very little difference to the coefficient of determination.

4.7 Example applications of the prediction method

Equation 1 may also be used to estimate the actual volumetric loss in capacity of a reservoir as follows:

$$\text{Volumetric loss in capacity} = \left(\frac{\text{SY} * \text{CATCHMNT}}{\text{MEANDBD}}\right) * \text{TIME} * \left(\frac{\text{TRAP}}{100}\right)$$

Equation 2

where TIME is the required time period in years and loss in capacity is determined in cubic metres.

The loss in capacity for the two reservoirs surveyed in Section 5, Reservoirs A and B, together with two larger reservoirs from the current data set, Angram and Walshaw Dean Upper, both in Yorkshire were estimated from the above equation as follows:

	Reservoir A	Reservoir B	Angram Reservoir	Walshaw Dean Upper Reservoir
Susceptibility Category	3	9	8	9
SY (from Table 4.6)	25 $t/km^2/yr$	135 $t/km^2/yr$	100 $t/km^2/yr$	135 $t/km^2/yr$
CATCHMNT	5.4 km^2	0.1 km^2	14.65 km^2	4.57 km^2
MEANDBD	0.25 t/m^3	0.20 t/m^3	0.45 t/m^3	0.57 t/m^3
TIME	60 years	67 years	78 years	82 years
TRAP	50%	100%	100%	100%
Original Capacity	36,500m^3	39,100m^3	4,738,000m^3	932,000m^3
Calculated loss in storage	16,200 m^3	4,500 m^3	253,900 m^3	88,800 m^3
Actual loss in storage	13,000 m^3	10,800 m^3	98,650 m^3	69,900 m^3

The calculated loss in storage for Reservoir A has been based on the period since 1940 when it is known that the reservoir was de-silted. A flood storage reservoir was constructed approximately 1.5 km upstream of the reservoir in the early 1970's. This would be expected to reduce the sediment yield as the reservoir changes from category 3 to category 2. Repeating the calculation to take account of this change in category gives very good agreement between the predicted loss in capacity (12,900 m^3) and the actual loss (13,000 m^3).

The calculated loss in storage for Reservoir B, which has been calculated for the entire period since construction, is low as compared to the actual loss in storage. This is probably due to the catchment size (as recorded by the undertaker) being underestimated. The figure represents the direct catchment only with no indirect catchment area recorded. If a similar size of indirect catchment is assumed, the calculated loss in storage is 9,000 m^3 which agrees well with the actual loss of 10,800 m^3.

In both cases the measured sediment densities were used since these were readily available. The calculated values of capacity loss are rather sensitive to the value of dry density. Assuming the nominal value of 0.45 t/m^3 suggested in Section 4.5 would have resulted in roughly a 50% reduction in calculated losses.

The example calculation for Angram Reservoir uses the nominal value of dry bulk density since no data is available for this reservoir. The calculated loss in storage is more than double the actual loss in storage. This reservoir is classified as susceptibility category 8, i.e. an upland peat or moorland catchment with some sediment control or reservoirs upstream.

As indicated in Table 4.6, there is potentially a large range of sediment yield rates for this susceptibility category which will depend, at least in part, on the exact nature and efficiency of the sediment exclusion measures at a specific reservoir. Use of the lower bound of the yield rates for this category (50 $t/km^2/yr$) would result in a better estimate (127,000 m^3) for this reservoir. Further work to sub-divide this category according to types of control measures could improve the accuracy of the prediction method for this category of reservoir.

The calculation for Walshaw Dean Upper Reservoir, using the measured mean bulk dry density of the sediment, provides a reasonable estimate of the loss in capacity – 88,800 m^3 as compared to the actual loss of 69,900 m^3.

4.8 Conclusions on use of prediction method for reservoir sedimentation in Britain

The values of sediment yield for each susceptibility category in Table 4.6 have been determined from a limited sample of reservoir data. In particular, the values of yield for the low susceptibility categories (categories 1 to 3) may have been unduly influenced by the classification of reservoirs such as Chew Valley which have unusually high yield rates for their current classification.

Nevertheless, the methods detailed above permit a reasonable first estimate of the loss in capacity to be expected in British reservoirs. Further work should concentrate on refining the methods for estimating the catchment sediment yield and seeking a method for estimating the mean dry bulk density of sediment in a reservoir based on catchment characteristics. Further work on pumped reservoirs would also be desirable, to include perhaps a measure of volume pumped as compared with the volume of runoff in the river catchment.

5 Field studies and sediment analysis

5.1 Introduction

Field studies at selected reservoirs were undertaken with the purpose of carrying out bathymetric surveys of the bed of the reservoir and taking undisturbed samples of the deposited sediments in the reservoirs. Field testing of sediments in-situ was also attempted. The bathymetric surveys provided information on the current storage capacities of the reservoirs as well as the geometrical data necessary for creating hydraulic models of the reservoirs to study the effects of dam failure on the accumulated sediment. The analysis of sediment samples taken from the reservoirs provided information on the properties of sediments in British reservoirs including those necessary to analyse the likely movement of the sediments under dam failure.

5.2 Selection of test reservoirs

Of the 2,365 dams currently on the BRE database for which a storage capacity is given, 244 dams (over 10%) have a capacity in the range of 25,000 to 35,000 m^3. This range in capacity is likely to represent the size of reservoir for which the question of sediment release under dam failure may influence the treatment of the reservoir under The Reservoirs Act (1975). Further discussion of the provisions of the Reservoirs Act are given in Section 6. Of these 244 dams, interrogation of the database reveals that:

- 66% are earthfill embankment dams
- 19% are service reservoirs
- 5% are various concrete dams
- 10% are of unknown type

Given that service reservoirs store only treated water and do not have a significant propensity to sedimentation, it is clear that earth embankment dams form the bulk of the dams for which the question of sediment release in failure might be relevant.

Two reservoirs featuring earth embankment dams and a capacity close to 25,000 m^3 were therefore selected for field studies and dam failure modelling.

These were:

- ‘Reservoir A’ – a lowland reservoir in Oxfordshire (see Plates 1 to 3).
- ‘Reservoir B’ – an upland reservoir in a peat catchment in the Pennines (see Plate 4).

To supplement the data for reservoirs with peat catchment areas, a third reservoir, Redbrook near Huddersfield (‘Reservoir C’), was also surveyed and sediment core samples taken. This reservoir is much larger than the other reservoirs (206,000 m^3) but is in a similar catchment type to Reservoir B thus giving some indication of the effect of reservoir size on the deposition characteristics for a given catchment type. Dam failure modelling of Redbrook reservoir was not carried out since the potential release of sediment is not significant in considering the classification of this reservoir.

5.3 Bathymetric surveys

Bathymetric surveys were conducted at each of the three reservoirs. These surveys provided information on the current storage capacities of the reservoirs as well as the geometrical information necessary for the mathematical modelling of dam failure scenarios for Reservoirs A and B.

The surveys were carried out using digital echo sounding equipment from a small boat. Post-processing of the data at Reservoir A enabled the depth to both the top and bottom of the deposited sediment layer to be determined. The echo sounding data was supplemented by manual probing to the level of the top of the bed and the bottom of the sediment layer. The results were generally in good agreement with the echo sounding data.

At Reservoirs B and C, which are both deeper than Reservoir A, it was only possible to determine the depth to the top of the deposited sediment layer from the echo sounding data. For all reservoirs depth measurements were taken on a grid spacing of approximately 10m intervals.

Drawings of the three reservoirs showing contours of depth below water level were prepared and are included in Appendix A (Figures A1.1, A2.1 and A3.1).

Depth-storage curves were deduced from the survey data for each reservoir as shown in Figures 5.1, 5.2 and 5.3.

For Reservoir A, Figure 5.1, separate curves for the volume of water stored (taken from the top of sediment layer contours) and the total volume of water and sediment stored (taken from the bottom of sediment layer contours) were deduced. It can be seen that the total volume of water stored is approximately 23,500 m^3 whereas the total volume of water and sediment stored is approximately 36,500 m^3.

For Reservoir B, Figure 5.2, it was possible to compare the depth-storage curve deduced from the current survey with a previous reservoir inspection survey carried out in 1981 and the original design drawings for the reservoir dated 1933. This indicates a 20% loss in storage from 39,100 m^3 in 1933 to 31,200 m^3 in 1981 and a further reduction in storage volume of 2,900 m^3 between 1981 and 2000, resulting in a total loss of 28% of original storage volume to date. The surveys suggest that the total volume of accumulated sediment in the reservoir is approximately 10,800 m^3.

Given that the current stored water volume is approximately 28,300 m^3, the issue of sediment release under dam failure is less important in terms of the current classification of this reservoir. However, given the rate of sedimentation observed in this reservoir, the water storage volume may fall below 25,000 m^3 within 25 years when the question of sediment release and reservoir classification may become an issue.

5.4 Sediment sampling

Field and laboratory testing of the sediment deposited in the three selected reservoirs was undertaken to determine their physical properties. The aim of this work was to provide information on the nature of sediments deposited in British reservoirs and to assign appropriate values of critical shear stress for analysing the potential for sediment release during dam failures.

Hand shear vane tests were attempted in the course of the survey at Reservoir A but the results were unsatisfactory due the influence of weed on the bottom of the reservoir and the highly fluid nature of the upper layer of the deposited sediment. All of the other tests, including a laboratory shear vane test, were carried out in the laboratory on sediment samples extracted from the beds of the three reservoirs.

Sediment samples were taken from the reservoirs using a submersible Makareth soil sampler. This equipment can be used from a small boat and comprises a Perspex sampler tube that is set vertically on the floor of the reservoir and then pneumatically thrust into the sediment and then withdrawn. The equipment is shown in use during the survey at Reservoir A in Plates 1, 2 and 3.

The number of Makareth samples taken were as follows:

- Reservoir A - 7 cores.
- Reservoir B - 4 cores, of which 2 cores were able to provide an adequate sediment sample.
- Reservoir C - 3 cores

The locations at which the core samples were taken are indicated on the reservoir survey drawings in Appendix A.

The samples were transported to the laboratory within the Perspex tubes. Once at the laboratory, the core samples were slowly extruded from the sampling tubes and a shear vane test was carried out at vertical intervals of 50mm. Following the shear vane test, the sediment sample representing the 50mm depth was used for the physical tests which included tests of moisture content, Atterburg Limits, bulk density, particle size distribution and loss on ignition. Hence the variation in these parameters with sediment depth was attained for each tube sample.

5.5 Results of laboratory analysis of sediment samples

Information on the physical properties of sediment deposited in British reservoirs is very scarce in the current literature. Therefore, the opportunity was taken to obtain a variety of data from the sediment samples collected in addition to the requirements for analysis of sediment release under dam failure. The full test results are provided in Appendix A.

5.5.1 Erosion shear stress of sediment samples

The critical hydraulic shear stress at which erosion of a sediment is initiated may be deduced from empirical formulae based on sediment properties that can easily be obtained from laboratory analyses.

Two such empirical methods have been considered in order to deduce the critical shear stress for the sediment samples taken from the three reservoirs:

i) Erosion shear stress determined from dry density of sediment as suggested in HR Wallingford Report 'Estuarine Muds Manual' (1992) and utilised in HR Wallingford Report 'The Feasibility of Flushing Sediment from Reservoirs' (1996);

ii) Erosion shear stress determined from laboratory vane shear stress data using the relationship proposed by Kamphuis and Hall (1983).

Figure A1.10 shows the variation in calculated erosion shear stress with sample depth using the two methods for the Reservoir A sediment samples. It can be seen that the upper 200-300mm of the samples shows very little resistance to shear with calculated erosion shear stresses typically less than 0.5 N/m^2. Typical values of erosion resistance for non-colloidal loams and silts are in the range of 2 to 2.5 N/m^2. The weak structure of the sediment in the upper layers of the samples was observed in the field whilst attempting in-situ vane shear tests and upon inspection of the samples collected in the Makareth tubes where the sediment appeared to be of a very fluid nature. This is confirmed by the low bulk dry density results (typically less than 100 kg/m^3 in the upper layer of the sediment) from the laboratory analysis of the samples.

It can be seen that there is a reasonable correlation between the erosion shear stresses predicted by the two empirical methods. In the upper layers of the sediment samples the laboratory shear vane results were below the resolution of the equipment used resulting in a zero value of shear resistance. Results could still be calculated for these very weak sediments using the equation given in the Muds Manual based on bulk dry density.

Figure A2.8 shows the variation in calculated erosion shear stress with sample depth for the Reservoir B sediment samples. There is less variation in shear stress with depth and between the two samples taken. The calculated erosion shear stresses are not as low as some of those recorded at Reservoir A but are still generally less than 1 N/m^2. There is a slight tendency to an increase in strength with depth for the two samples analysed. There is a very good correlation between the values of erosion shear stress predicted by the two methods.

Figure A3.8 shows the variation in calculated erosion shear stress with sample depth for the Reservoir C reservoir sediment samples. Samples RB1 and RB3 show a tendency to an increase in strength with depth and the values of erosion shear stress are generally higher than for Reservoir B and the upper layers of Reservoir A. There is a good correlation between the values of erosion shear stress predicted by the two empirical methods.

Sample RB2 shows a rather random variation in shear strength which may be due to the sample tube having penetrated the original ground beneath the sediment at this particular sampling point.

6 Sediment release under dam failure

6.1 *Introduction*

The Reservoirs Act 1975 relates to large raised reservoirs which are defined in Clause 1(1) as those designed to hold, or capable of holding more than 25,000 m^3 of water above the natural level of any part of the land adjoining the reservoir. The 'Guide to the Reservoirs Act' considers that the two tests given in the definition in Clause 1(1) for reservoirs falling within the ambit of the Act should be regarded as alternatives. It states that:

"Where it can be shown, by whatever means, that the reservoir was designed to hold more than 25,000m^3 of water, then the degree of siltation is immaterial; the reservoir must be regarded as falling within the ambit of the Act. Only where there is no clear evidence about the design capacity should the second test ("capable of holding") *come into play.*

In such cases, there should be a hydrographic survey, by a professional survey firm, carried out under the supervision of a qualified civil engineer, as defined in the Act. If, after taking into account the accuracy of such surveys, it cannot be conclusively demonstrated that the capacity is below the threshold value of 25,000m^3 the reservoir should remain on the register."

Clause 13(1) provides for the discontinuance of a reservoir within the Act. It states that:

No large raised reservoir shall be altered in order to render it incapable of holding more than 25,000 cubic metres of water above the natural level of any part of the land adjoining the reservoir, unless a qualified civil engineer is employed to design or approve and to supervise the alteration."

While it is difficult to consider natural siltation as a process that is designed or approved and supervised, it is clear that sedimentation does have an effect on the amount of water that would be released in the event of dam failure. The status of deposited sediment in respect of reservoir capacity is not defined in the Act but guidance is provided in the Guide. The Guide states that the consideration of sediment as part of the 'escapable contents' of a reservoir is a reasonable concept. It considers the Act to be a suitable model for any situation where liquid or semi-liquid material has the potential to flow and is stored above the level of the surrounding land with the exception of mine and quarry lagoons which are covered by the Mines and Quarries (Tips) Act.

Guidelines are therefore required to address the question of the volume of sediment released from a reservoir during dam failure. Such guidelines will be useful in one of the two following circumstances:

(a) Where the design capacity cannot be determined and where a hydrographic survey shows that the water capacity is a little less than 25,000 m^3. In this case the reservoir might be removed from or retained on the register under Clause 1(1) depending on determination of the total escapable volume.

(b) Where works are carried out in order to effect the discontinuance of the reservoir under Section 13. If the reservoir is to be discontinued, the volume of water plus mobile sediment (i.e. total escapable content) must be less than 25,000 m^3 following completion of the works.

Guidelines for flushing sediment from reservoirs using bottom outlet gates are available (HR Wallingford, Report SR 566) but no research is apparently available on the likely potential for sediment release arising from dam failure. Research was therefore undertaken with the aim of providing such guidance for British reservoirs.

The research was carried out in two stages:

1. Field investigations were carried out at selected reservoirs to conduct bathymetric surveys and to take samples of the accumulated sediment for physical laboratory testing;

2. Using the results of the surveys and the sediment properties, mathematical modelling of two selected reservoirs was carried out to analyse the potential for sediment release in the event of dam failure.

6.2 Aim of research

The aim of the research is to provide guidelines for estimating the likely quantity of accumulated sediment which may be released from a reservoir in the event of dam failure. Such guidelines are of particular relevance to reservoirs whose water storage capacity is less than 25,000 m^3. For such reservoirs, the contribution of released sediment may result in the 'total escapable contents' of the reservoir exceeding 25,000 m^3.

In order to develop these guidelines, two reservoirs of water storage capacity close to 25,000 m^3, Reservoir A in Oxfordshire and Reservoir B in the Pennines, were selected for detailed assessment as described in Section 5.2. The results will inform further work on producing general guidelines for British reservoirs.

The assessment process comprised the following steps:

(i) Simulation of dam failure using DAMBRK software and the characteristics of each dam to determine the outflow hydrograph from each reservoir in the event of dam failure.

(ii) Creation of a three dimensional finite element mesh model of each reservoir using SMS software and the bathymetric surveys of the reservoirs.

(iii) Two dimensional (depth averaged) hydraulic modelling of the reservoir using RMA2D software, the mesh created in (ii) and the outflow hydrograph generated in (i) to determine the water depth, two dimensional velocity components and hydraulic shear stress at the bed of the reservoir at each node in the finite element mesh.

(iv) Analysis of the hydraulic modelling results in conjunction with sediment properties from the laboratory analysis of samples collected from the reservoirs to estimate the quantity of sediment released from each reservoir under dam failure.

For both reservoirs, failure was assumed to occur by a seepage mechanism under 'sunny day' conditions with only a nominal inflow into the reservoir. For Reservoir A, failure under a 10,000 year return period inflow event by an overtopping mechanism was also considered. A high flow failure event for Reservoir B was not considered because the catchment area for that reservoir is very small and it is unlikely that high inflows to the reservoir would occur in practice.

6.3 *Simulation of dam failure*

As discussed in Section 5.2, at least 80% of non-service reservoirs in Britain of capacity between 25,000 m^3 and 35,000 m^3 are retained by earth embankment dams. The two reservoirs selected for detailed assessment, Reservoirs A and B, are both retained by earth embankments.

Earth embankment dams can fail by a number of mechanisms. Typically, failures arise from either internal erosion (through the embankment or within the foundation) or as a result of overtopping of the crest during floods. Internal erosion will normally progress until the crest of the dam slumps, causing the dam crest to be overtopped. In both of these cases, the significant escape of water is normally over the crest of the dam and through the resulting eroded breach in the embankment. Where there is no internal erosion, it is possible that the physical characteristics of the embankment (e.g. downstream face protection) will arrest the progressive failure of the embankment before the breach deepens to the full height of the dam.

The methods available for predicting the size and shape of a breach, the time for development of the breach and the resulting outflow hydrograph through the breach for a particular dam are currently at an early stage of development. The software package DAMBRK, developed by the United States' National Weather Service, is commonly used to predict the outflow hydrograph from a dam failure. The program requires that the following breach parameters are specified for the dam: side slopes of breach (assumed to be trapezoidal in cross section); maximum depth of breach; final breach width; time for full development of breach.

In this study the guidelines on breach parameters for earth embankments prepared by the Water Research Centre (1990), which represents current practice, have been adopted. The guidelines recommend the following values for the parameters:

- Side slopes of breach to be 1V:0.5H;
- Maximum depth of breach to be equal to height of dam;
- Average final breach width to be 2 x depth of breach;
- Time to failure in seconds to be 100 x depth of breach in metres.

The DAMBRK methodology recommends the following ranges of parameters for the breach characteristics for a well engineered earth fill dam:

- Side slopes of breach between 1V:0.25H and 1V:2H;
- Average final breach width between 1 x and 3 x depth of breach;
- Time to failure between 0.5 hours and 3 hours.

The sensitivity of the DAMBRK calculated outflow hydrographs to a variation of the breach parameters within the suggested ranges was examined for the case of the Reservoir A dam. The results indicated that the peak outflow from the dam was rather sensitive to the values of breach width and time to failure. Reducing or increasing the breach width within the suggested range resulted in an approximate 50% decrease and 50% increase in peak flow respectively. For the two dams considered, the calculated times to failure were significantly shorter than 0.5 hours. For times to failure of between 0.5 and 3 hours, the peak flows are significantly reduced.

Figures 6.1 and 6.2 show the outflow hydrographs calculated by DAMBRK for Reservoir A under dam failure for the two inflow conditions considered – 'sunny day' failure with a nominal reservoir inflow and failure under a 10,000 year return period inflow.

For the 'sunny day' simulation a piping failure of the dam was assumed with the reservoir level at the normal operating level.

For the 10,000 year flood simulation an overtopping failure was assumed with the reservoir level at the dam crest level. An approximate inflow hydrograph was calculated from the reservoir catchment parameters using the Flood Estimation Handbook (FEH) method as shown in Figure 6.3. The simulation assumed that dam failure occurred at the time of peak inflow to the reservoir (i.e. at time 10 hours on the FEH hydrograph scale). The effect of the flood inflow to the reservoir is to increase the peak outflow rate under dam failure and to increase the duration of the outflow.

Figure 6.4 shows the outflow hydrograph calculated by DAMBRK for Reservoir B for a 'sunny day' failure with a nominal reservoir inflow. A piping failure of the dam was assumed with the reservoir level at the normal operating level.

It can be seen that the peak outflow resulting from the Reservoir B failure simulation (66 m^3/s) is significantly higher than the outflow from the Reservoir A failure simulation (13 m^3/s for the 'sunny day' failure and 18 m^3/s for the flood event). Although the two reservoirs are almost equal in volume, Reservoir B reservoir is twice as deep as Reservoir A and hence the predicted breach in the dam is proportionally wider and deeper resulting in an outflow under dam failure which is much higher.

Figures 6.5 and 6.6 show the calculated rates of draw down of water level in Reservoir A and Reservoir B respectively as a result of the outflow under dam failure. The differences in the curves are due to the different outflow rates discussed above and, for Reservoir A, the effect of the flood inflow to the reservoir tending to maintain the water level as compared to the 'sunny day' failure. The differences in water depths have implications for the development of bed shear stress as discussed in Section 6.5.

The amount of sediment that might be released from a reservoir in the event of dam failure will depend on, amongst other things, the peak flow rate out of the reservoir and the duration of the flow. It has been shown that these depend to a certain extent on the characteristics of the breach formed. Given the current knowledge and practice in predicting breach formation, there is therefore an inherent degree of uncertainty in predicting both the outflow from the reservoirs and the quantity of sediment released under dam failure.

6.4 Hydraulic modelling

Hydraulic modelling of Reservoirs A and B was carried out in order to determine the hydraulic shear stresses acting on the reservoir bed under dam failure.

A finite element mesh model of each reservoir was prepared from the bathymetric survey data using the Surface Water Modelling System software package (SMS) developed by the Brigham Young University. A two dimensional (depth averaged) hydraulic modelling program, RMA2D, developed for and maintained by the US Army Corps of Engineers was used to model the flow of water in the reservoirs using the mesh prepared with SMS.

The hydraulic model determines the water depth and orthogonal components of depth averaged water velocity at each node in the mesh at each timestep over the duration of the event modelled. Due to the short duration of the dam failure events and the rapid changes in flow and water level in the reservoirs a timestep of 0.01 hours (36 seconds) was used for all model simulations.

Three simulations were carried out as follows:

i) Reservoir A – 'sunny day' failure;
ii) Reservoir A – 10,000 year return period inflow failure;
iii) Reservoir B – 'sunny day' failure.

The upstream boundary condition for each simulation is the inflow to the reservoir. For 'sunny day' failure simulations a nominal 0.1 m^3/s inflow was assumed. For the 10,000 year event at Reservoir A, the inflow hydrograph calculated from the reservoir catchment parameters using the Flood Estimation Handbook method (Figure 6.3) was used. The simulation assumed that dam failure occurred at the time of peak inflow to the reservoir.

The downstream boundary condition for each simulation is the water level in the reservoir at the breach in the dam. This boundary was adjusted for each simulation until the modelled outflow from the reservoir matched the outflow hydrograph calculated by the DAMBRK software.

From the results of the model simulations, the hydraulic shear stress acting on the bed of the reservoir at each node was calculated using the Manning shear stress equation for each timestep in the simulation.

6.5 Results of hydraulic modelling

6.5.1 General

The results of the hydraulic modelling for the three simulations performed are presented in two ways. Firstly, as a series of plots of bed shear stress contours at intervals over the duration of the simulation. Secondly, as a sample plot of velocity magnitude contours and velocity vectors at a given instant during the simulation.

The plots of bed shear stress contours show how the shear stress on the reservoir bed develops over time as water flows through and out of the reservoir during the dam failure event. Areas of high bed shear stress, greater than the critical erosion shear stress of the sediment, indicate where erosion of the accumulated sediment will occur.

The plots of velocity magnitude contours and vectors illustrate the flow patterns that develop in the reservoir during the dam failure event.

6.5.2 *Reservoir A*

Figures 6.7 and 6.8 show the development of bed shear stress at Reservoir A for the 'sunny day' failure simulation and the 10,000-year flood simulation respectively. Similarly, Figures 6.9 and 6.10 show the flow patterns in the reservoir for the two simulations.

For the 'sunny day' simulation the zone of high bed shear stress (greater than 1 N/m^2) resulting from dam failure is initially limited to a semi-circular zone around the dam breach where the flow field is concentrated and hence velocities are high. As the outflow from the reservoir increases to its peak flow at 0.07 hours the velocities in the constriction half way along the reservoir increase such that shear stresses locally exceed 1 N/m^2. As the outflow reduces the velocities and hence shear stresses initially reduce at this point. However, as the water level in the reservoir draws down the depth of flow reduces and hence the velocity at the constriction increases resulting in a high shear stress at this point towards the end of the simulation. The extent of the zone of high shear stress around the breach does not vary significantly over the duration of the event.

For the 10,000-year flood simulation the development of the zones of high shear stress at the breach and at the constriction in the reservoir is not as rapid as compared to the 'sunny day' failure. Although the peak outflow for this simulation is around 40% higher than for the 'sunny day' failure and the time to peak outflow is similar in both simulations, the reservoir draw down for the flood simulation is less rapid due to the large inflow to the reservoir. Therefore the depth of water in the reservoir is greater and so the velocities and bed shear stresses are lower compared to the 'sunny day' simulation. However, the large inflow and shallow water depth at the upstream end of the reservoir means that velocities and shear stresses are high in this area for this simulation.

6.5.3 *Reservoir B*

Figure 6.11 shows the development of bed shear stress at Reservoir B for the 'sunny day' failure simulation. Figure 6.12 shows the flow patterns in the reservoir for the same simulation.

The zone of high bed shear stresses (greater than 1 N/m^2) are confined to a semi-circular zone around the breach which develops rapidly under the outflow hydrograph. The regular shape of this reservoir means that the velocity field attenuates uniformly away from the breach and there are no localised zones of high velocity and shear stress. In this case sediment erosion will be limited to a critical zone surrounding the breach.

6.5.4 *Summary*

The results of the hydraulic modelling for the two selected reservoirs show that a roughly semi-circular zone of high flow velocity and bed shear stress develops around the breach in the dam under dam failure. Depending on the plan shape of the reservoir, localised areas of high flow and bed shear stress may develop at points where the reservoir is narrow in the flow direction or shallow in flow depth. In such areas the effect of a high inflow to the reservoir is to further increase the local velocities and shear stresses.

6.6 Analysis of sediment release

6.6.1 *Methodology*

In order to estimate the approximate volume of sediment released under dam failure for each of the three simulations carried out, the following method was applied:

(i) calculate the erosion depth at each node in the hydraulic model at each timestep using a simplification of the Partheniades method for particle erosion using the critical hydraulic shear stress and bulk density of sediments in reservoir determined in Section 2;

(ii) summate the depth of erosion over the duration of the simulation to deduce the total erosion depth at each node;

(iii) from contour plots of total erosion depth deduce the area for each erosion depth interval and summate to deduce the total erosion volume for each simulation.

6.6.2 *Results*

The results from step (ii) above are illustrated in Figures 6.13, 6.14 and 6.15 as contour plots of total erosion depth for Reservoir A (‘sunny day’ failure), Reservoir A (failure with 10,000-year flood) and Reservoir B (‘sunny day’ failure) respectively.

The results for total sediment erosion for each simulation, calculated in step (iii) above are as follows:

Reservoir	**Failure condition**	**Reservoir water storage volume**	**Initial volume of sediment in reservoir**	**Total volume of sediment eroded under dam failure**
A	'Sunny Day'	23500 m^3	13000 m^3	185 m^3
A	10,000-year flood inflow	23500 m^3	13000 m^3	2049 m^3
B	'Sunny Day'	28300 m^3	10800 m^3	25 m^3

6.6.3 *Conclusions*

It can be seen that the estimated volumes of sediment eroded under 'sunny day' dam failures for the two reservoirs considered is small with the total depth of erosion exceeding 50mm only in localised areas near the breach in the dam and at local constrictions in the reservoir flow path.

For dam failure with a high inflow to the reservoir the quantity of sediment eroded is significantly higher for the particular reservoir considered. In this case, the volume of eroded sediment results in the total 'escapable content' of the reservoir exceeding 25,000 m^3 although the total volume of water stored is less than 25,000 m^3. The high inflow to the reservoir combined with low water levels due to dam failure creates a 'flushing effect' which erodes sediment in a channel along the original flow path of the reservoir. The quantity of sediment eroded around the breach forms a small proportion of the total volume eroded, with the majority of the material being eroded in the shallow, narrow flow path in the upstream part of the reservoir. The volume eroded (2409 m^3) represents approximately 16% of the sediment accumulated in the reservoir.

In addition to the volumes shown above, the total volume of sediment escaping the reservoir will include that of the breach in the dam itself (90 m^3 in the case of Reservoir A and 480 m^3 in the case of Reservoir B). There is also a further contribution of a small amount of material from the reservoir bed immediately adjacent to the breach and in the upstream part of the reservoir resulting from the need to ‘cut’ a flow channel in the hydraulic model in these areas.

The estimates of sediment loss above relate only to the volume of sediment lost over the duration of a dam failure event. In practice, it would be expected that a further loss of sediment from the reservoir would occur beyond the period of dam failure as water flowing into and through the reservoir would continue to erode and entrain sediment from the reservoir before flowing out through the breach. At times of high river flow into the reservoir this could result in significant additional quantities of sediment being released from the reservoir.

Further work will need to be carried out to assess how far these results can be expanded to provide general guidelines for reservoirs of this size in Britain. However, the results suggest that the volume of sediment released from reservoirs of this size under dam failure is not significant when the inflow to the reservoir is small, but can become significant when a failure occurs during high flood flow events.

7 Reducing sedimentation in reservoirs

7.1 *Options for action*

The methods for reducing reservoir sedimentation divide into four main options:

- minimise sediment loads entering reservoirs
- minimise deposition of sediment within the reservoir basin
- remove previously accumulated sediment
- replace lost reservoir capacity

Bruk (1985) summarised the views of an international panel of expert contributors and concluded that, in the long run, watershed management is the best way to reduce the yield of sediment and its entry into the reservoir. For large basins, however, this may be a slow and prohibitively expensive process but protecting the existing regime to prevent deterioration is also important. The construction of auxiliary check dams or silt traps may have a quicker effect but these will in turn fill with sediment and so may not last long unless actively managed, which again increases the costs.

By-passing of sediment laden flows is another effective method recommended for consideration in the design stages of any project. In Britain there are a number of chains of reservoirs built with bypass channels and the use of these should be maintained.

Flood flushing and venting of turbid currents can prove to be an effective means of reducing deposition in reservoirs but this depends on provision of suitable bottom outlets and an excess of water. Britain does not generally provide suitable conditions for effective flushing particularly in the case of water supply reservoirs.

Removal of sediment deposits by dredging or excavation is a costly operation which may be justified in certain circumstances by the economic value of the water and the impossibility of replacing lost reservoir capacity. Disposal of the excavated silt may also cause difficulties unless it can be used for the improvement of surrounding agricultural land.

Pattinson et al (1994) outlined the use of a holistic 'staged catchment management' approach whereby the catchment, the transfer network and the reservoir itself are seen as components in a system to minimise water treatment costs. It would seem appropriate that a similar framework be adopted for the management of reservoir sedimentation, in such a way as to maximise water yield and minimise undesirable effects.

7.2 Catchment management measures

"Reservoirs are greatly influenced by tributary inflows and their water quality conditions reflect geographic, climatic and watershed characteristics".

Kennedy et al, 1985.

Workers such as Morgan (1995) have described approaches to soil conservation based upon agricultural practices and mechanical methods of reducing soil transport. It seems self-evident that the nature of the vegetation and land use in a catchment will have some impact on the sediment yield of rivers draining it, although this will not necessarily be demonstrable in a simple statistical analysis of the data because of the many other influencing factors (White et al, 1996). Basson and Rooseboom (1999) also comment upon the complex nature of the relationship between erosion and sediment yield, and point out that it may be possible to reduce expenditure by identifying major sediment sources and concentrating soil conservation measures in those areas. For example, almost 50% of the sediment load of the Yangtse is said to come from 13% of the total catchment. They do, however, acknowledge that soil and water conservation programmes are difficult to organise, expensive and only give sediment reductions in the long term (see for example Trimble, 1981). Reported reductions in sediment yield are variable, but often in the range 25-72%.

Mahmood (1987) states that, intuitively, the first method of reducing reservoir siltation would be to reduce sediment yield from the basin upstream by watershed (catchment) management. This might include afforestation, land use change and construction of micro-structures to trap sediment. However, he suggests that the facts do not support the efficacy of such an approach with respect to reservoir sedimentation. He uses Trimble’s work on Coon Creek to support the conclusion that over periods of economic or engineering interest the sediment yields will be largely unaffected by watershed management, since other sources within the basin will make up for any reduction in erosion on the slopes. He gives the example of the Mangla basin in Pakistan, where an extensive watershed management project was initiated on the erodible rocks: unconsolidated loess, limestones and schists which have suffered much tectonic disturbance. Over a period of 4-14 years of operation no discernible effect upon river sediment loads was detected. Mahmood concludes that the project may have had a beneficial effect on the local environment but its contribution to reducing sedimentation of the reservoir was doubtful.

Other workers overseas, however, have extolled the virtues of catchment-based approaches to sediment reduction. Sharma (1996) investigated sediment yields in the arid zone of India, where sediment yields were 270 to 1430 $m^3.km^{-2}.yr^{-1}$ and 100 small reservoirs (400 to 700 Ml) were reduced in capacity by 1.9% to 7.8% annually. Following large-scale government-funded soil conservation programmes he concluded that sediment yield could be reduced by 65-94% through promotion of vegetation instead of bare soil and by 70% with construction of check dams in the drainage basin. An earlier study by Rapp et al (1972) monitored sedimentation in four reservoirs in Tanzania by periodic re-levelling and concluded that some of them would have a total life of only 30 years and that they would be economic for an even shorter period. Annual sedimentation was 195 to 729 $m^3.km^{-2}.yr^{-1}$. Splash erosion and sheet wash were observed to be severe on some of the bare, overgrazed slopes and to be more important than contributions from stream bank or gully erosion in several cases. Improved vegetation cover was again recommended as a strategy to reduce sedimentation, despite the decreased water yield which would also result, but the likely benefits were not quantified here.

In Britain, Newson (1988) described some of the work of the Institute of Hydrology and discussed implications for upland land use planning and land management. He included the two scenarios of land allocation (on the basis of sensitivity or capability maps) and accommodation, where land is managed by a combination of 'free' market forces and technical dialogue. He suggested that in practice a middle way was likely, with 'keep off' attitudes only prevailing for very sensitive sites or for persistent and deliberate contributions to the deterioration of upland water quality.

Many individual studies on British lakes and reservoirs have reported the effects of land use change upon sedimentation rates. For example Rowan et al (1995) provisionally linked a period of increased sedimentation in Abbeystead reservoir, Lancashire, from 1930-1948 with agricultural land improvement in the drive to increase food production associated with the Second World War. Sedimentation in this period peaked at 373 $t.km^{-2}.yr^{-1}$, compared to only 78 $t.km^{-2}.yr^{-1}$ for the previous 55 years. Heathwaite (1993) measured sedimentation in Slapton Ley, a natural lake in southwest England, and identified an increase in erosion since 1945 which was possibly associated with a post-war increase in the area of arable and temporary grassland. A major peak in sediment influx in 1987 (to over 1 $g.cm^{-2}yr^{-1}$) was tentatively linked to recent conversion of permanent to temporary grassland, including ploughing of riparian areas.

Dearing et al (1981) investigated sedimentation in Llyn Peris, North Wales, and linked a much increased rate since 1965 (approximately 41 $t.km^{-2}.yr^{-1}$,compared to less than 15 $t.km^{-2}.yr^{-1}$ for most of the rest of the 20th century) with dramatically increased sheep population in Snowdonia. It was suggested that overgrazing leads to a decrease in tree cover and an increase in peat erosion and stream channel erosion. The possible influences of tourism (trampling) and dust from quarrying were also mentioned.

Van der Post et al (1997) also discussed the influence of grazing pressure in a study of sedimentation at Blelham Tarn in the English Lake District. They plotted the annual sediment accumulation against the number of sheep on agricultural census returns for the two parishes adjacent to the lake and found an extremely close relationship as shown in the Figure 7.1.

Several studies have considered the impact of afforestation upon sedimentation. Battarbee et al (1985) compared non-afforested with recently afforested sites in Scotland and suggested that a 20-fold increase in sedimentation rates resulted, although they did acknowledge that this effect may only last for approximately 10 years, until the forest canopy closes and drainage channels stabilise. Burt, Donohoe and Vann (1984) and Francis and Taylor (1989) reported large increases in short-term stream sediment loads (2.5 to 4.8 times the previous values) on catchments ploughed prior to afforestation. Stott (1997) provides a helpful summary table of other studies in the literature, which again suggests that the short term increase in suspended sediment yield may be associated with ploughing or felling rather than with established forest. Longer term effects were also considered by Dearing (1992), who investigated sedimentation in Lyn Geirionydd, North Wales, and concluded that afforestation in the 20th century did not appear to have significantly increased sediment yields, whereas unvegetated spoil heaps from nearby mining did act as significant point sources.

Foster et al (1987) summarised data from 20 studies and indicated that recent maximum sediment yields under cultivation and moorland were noticeably higher than those found under forest, given the same catchment: lake volume ratio. More recently Foster and Lees (1999 a and b) have undertaken studies of nine lakes and reservoirs in northern England as part of the LOIS project and suggested that average post-1953 sediment yields from pasture, arable, moorland and forested catchments were respectively 13, 31, 29 and 13 $t.km^{-2}.yr^{-1}$. These values are all low compared to those discussed in Section 2 and reflect the nature of the catchments measured but illustrate the relative effects of land use.

In conclusion it has been found that catchment measures and land use have important impacts on sediment yield. In Britain, because erosion rates are generally low, controlling areas of high erosion for example where there is overgrazing or where erosion from bare soil occurs is desirable. However changes in land use including re-afforestation in the short term can significantly increase sedimentation rates and either protection against such changes or mitigation measures to control sediment are needed if reservoir sedimentation rates are not to increase.

7.3 Controlling sedimentation rates – releasing sediment through bottom outlet valves

One possible way to reduce the sedimentation in reservoirs is to use the bottom draw off valves to flush or scour sediment previously deposited. This is a procedure frequently planned into the operation of reservoirs overseas in order to maintain capacity (e.g. the Cachi reservoir in Costa Rica described by Jansson and Erlingsson, 2000). In Britain the practice has been much less common and there is therefore relatively little information available by which to assess its effectiveness or likely adverse impacts.

It may be informative, therefore, to review measurements of sediment release from reservoirs in the southern Pennines and to compare the amount of sediment passing downstream under "normal" operation with that occurring when the valves are opened. Butcher et al (1992) have presented some results for the amount of sediment measured passing over the spillway during rainfall events for two reservoirs in Yorkshire (Wessenden Head and Blakeley). These reservoirs are known to have relatively high sedimentation rates as a result of peat erosion in the catchments.

Sediment passing over the spillway in one event monitored at Wessendedn Head Reservoir was 40 kg, or 26% of the incoming load. Measured trap efficiencies (proportion of incoming suspended sediment not outflowing) ranged from 0 to

97.3% for individual storms. Monitoring only continued for 6 weeks so it is not possible to estimate an annual total accurately, but a broad estimate of 5-15 tonnes passing over the spillway each month in winter seems reasonable.

Pemberton (1987) also investigated sediment discharged from reservoirs as a result of normal water abstraction for treatment and supply. For two small reservoirs (Holmestyes and Kinder) she estimated annual removal of approximately 15 tonnes of sediment to the water treatment works, relatively small compared to the amounts thought to pass over the spillway as discussed above.

Pemberton (1987) also made extensive measurements of sediment release during the opening of bottom drawoff valves for safety checks. Data were collected from 25 reservoirs on four separate occasions between 1985 and 1987. Samples of water were obtained at intervals of 30 seconds until the valve was fully open, then every one or two minutes until the procedure was completed. The length of time the valve was open varied depending upon the size and nature of the particular aperture, varying from 10 minutes to one and a half hours. Replicate sampling suggested that values are accurate to within 4%. Maximum suspended sediment concentrations and sediment loads are presented in the table below. There is wide variation both between reservoirs and between successive openings of the valves. Particularly high concentrations occurred in the first set of tests, since these were the first to have been performed for some time, and the results at Green Withens and Blakeley were spectacular (see Table 7.1 below).

Table 7.1 Sediment Release (peak suspended sediment concentration and load) during testing of bottom outlet valves in Yorkshire Reservoirs 1985-1987 (after Pemberton, 1987)

Reservoir		Oct 85	May 86	Nov 86	Apr 87
Baitings	Peak (mg.l^{-1})	6770	-	3328	295
	Load (kg)	1525	-	133	-
Blackmoorfoot	Peak (mg.l^{-1})	554	293	2239	531
	Load (kg)	101	41	28	14
Blakeley	Peak (mg.l^{-1})	186600	26041	10809	26559
	Load (kg)	62000	9288	15408	28512
Boothwood	Peak (mg.l^{-1})	709	-	375	118
	Load (kg)	106	-	43	10
Boshaw Whams	Peak (mg.l^{-1})	1062	403	596	952
	Load (kg)	6	1	3	3
Brownhill	Peak (mg.l^{-1})	455	93	34	44
	Load (kg)	46	9	1	22
Butterley	Peak (mg.l^{-1})	4695	1645	1769	1234
	Load (kg)	54000	1039	892	126
Deanhead	Peak (mg.l^{-1})	174	-	-	-
	Load (kg)	-	-	-	-
Deerhill	Peak (mg.l^{-1})	753	505	26	971
	Load (kg)	248	40	38	62
Digley	Peak (mg.l^{-1})	296	61	478	-
	Load (kg)	293	-	1309	-
Gorple Lower	Peak (mg.l^{-1})	-	65	257	112
	Load (kg)	-	20	68	17
Gorple Upper	Peak (mg.l^{-1})	215	-	256	139
	Load (kg)	112	-	62	29
Gorpley	Peak (mg.l^{-1})	12353	7603	1041	966
	Load (kg)	600	-	-	-
Green Withens	Peak (mg.l^{-1})	568800	28187	1336	3389
	Load (kg)	225225	5873	479	2119
Holme Styes	Peak (mg.l^{-1})	3617	982	1282	941
	Load (kg)	61	23	24	28
Ogden	Peak (mg.l^{-1})	-	190	602	222
	Load (kg)	-	51	65	23

Table 7.1 (contd.) **Sediment Release (peak suspended sediment concentration and load) during testing of bottom outlet valves in Yorkshire Reservoirs 1985-1987 (after Pemberton, 1987)**

Reservoir		Oct 85	May 86	Nov 86	Apr 87
Ringstone	Peak ($mg.l^{-1}$)	8818	4168	2500	575
	Load (kg)	1001	1087	386	214
Scammonden	Peak ($mg.l^{-1}$)	7464	2763	7012	-
	Load (kg)	13275	2904	2988	-
Walshaw Dean Lower	Peak ($mg.l^{-1}$)	288	90	1018	83
	Load (kg)	450	77	297	97
Warley Moor	Peak ($mg.l^{-1}$)	1783	287	149	258
	Load (kg)	664	176	80	99
Wessenden Head	Peak ($mg.l^{-1}$)	408	402	265	274
	Load (kg)	305	164	71	55
Widdop	Peak ($mg.l^{-1}$)	237	137	181	389
	Load (kg)	115	56	81	34
Withens Clough	Peak ($mg.l^{-1}$)	266	-	348	271
	Load (kg)	278	-	136	39
Yateholme	Peak ($mg.l^{-1}$)	105	99	155	233
	Load (kg)	-	-	-	-

Note: Where no load is quoted this is usually because of lack of discharge data

The data show that the actual volume of sediment removed by outlet valves is relatively small and limited to a zone of influence around the intake. However if the valve is opened after some time of inaction then there is the potential for very high silt concentrations to temporarily be discharged (Figure 7.2). This type of effect seems to have been the result of the accumulation of sediment around the valves over a number of years, and the highest concentrations did not occur in subsequent tests. At Digley, where the reverse was true in November 1986, the flow from the valve was observed to stir up vegetation and sediment from the base of the channel, giving a false impression of the actual sediment removed from the reservoir. At Butterley the subsequent tests only included partial opening of the valve for fear of the effects of the sediment on the downstream ecosystem.

The mean loss of sediment through short-term opening of bottom outlet valves was just over 18 tonnes for the first set of tests but steadied to between 1 and 2 tonnes for each subsequent set of tests. This figure is, however, very skewed by the inclusion of the three most dramatic examples at Blakeley, Green Withens and Scammonden.

The effects of opening the outlet valves on the downstream river are discussed further in Section 9.

7.4 Sediment exclusion measures

There are a range of options for exclusion of sediment from reservoirs most of which have been attempted in Britain including:

- Settling Basins, Boulder and Gravel Traps, Settling Areas
- Bypass channels with sediment excluding/splitting structures
- Use of catchwater channels
- Use of offstream Reservoirs

7.4.1 *Settling Basins, Gravel Traps and Catchwater/Bywash Channels*

Settling Basins are known by a number of different titles such as ‘silt pond’ or ‘residuum lodge’ and, in a number of cases, smaller upstream reservoirs are left to act as silt traps to a larger downstream reservoir chain and no longer used for normal releases. The experience in use of sediment trapping in Britain has been variable, in one case the sediment trapped and the bank of the silt trap were washed into the main reservoir during a large storm and in some cases the removal of sediment from silt traps was discontinued due to high costs and manpower requirements. The removal and disposal of sediment trapped may be problematic and more expensive than raising the main reservoir. Where fine sediments are the main concern then to be effective a large settling area may be needed such as shown in Figure 7.3. For removal of the material a suitable bypass will be needed and access for sediment removal provided.

The very fine sediment found in peat catchments is probably also much more difficult to control than is generally the case elsewhere and smaller structures or desanders used in Scotland on gravel catchments have also been effective in reducing sediment flows to hydropower turbines.

Some of the difficulties in removing sediment from older silt traps are illustrated in Figure 7.4.

Although the theoretical trapping performance of structure can be very high there are a number of practical factors that mitigate against ideal operation. Analysis of sedimentation rates in Yorkshire reservoirs with and without sediment control devices was carried out by White et al (1996). In this study the long term effectiveness of different measures was assessed by comparison of observed siltation rates of reservoirs with and without sediment control measures. The assumption behind such a comparison is that siltation rates are similar in each case modified only by the structural measures. When trying to assess the effectiveness of sediment control measures in the long term, the situation is complicated by the fact that sediment control measures would be expected where the problems anticipated by the dam designers to be the most acute. Also in most cases where residuum lodges are used, they are used in chains of reservoirs and combined with bywash channels or other methods of sediment control. Nevertheless the data analysed suggested that sediment control did reduce sedimentation significantly as shown in Figure 7.5.

The results suggest that there is a significant benefit that has resulted from the use of residuum lodges, bypass channels and catchwaters although further measurement and analysis would be needed to separate the different effects of combined structures and the influence of sediment yields.

7.5 Offline reservoirs

As discussed in earlier sections, bunded or offline reservoirs play a critical part in water supply for the Thames and Anglian areas. The Anglian reservoirs are relatively young and although recent surveys have been carried out suggesting sedimentation rates not significantly reduced from that which would be expected for impounding reservoirs, results may be significantly influenced by differences in the methods used for the original and recent surveys. There is no data available for the older reservoirs of the Thames and Lee catchments although the higher turnover and periodic emptying for maintenance may have reduced the effective 'trapping efficiency'. These relatively shallow reservoirs may also suffer more from deposits of organic material generated within the reservoir than those found in more acidic peat catchments.

8 Removal of sediment deposits

8.1 *Introduction*

Removal of sediment from reservoirs in Britain has usually only been undertaken where necessitated by engineering works such as clearing blockages of outlet valves, but in many cases overseas it has been seen as a possible means to sustain reservoir capacity and thus prolong life (Basson & Rooseboom, 1999). Although in the past it has been cheaper to build new reservoirs than remove and dispose of sediment this economic balance is shifting as the number of suitable reservoir sites becomes more restricted and the development of alternative water resources more costly. Acting against any widescale sediment removal is the need to maintain the environmental benefits that siltation at the margins of a reservoir may bring in creating wetland habitats and the problems of extracting, transporting and disposing of the sediment.

There are a number of practical means of removing sediment from reservoirs. As well as the hydraulic methods such as flushing, there are mechanical methods such as dredging, excavation and siphoning (Brabben, 1988). Sediments may be removed from the shore or from a boat depending on the reservoir characteristics and the quality of the sediments. Simple suction devices cannot usually be applied due to the cohesive nature of the sediments and therefore the head of such devices often incorporates water jet nozzles or a rotating head to loosen the material for easy dredging. The increase in turbidity caused through the action of some dredging techniques can present water quality problems. This tends to promote hydraulic methods or mechanical excavation that usually require the reservoir level to be lowered or the reservoir to be by-passed and emptied. Clearly, the decision to remove sediment from a reservoir will normally demand some compromises to be made with respect to either water quality or reservoir operation. Morris and Fan (1988) provide many examples of reservoir desilting operations from around the world that illustrate the wide variety of techniques available.

The three aspects to be considered in planning sediment removal from a reservoir are:

- The economics of the proposal - the cost of removing, transporting and disposing of sediment compared with the value of the storage won;
- The environmental impact of the proposed method - the impacts associated with water quality in drawoffs and downstream reaches, transportation and disposal of sediment;
- The implications for reservoir operations and water treatment.

There are two CIRIA reports covering the removal and disposal of dredged material. CIRIA Report 169 (1997) 'Inland dredging - guidance on good practice' is supplementary to Report 157 (1996) 'Guidance on the disposal of dredged material to land', produced in response to the introduction of the Waste Management Licensing Regulations (DoE, 1994).

One water company in northern England has investigated the feasibility of options for desilting reservoirs. The study concluded that desilting a reservoir full of water would produce dredgings with a very high moisture content, making disposal both difficult and expensive. Desilting of reservoirs whilst the water level is drawn down is certainly cheaper, although moisture content may still be a problem. It was recommended that pilot trials be considered to establish the feasibility of transporting the silt and if necessary to evaluate the relative benefits of possible dewatering techniques. These might include harrowing or heaping to encourage natural drainage, use of a mobile filter belt plant (with or without chemical treatment) and use of a mobile centrifuge plant (with polyelectrolyte dosing). The economic case for sediment removal however was not clear and the trials recommended were not carried out.

The costs of excavation, transport and disposal of sediment depend upon a large number of factors, many of which are site specific. One major problem may be the identification of a local site suitable for disposal. If it is possible to use the material for capping and landscaping an existing landfill site, or to use it as an agricultural soil conditioner, then the costs of disposal will be much less than if the material is put into landfill. Transport of large volumes of material on minor roads may cause physical damage, noise and air pollution and may not be deemed acceptable in environmentally sensitive areas, National Parks etc. The economics of desilting also depends upon the equivalent cost of alternative resource options.

8.2 Experience in removing sediment from British reservoirs

Research has indicated that, historically, very little work has been undertaken by the owners of British reservoirs to remove sediment. Most of the British experience in dredging techniques has been gained on waterways rather than at reservoirs - the CIRIA guides reflect this. Where reservoir desilting has been undertaken, it has usually not been to restore lost storage but for various other purposes such as:

- Restoration of visual amenity, typically at ornamental lakes (e.g. Newton Park Lakes near Bath) where the quantity of dredged material is small and temporary loss of water quality is acceptable;

- Excavation of sediment near dam bottom outlet facilities to undertake maintenance activities (e.g. March Haig and Holmstyes Reservoirs in Yorkshire);

- Other reasons (e.g. The Castle Pond at Pembroke has been dredged for navigation purposes).

Historically, many reservoirs were constructed with residuum lodges that were regularly excavated using manual methods. The rising cost of manual labour over the last century has resulted in some of the residuum lodges becoming neglected, thereby accelerating the rate of sedimentation in the main reservoir. The lack of good vehicular access to the site of some residuum lodges has also been a contributing factor.

An example of a major British reservoir desilting operation is Grimwith Reservoir in Yorkshire, which was dredged in the late 1970's. As with most other reservoir desilting operations in Britain, this was planned as a response to an engineering requirement to undertake works to the dam structure. In dewatering the reservoir for enlargement works, it was found that the sediment concentrations of the water flowing through the lowered reservoir became unacceptable to quality standards for the downstream watercourse. A cutter suction dredger, typically used for estuaries and docks, was used to dredge sediment from the bottom of the reservoir and pump it to a purpose-built settling lagoon adjacent to the reservoir. Sand and silt was removed at a rate of 24,000 m^3 per week. An estimated 200,000 m^3 of sediment was removed at a cost (in 1976) of about £200,000 for the dredging and about £150,000 for the lagoon. At 2000 prices, this would amount to an approximate cost of £9 per m^3 of reservoir storage restored. The lagoon site was close to the original dam and within the boundary of the enlarged reservoir and thus the indicative costs do not fully include the transport, disposal or site acquisition costs that may be associated with other desilting projects.

8.3 Environmental considerations in removing sediment from reservoirs

There are a number of environmental considerations related to the removal, transport, disposal and re-use of reservoir sediment. These typically fall into one of the categories listed in Table 8.1 below. The removal of sediment from reservoirs need not have an adverse effect on the environment. Indeed, the opposite effect is possible if a sensitive approach is adopted.

If the natural variation in sediment yield with flow is well enough understood (e.g. through sediment monitoring in the river upstream of the reservoir), it should be possible to periodically operate dam bottom outlets in a controlled manner to so that sediment does not build up around the outlet. The most appropriate time for such operations is during high flows when the reservoir is spilling. Reservoir operators have occasionally faced prosecution by the Environment Agency for indiscriminate use of bottom outlets that can lead to very large increases in sediment concentrations downstream. However, there should be scope for controlled releases of sediment within agreed limits and operators are encouraged to present well-reasoned proposals to the Agency for their consideration. However it is unlikely that 'natural' conditions in the receiving river could be truly recreated through bottom outlet operation as the nature of the sediment released will often be much finer. Experience should be gained from the regular bottom outlet gate/valve operations that are normally required to demonstrate reservoir drawdown capability to meet dam safety requirements.

Table 8.1 Environmental Aspects of Sediment Removal from Reservoirs

Category	Examples of Possible Issues
Removal of Sediment	• Loss of habitat - dredging reservoirs, particularly at the shallow headwaters and reservoir margins can destroy habitats and affect wetland birds, etc. • Impact of desilting method adopted – if the water sustains flora or fauna of particular value, or if fish issues are important, then dredging might be necessary to avoid lowering the water level. • Temporary loss of reservoir water quality through increased turbidity. • Long-term improvement in reservoir water quality through removal of organic material. • Possible reduction in downstream river water quality during dredging. • Loss of land for containment areas to drain/treat sediment. • Timing of operation with respect to migratory of fish, freezing of reservoir etc. • Security of temporary holding lagoon against release through embankment failure, public safety etc. • Improvement in potential for recreational reservoir use.
Transportation	• Reservoirs are often in remote areas – transportation on minor roads can place pressure on local communities (noise/air pollution and physical damage to roads). • The impact of transportation can be much reduced if the sediment can be effectively dewatered at or near the reservoir site using, for example, a hydrocyclone and/or a filter bed press.
Disposal	• Viability of disposal to land depends on level of contaminants. • Contamination of groundwater by leaching. • Gas release from landfill sites.
Re-use	• Examples of re-use include sand/gravel/bricks for the construction industry and fertiliser. • Can be used to fill in disused quarry areas or mines. • Can be used to cap landfill sites.

8.4 *Economics of sediment removal and disposal*

It would be reasonable to assume that in general terms the removal of sediment from British reservoirs is usually not economic at the present time. This seems apparent given the very limited number of desilting contracts undertaken each year at British reservoirs. It is also apparent that there has been very little strategic planning on the part of major reservoir owners to account for the gradual loss of reservoir yield through sedimentation. The economics of such a process have usually only been considered to meet the requirements of particular projects where some reservoir desilting is necessary. It is therefore quite possible that desilting is more economically feasible than the current level of reservoir desilting contracts would suggest.

For most British reservoirs, only mechanical methods of removal are likely to be feasible. To determine the most cost-effective mechanical method for a particular application, it is advisable to contact specialist contractors and to consider a number of options. Perhaps the most common method employed in Britain is the use of a barge-mounted backacter but the reach of such machines is limited and they are better suited to waterways where the material can be placed directly onto banks or into trucks. Suction dredgers have been successfully used in reservoirs and should also be considered.

If it is possible to use the material for capping and landscaping an existing landfill site, or to use it as an agricultural soil conditioner, then the cost of disposal will be much less than if the material is put into landfill.

It is difficult to provide guideline figures for the costs involved with the removal of sediment from reservoirs because of the wide range of factors involved. The economics of desilting depends upon the cost of alternative water resource options within the region. The cost of desilting will depend on the method adopted for removing the sediment, the facilities available for temporary storage, the distance involved in transporting the material to the disposal site, the nature of the disposal method, the potential for re-using the material and possibly many other factors. Typical figures for dredging material and transporting it to shore are currently £1.50 to £2 per cubic metre. The total price for excavation, treatment, transportation and disposal will be much higher and perhaps £10 per cubic metre might be a typical all-in unit cost. The costs associated with a sustained programme of sediment removal can generally be expected to increase as suitable sites for sediment removal can generally be expected to increase as suitable sites for

sediment disposal close to the reservoir are used up, forcing increased haul distances.

8.5 *Disposal and possible re-use of sediment removed from reservoirs*

The Waste Management Licensing Regulations (DoE, 1994) came into force on 1 May 1994 and cover the disposal of dredged material to land. Under the regulations, unless it can be shown that the dredged material is not waste (i.e. it has not been discarded), or that the proposed disposal method meets one of the specified exemptions, a Waste Management Licence will be required. This is notwithstanding the fact that the disposal of dredged material may be exempt from Landfill Tax if classified as inert waste.

CIRIA Report 157 provides guidance on planning the disposal of dredged material and PIANC (1992) has produced a guide on the beneficial uses of dredged material. Dredged material is potentially a valuable resource and has a wide range of possible uses. The potential for re-use of material will depend in the first instance on the material characteristics and the level of contaminants. Options for re-use include:

- Engineering uses: land creation, land improvement, capping of landfill sites.

- Agricultural and product uses: construction materials, topsoil, fertilisers.

- Environmental enhancement: the PIANC guide provides details of many examples from around the world where dredged material has been used for wetlands restoration/rehabilitation, improvement of upland habitats and fisheries.

For example, in Yorkshire, a company has been removing reservoir sediment for some years for incorporation into potting compost and marketing the product commercially. Research at the University of Huddersfield and elsewhere found the material to be very similar to peat-based compost in performance for domestic garden use. The sediment is removed from either residuum lodges or from within the reservoir without charge to the water company. Given the pressure to conserve Britain's lowland raised bogs, the possibility of a viable alternative to peat composts is welcomed.

In considering the options for the disposal of sediments, it is important to undertake laboratory testing of samples to evaluate the presence of contaminants.

CIRIA Report 169 provides a list of the chemicals and properties that a laboratory analysis should check for. Even though the majority of British reservoirs do not have highly urbanised/industrialised catchment areas, the natural leaching of dissolved elements from rocks may cause contamination. In agricultural areas, fertilisers and pesticides can also be a source of sediment contaminants. Given the modest cost of laboratory testing, this should be undertaken regardless of the intended end use for the dredged material.

9 Environmental consequences of reservoir sedimentation

9.1 *Present consequences*

There are a number of direct and indirect consequences of reservoir sedimentation, the most obvious direct consequence being the loss of water resource. However, there are also positive impacts:

- Generation of valuable wetland habitat with biological diversity
- Reduction of fine sediment discharge and hence improved water quality
- Opportunity for uses of sediment deposits in substitution of other peat based compost
- The controls on the use of reservoir catchments may be significantly benefiting the environment

Negative impacts include:

- An average rate of siltation around 0.13% loss per year suggests a mean loss in storage of 3% over a 20 year planning horizon. Replacement resources may be required.
- Periodic operation of bottom outlet valves is required for safety reasons, the high sediment concentrations that may be generated on first opening of the valve may be detrimental
- Restrictions on draw down of reservoirs through bottom outlet valves may be necessary to prevent sediment being mobilised during storms.
- Removal and transport of sediment deposits may have environmental impacts in remote areas

The likely scale of downstream effects of sediment discharge was investigated by Pemberton (1987) and is highlighted by the experience at Grimwith. Together with a team of co-workers Pemberton collected samples at several sites downstream during a number of scour valve tests. Data illustrated for Holme Styes reservoir in May 1986 indicated a peak suspended sediment concentration of just less than 1000 $mg.l^{-1}$ immediately downstream of the valve, decreasing to 300 $mg.l^{-1}$ by the time it reaches The Nook (in the centre of Holmfirth, some 3km downstream) as illustrated in Figure 9.1. During the test at Scammonden reservoir, in June 1986, the sediment concentration immediately downstream peaked at 2763 $mg.l^{-1}$, but then it rose to over 5000 mg l^{-1} as a result of additional scouring by the increased flow moving downstream, and was still elevated to 750 $mg.l^{-1}$ by the time the wave reached Barkisland at 4km downstream. Experience suggests that such levels of suspended sediment would be exceptional under natural flow conditions on these rivers, probably only occurring on a very small minority of days with the highest flows.

Pemberton (1987) also monitored a longer period of drawdown from July to September 1986, when the valves at Wessenden Old reservoir were opened to facilitate engineering works. A heavy rainfall event in August caused partial refilling then rapid drainage again by the middle of September. The final week of the initial drawdown removed 8 tonnes of sediment from the reservoir, followed by approximately a month of quiescence when only a few hundred kg were removed. From 18 to 22 October there was heavy rainfall (59.5mm) and the additional flow removed another 9 tonnes of sediment before the valves were closed on 22 October. A total of 22.15 tonnes was calculated to have been removed from the reservoir during a period of just over 3 months. In practice reservoir managers would be unlikely to sanction opening of valves during summer unless absolutely necessary, since water is valuable at this time of year. A three month draw down in winter would seem likely to have produced a greater removal of sediment, given the evidence of the October rainfall event. Even this, however, seems likely to remove only a small percentage of the incoming sediment, which in this reservoir is known to approach 200 t.km-2.yr-1 (Labadz et al, 1991).

Much more serious consequences occurred when drawing down the old Grimwith Reservoir to allow construction of the enlarged dam as reported in a local association meeting of the Institution of Civil Engineers (Yorkshire Branch) in 1979. Ward (1979) reported how attempts to empty the existing reservoir started in December 1975 and continued until mid-January 1976 when the reservoir bottomed and silt was discharged into the River Dibb, giving a sediment concentration in excess of 1500 mg.l-1 and causing a fish kill. As a result of wet weather the reservoir did not bottom again until February 19th, when considerable amounts of silt again escaped and further fish deaths were caused. Complaints were received from anglers and the general public covering a distance of some 33km downstream into the River Wharfe, and the suspended sediment concentration in the River Dibb (1.3km downstream) peaked at 7736 mg.l-1. This indicates the potential for removal of sediment by opening the valves, but also demonstrates the serious environmental consequences for downstream channels which are likely to make such operations impossible for most British reservoirs. In the case of Grimwith, the operational solution was to dredge the reservoir using a commercial cutter suction dredger and to build a tailings pond as described in Section 8.

9.2 Future sedimentation rates

One major concern at the current time is the likelihood of climate change and its potential impacts. There is an emerging consensus among the scientific community that the future climate and hydrology of the UK will be characterised by increased winter rainfall and flooding plus a greater likelihood of summer droughts and intensified storm activity (Wilby et al, 1997). A new report by Parry et al (2000), as part of the ACACIA project (funded by the European Commission), suggests that mean annual temperatures in Europe have risen by about 0.8°C during the 20th century, with the decade 1990-1999 being the warmest on record, both annually and for the winter season. Precipitation over northern Europe has increased by 10-40% during the 20th century. Their report goes on to consider likely impacts and potential adaptation in a variety of sectors , including water resources. Lessons may also be learned from studies such as that by Palutikof et al (1997) which considered the economic impacts of the hot summer and unusually warm year of 1995 in the UK. This concluded that the added direct cost of supplying water in 1995/6 compared to 1994/5 was at least £96 million, but that further modelling and analysis was necessary to enable water resource mangers to choose appropriate response strategies.

Likely effects of climate change and implications for water resources in Britain were discussed in some detail by Arnell (1996). He outlined possible approaches to the control of supply and demand for water, and presented analysis which suggests that a 1 degree rise in temperature could lead to an additional 4% on domestic demand in southern England by 2021. One conclusion was that the sensitivity of water supply systems to climate change depends significantly on current storage and yield relative to inflows. Direct river abstractions would be adversely affected during summer in southern Britain, because summer river flows are expected to reduce. In Northern and upland Britain the effects on summer river flows are expected to be smaller. Small reservoirs with little storage, which rely on frequent replenishment, would also be affected by the predicted changes which give reduced spring and summer inflows. The water industry in Britain is currently planning strategies to meet these changing circumstances and a number of options have been evaluated including transfer of water between basins, development of new resources, treatment of effluent, control of losses by leakage and management of demand by customers (eg. Sherriff et al, 1996). The Environment Agency is publishing its new water resources strategies for England and Wales in March 2001.

One possible impact of climate change in the coming decades is increased autumn rainfall (Arnell, 1996) which may give increased soil erosion, especially when such events occur on bare prepared ground as was the case in the autumn of 2000. This may in turn lead to increased reservoir sedimentation, although the storage in the fluvial system may often reduce the effect. Wilby et al (1997) investigated the impact of historical weather patterns on historic and contemporary catchment sediment yields (estimated from lake and reservoir sediment cores). Despite contrasting land use and geographical locations for their four catchments, the winter frequency of cyclonic patterns emerged as the most significant variable correlating with historic sediment yields. This was more significant than rainfall total, suggesting that other factors such as extreme events, storm interval times, antecedent soil moisture, rainfall intensities and storm durations are perhaps incorporated within the existence of the cyclonic pattern. The frequency of cyclones across the British Isles has been increasing steadily since the 1890s and, should this trend persist, erosion rates and sediment yields will increase under current agricultural land use scenarios.

Given the uncertainties of modelling climate change and those of predicting sediment yield from a particular catchment under current conditions, any effort to model the likely increase in sediment yield due to climate change is at present lacking in accuracy. Evans (1990) suggested that, with global warming, there may be an increase in land at moderate to very high risk of erosion , from 23.9% in 1990 up to 46.1%. Specifically, 126 soil associations (the soil types defined in the detailed mapping of soils in Britain) are likely to see greater risk of erosion. Conversely, 10 soil associations would be less vulnerable to wind erosion but this would be because most of the peat susceptible to erosion would have wasted away. No figures were given for actual erosion rates.

Boardman et al (1990) present figures for soil erosion in the South Downs, assuming no change in land use. They suggested that a 5% increase in mean annual rainfall would result in a 11.5% increase in erosion rate, whilst a 20% increase in rainfall would give a 34.6% increase in erosion. Obviously these are simulated figures for one site, and extrapolation to other sites or larger catchments should be treated with caution. Nevertheless, the increases illustrate the likely magnitude of the problem. If land use change is incorporated in the model (for example an increase in irrigation and the proportion of land under maize) the effect is likely to be even more marked.

Wilby et al (1997) discussed linkages between occurrence of cyclonic weather patterns and sedimentation rates in 4 lakes, and demonstrate a relationship between these and sedimentation, but conclude that the impact of climate change on sedimentation for a particular lake or reservoir will depend upon storage in the catchment, on the hillslopes and in the channels, as well as on the changes in rainfall, temperature and land use.

Evans (1990) has identified those soil associations in England and Wales most at risk of accelerated erosion as a result of intensification of agriculture or climate change. More than 36% of arable England is at moderate to very high risk. In these areas soil conservation measures are vital for sustainable agriculture, regardless of whether there are reservoirs which might experience rapid sedimentation as a result. However results of repeated measurements on reservoirs have not so far shown significant changes in sedimentation except where changes in land use have occurred.

For water resource purposes, catchment management is the most desirable long term solution to excessive reservoir sedimentation. However, it may be a slow and expensive or even politically unacceptable option in some circumstances. The transfer system may also be used to minimise delivery by means of sediment control measures, and operation of the reservoir itself may be seen as the final stage in the reduction of sedimentation.

10 Potential areas for further research

As a result of this study, a number of potential areas for further research have been identified as follows:

1. Refinement and application of the Classification Method to all potable supply reservoirs to give more definitive rates of siltation and loss of capacity. Use could be made of new rainfall-runoff information from Flood Estimation Handbook and soil association assessments of soil at risk of erosion. This would allow a better geographic representation of the spatial extent of likely sedimentation.

2. Incorporate the above into regional assessments and study the likely impacts on water resource planning.

3. Improve the classification and review siltation rates for pumped storage reservoirs.

4. Attempt to refine predictions of sediment movement under dam failure conditions to produce a working guide for engineers.

5. Draw up guidelines for the routine operation of bottom outlet valves as required for reservoir safety.

6. Carry out further data collection, experimental and economic analysis on effectiveness of sediment reduction measures including derivation of better designs for residuum lodges / silt traps.

7. Consider further the impact of predicted changes in sedimentation patterns due to climate change.

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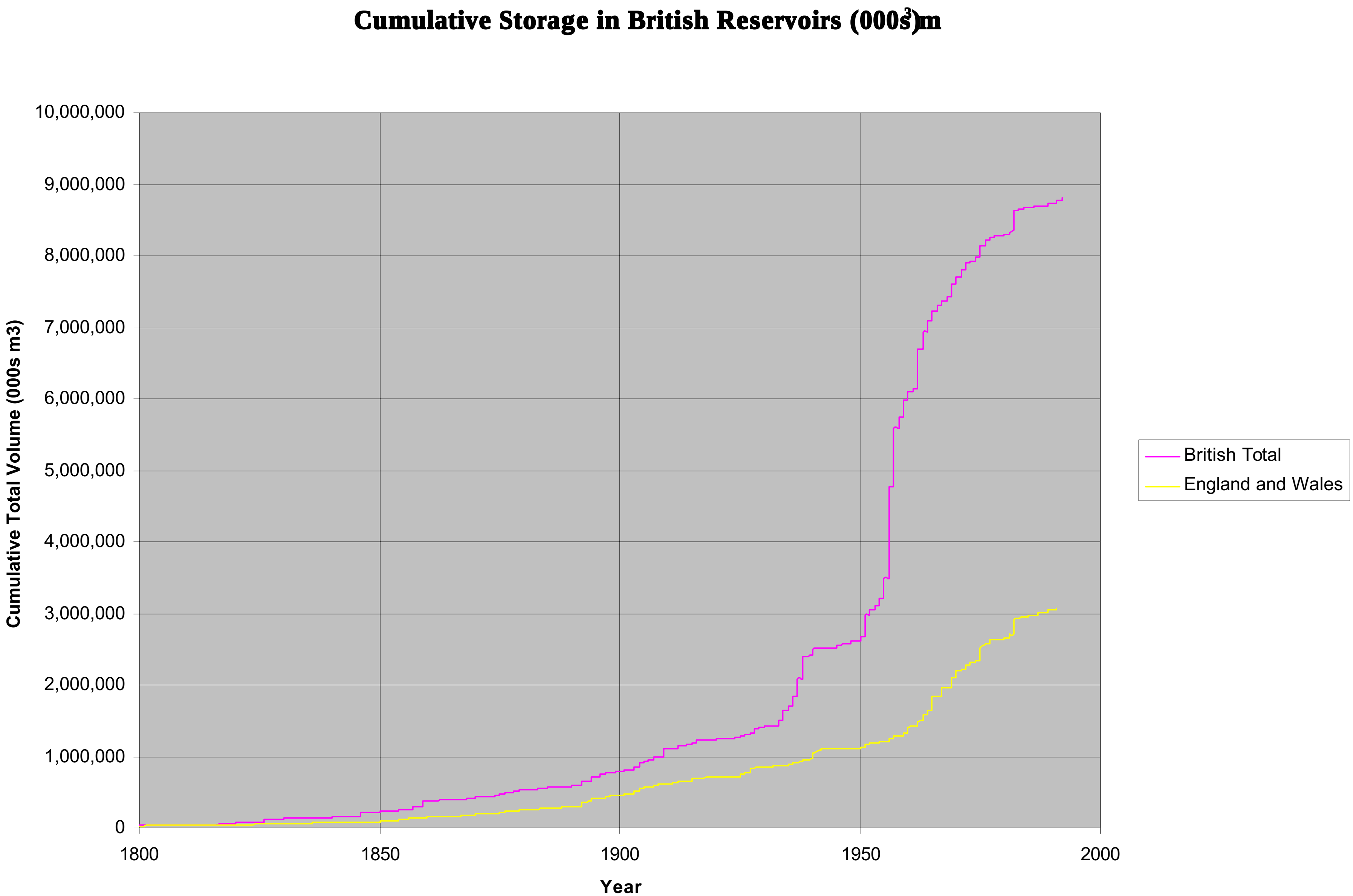
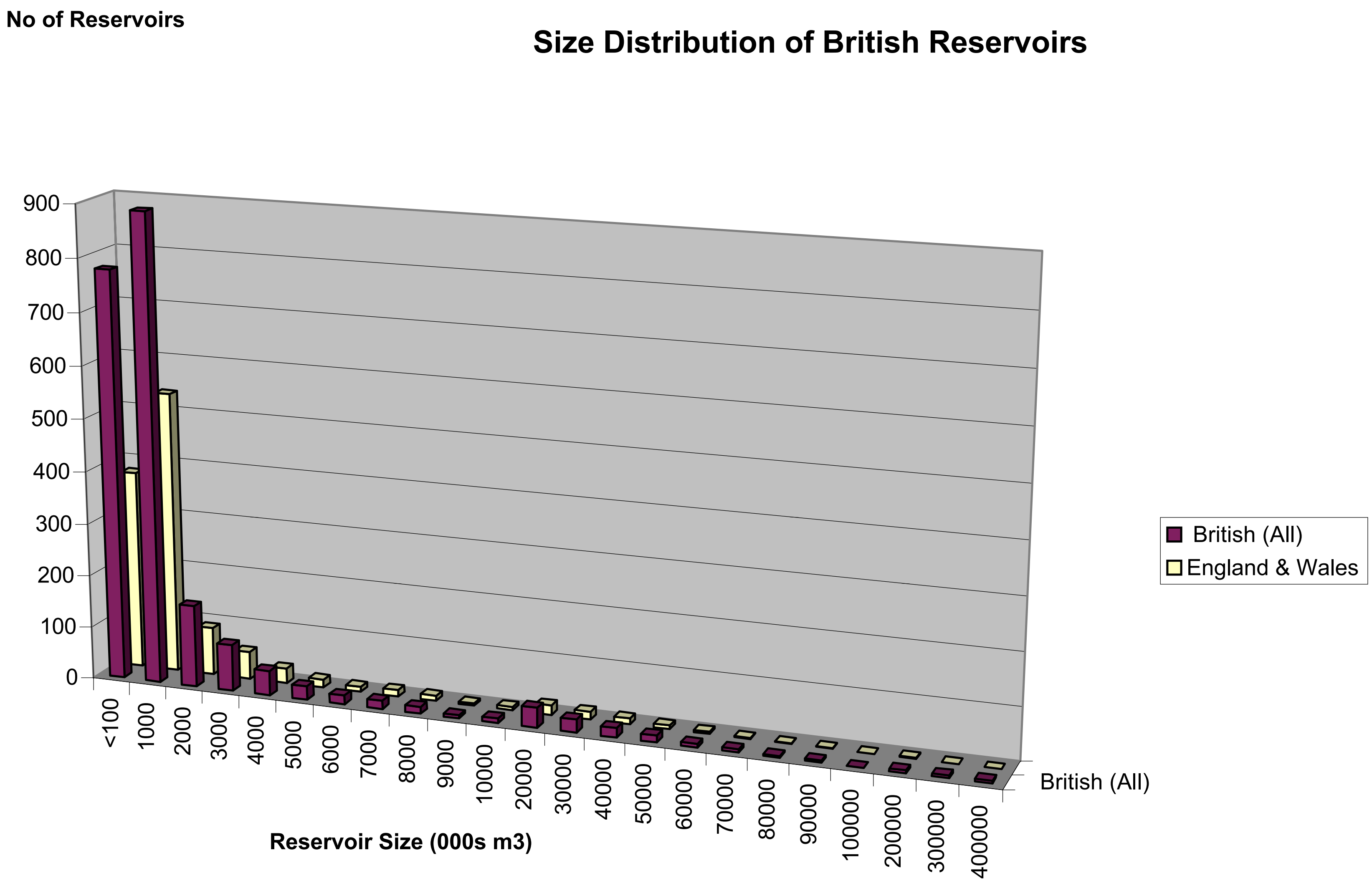
Location of Reservoirs in BRE Database

Figure 3.1



Cumulative Storage in British Reservoirs (000s m3)
10,000,000
9,000,000
8,000,000
7,000,000
6,000,000
5,000,000
4,000,000
3,000,000
2,000,000
1,000,000
0
Cumulative Total Volume (000s m3)
1800
1850
1900
1950
2000
Year
British Total
England and Wales

Figure 4.1


No of Reservoirs
Size Distribution of British Reservoirs
900
800
700
600
500
400
300
200
100
0
<100
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
20000
30000
40000
50000
60000
70000
80000
90000
100000
200000
300000
400000
Reservoir Size (000s m3)
British (All)
British (All)
England & Wales

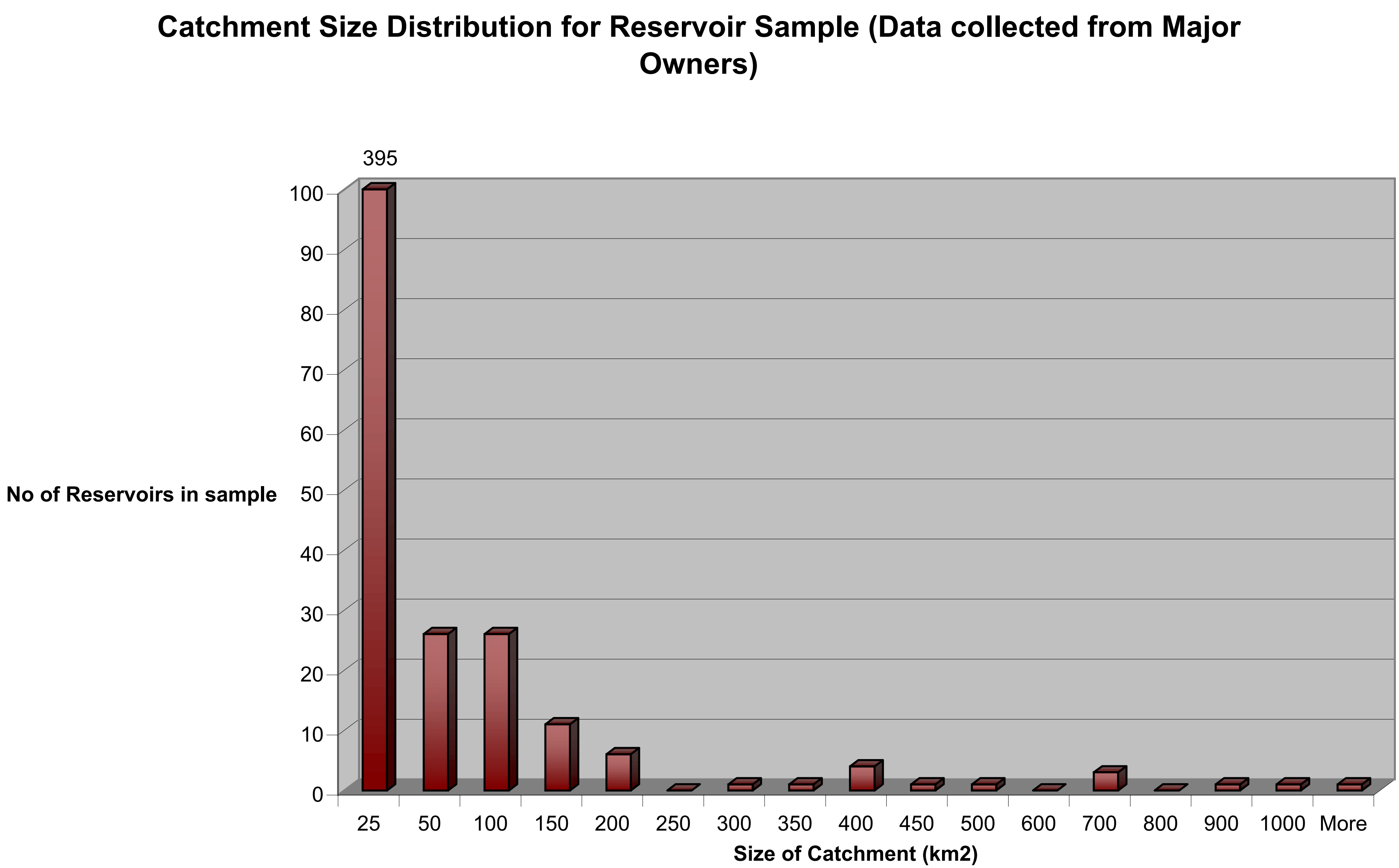

Catchment Size Distribution for Reservoir Sample (Data collected from Major Owners)
395
100
90
80
70
60
50
40
30
20
10
0
No of Reservoirs in sample
25
50
100
150
200
250
300
350
400
450
500
600
700
800
900
1000
More
Size of Catchment (km2)

Figure 4.3

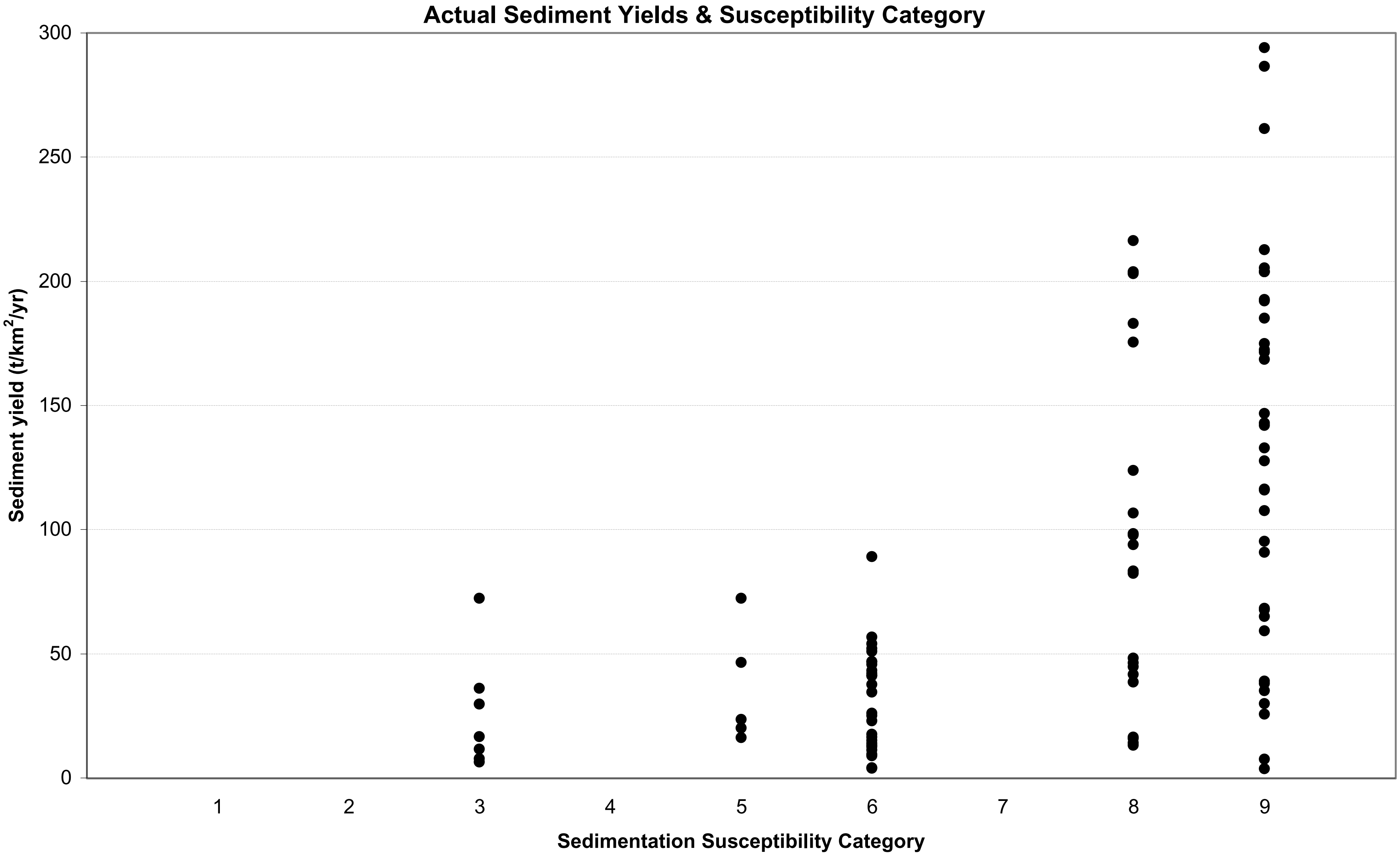
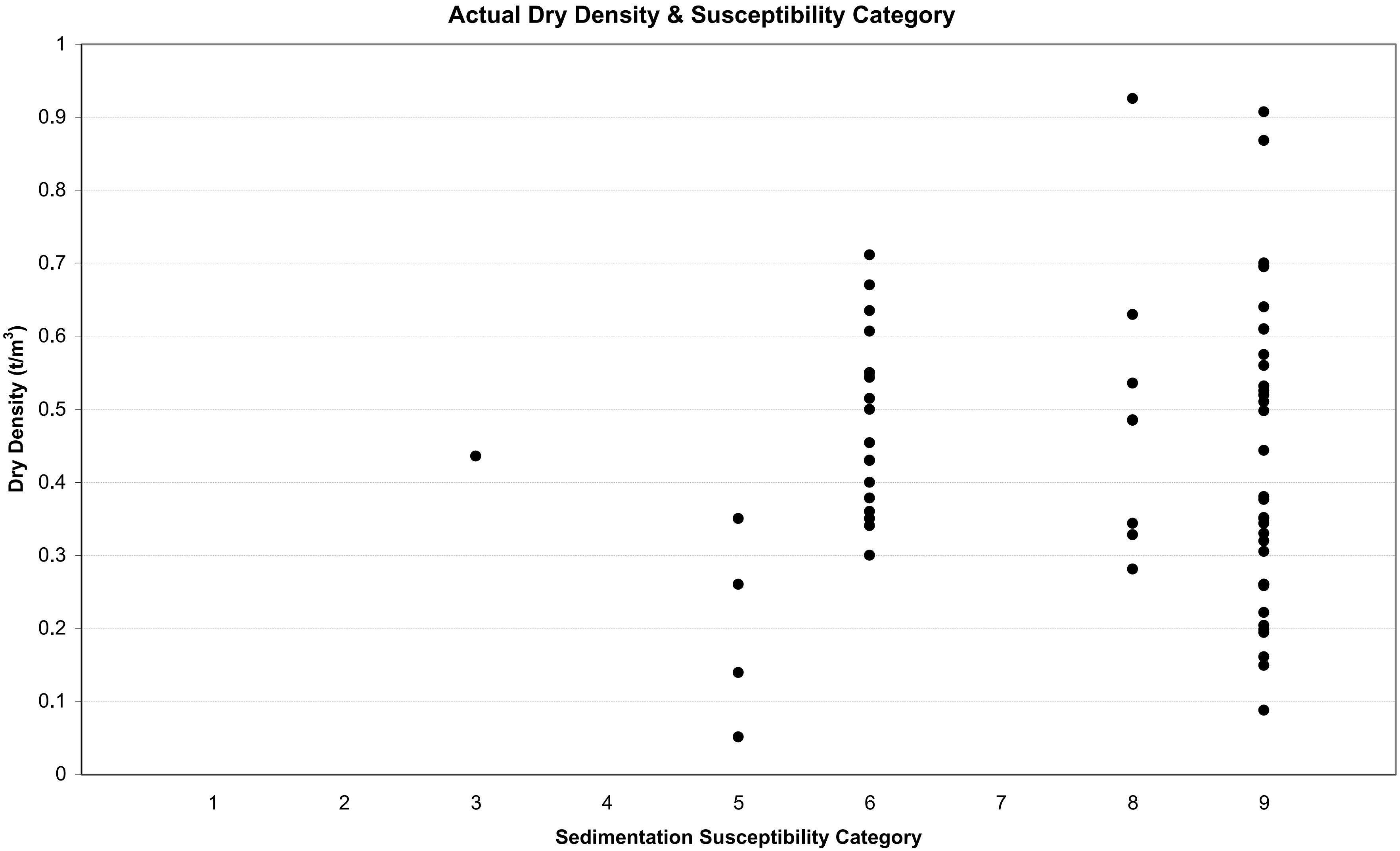

Actual Sediment Yields & Susceptibility Category
Sediment yield (t/km²/yr)
300
250
200
150
100
50
0
1
2
3
4
5
6
7
8
9
Sedimentation Susceptibility Category

Figure 4.4



Actual Dry Density & Susceptibility Category
Dry Density (t/m³)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1
2
3
4
5
6
7
8
9
Sedimentation Susceptibility Category

Figure 5.1

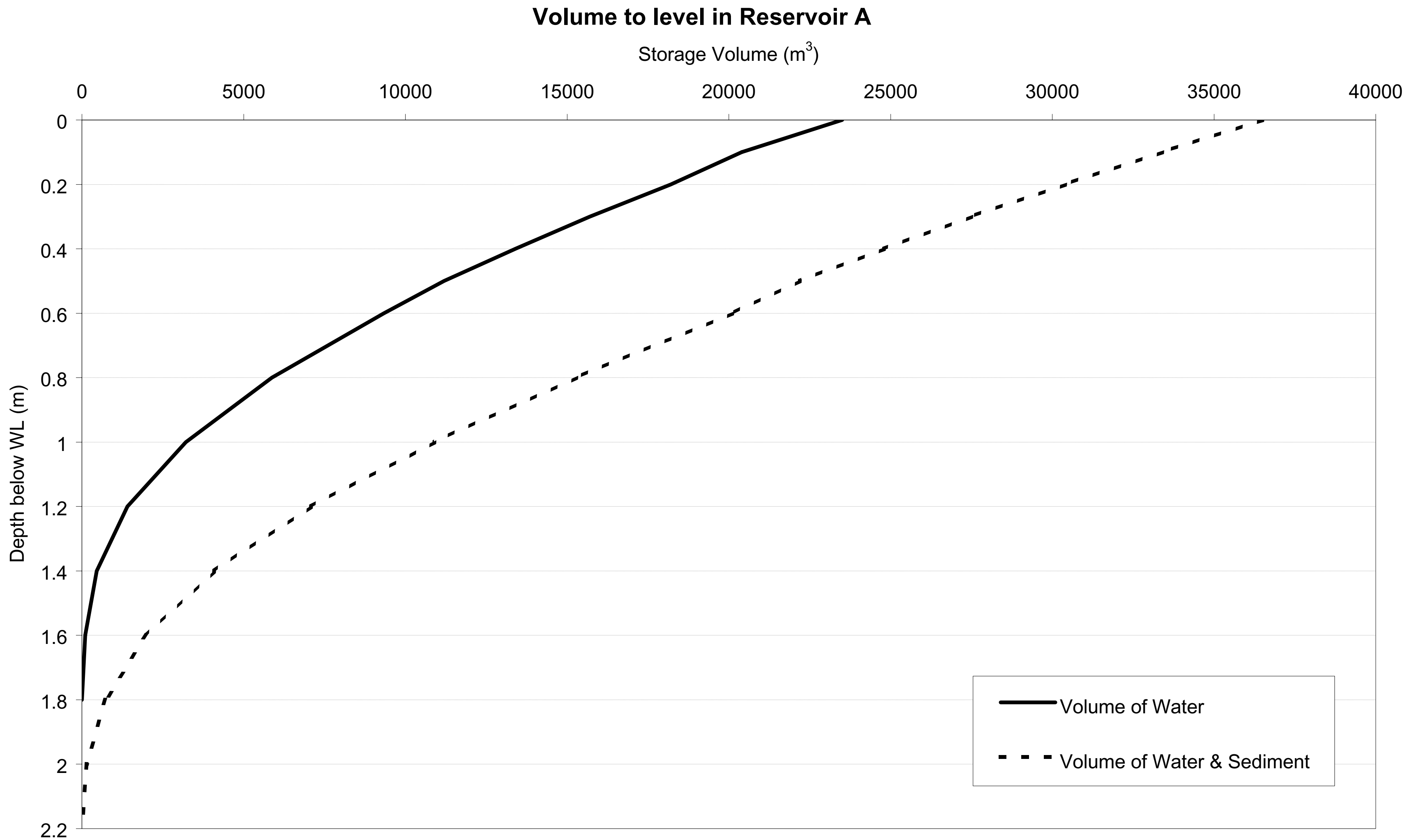
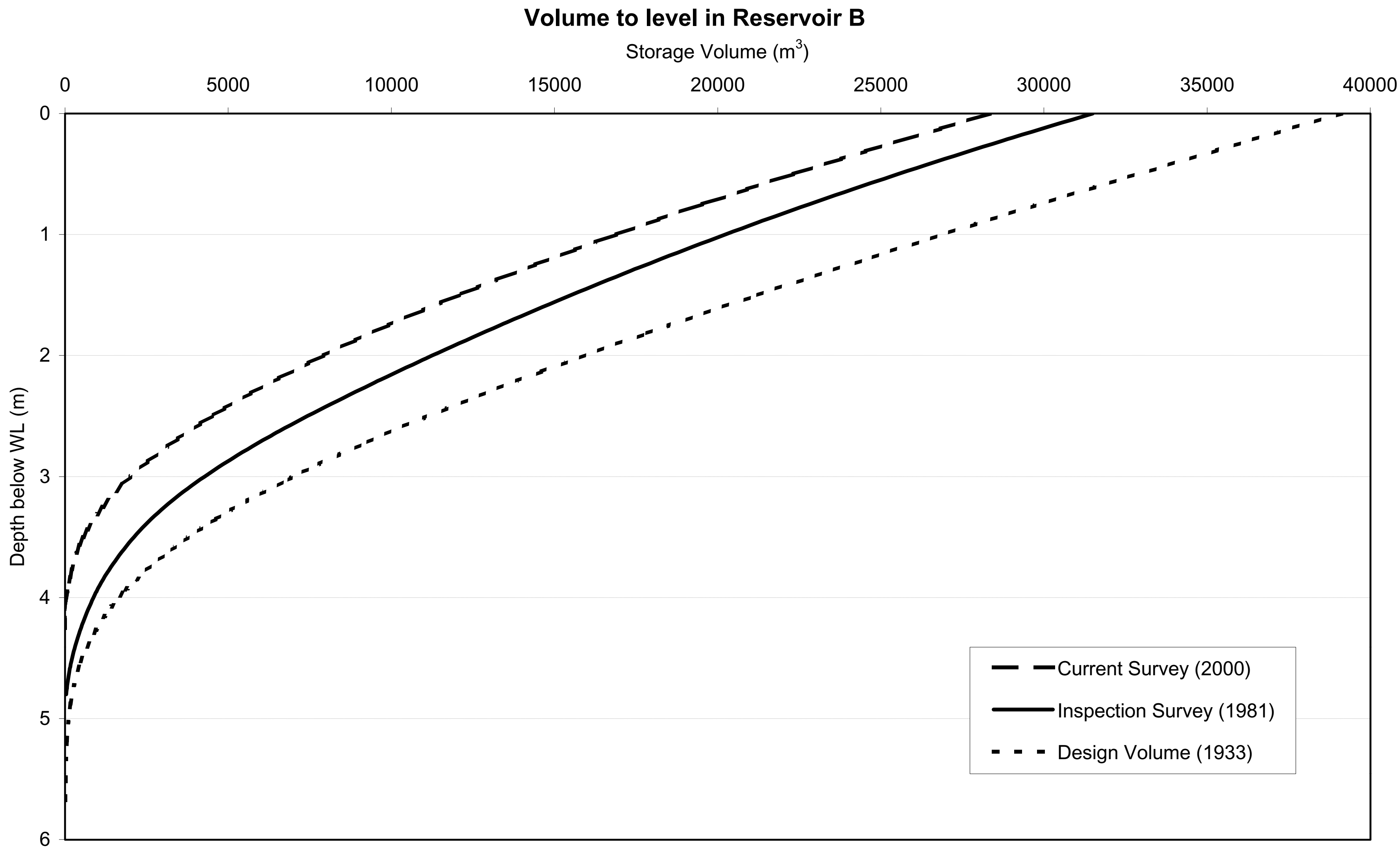


Figure 5.1

Figure 5.2



Volume to level in Reservoir B
Storage Volume (m3)
0
5000
10000
15000
20000
25000
30000
35000
40000
0
1
2
3
4
5
6
Depth below WL (m)
Current Survey (2000)
Inspection Survey (1981)
Design Volume (1933)

Figure 5.3

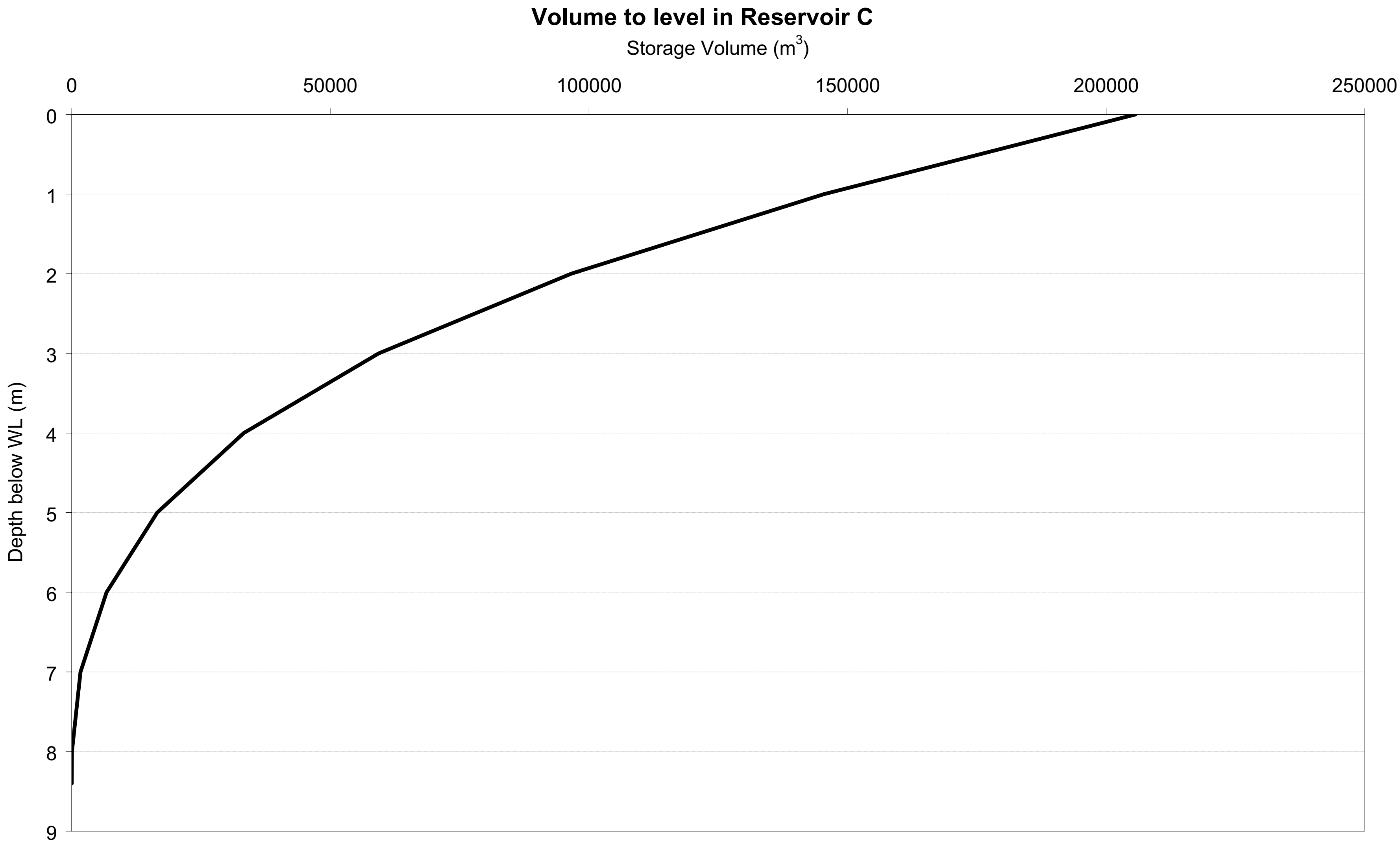


Figure 5.3

Figure 6.1

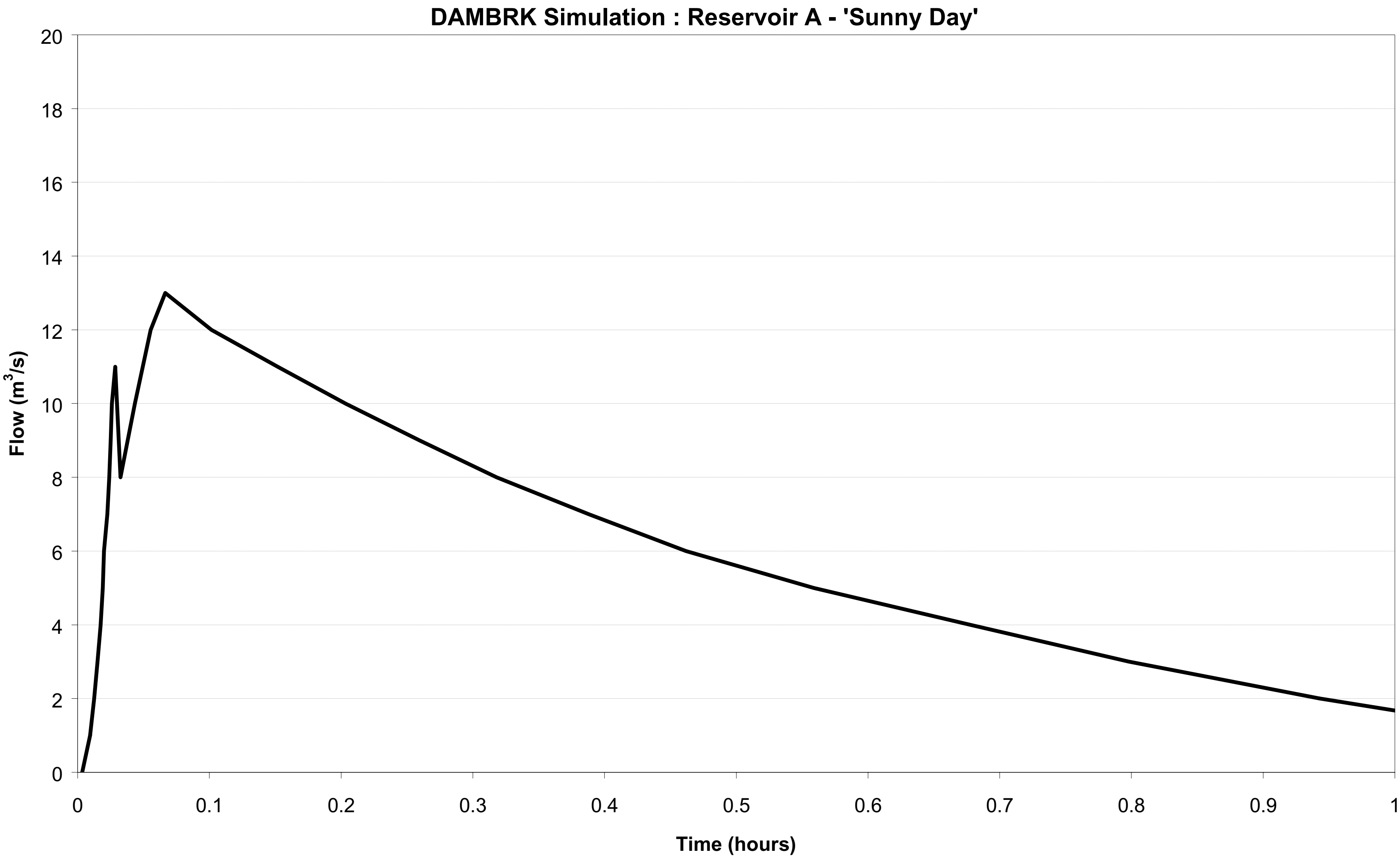


Figure 6.1

Figure 6.2

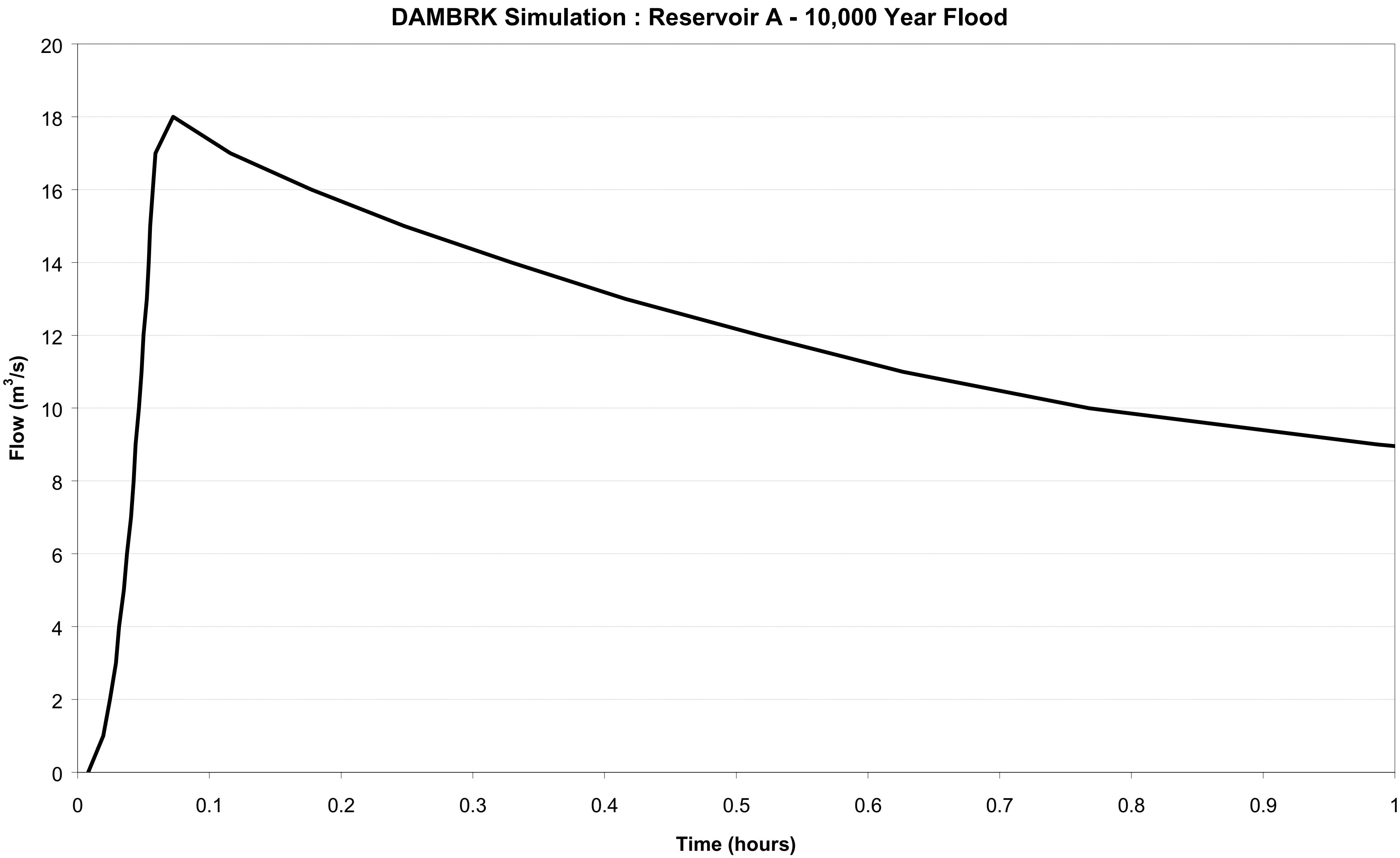


Figure 6.2

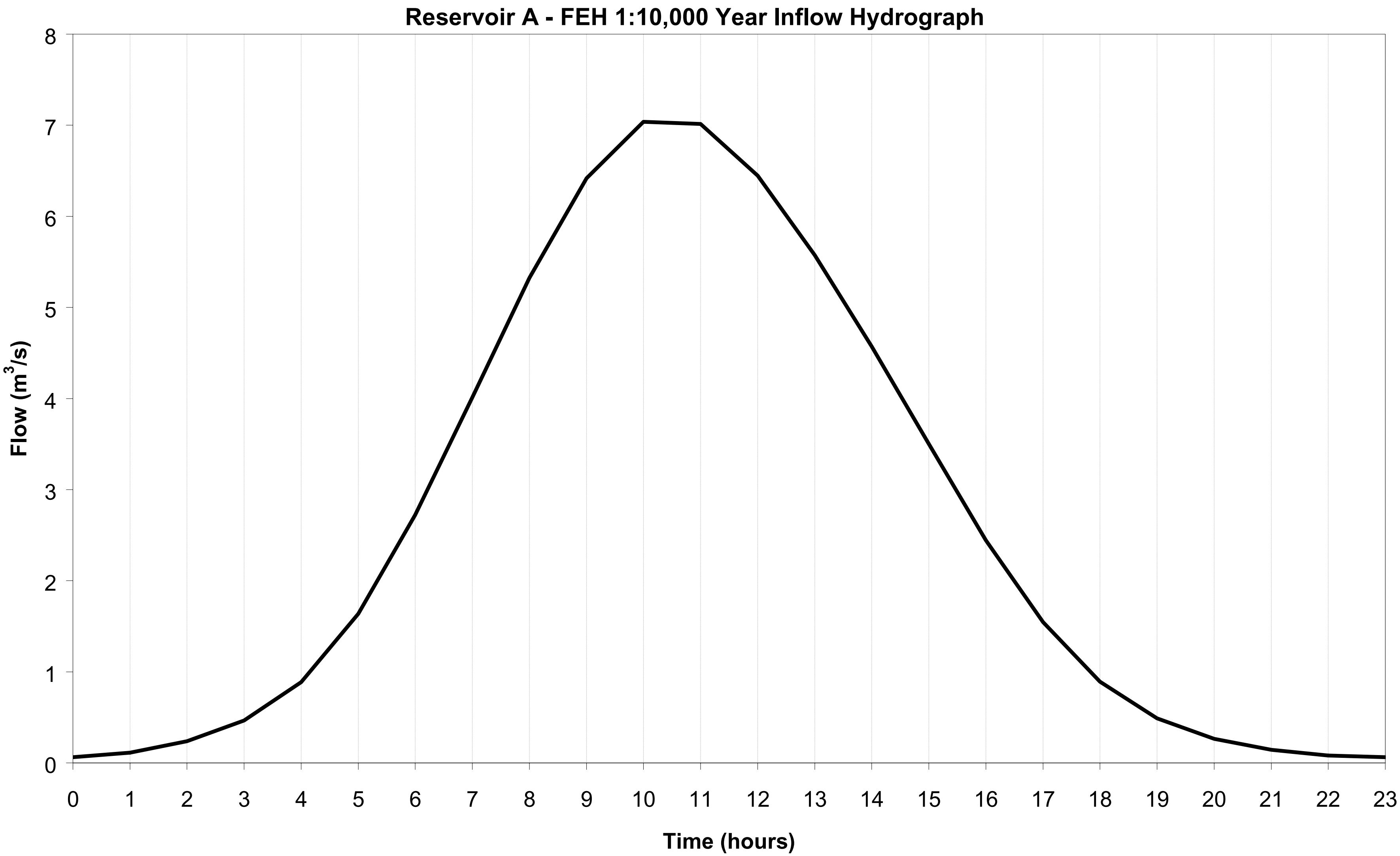

Reservoir A - FEH 1:10,000 Year Inflow Hydrograph
Flow (m^3/s)
0
1
2
3
4
5
6
7
8
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Time (hours)

Figure 6.3

Figure 6,4

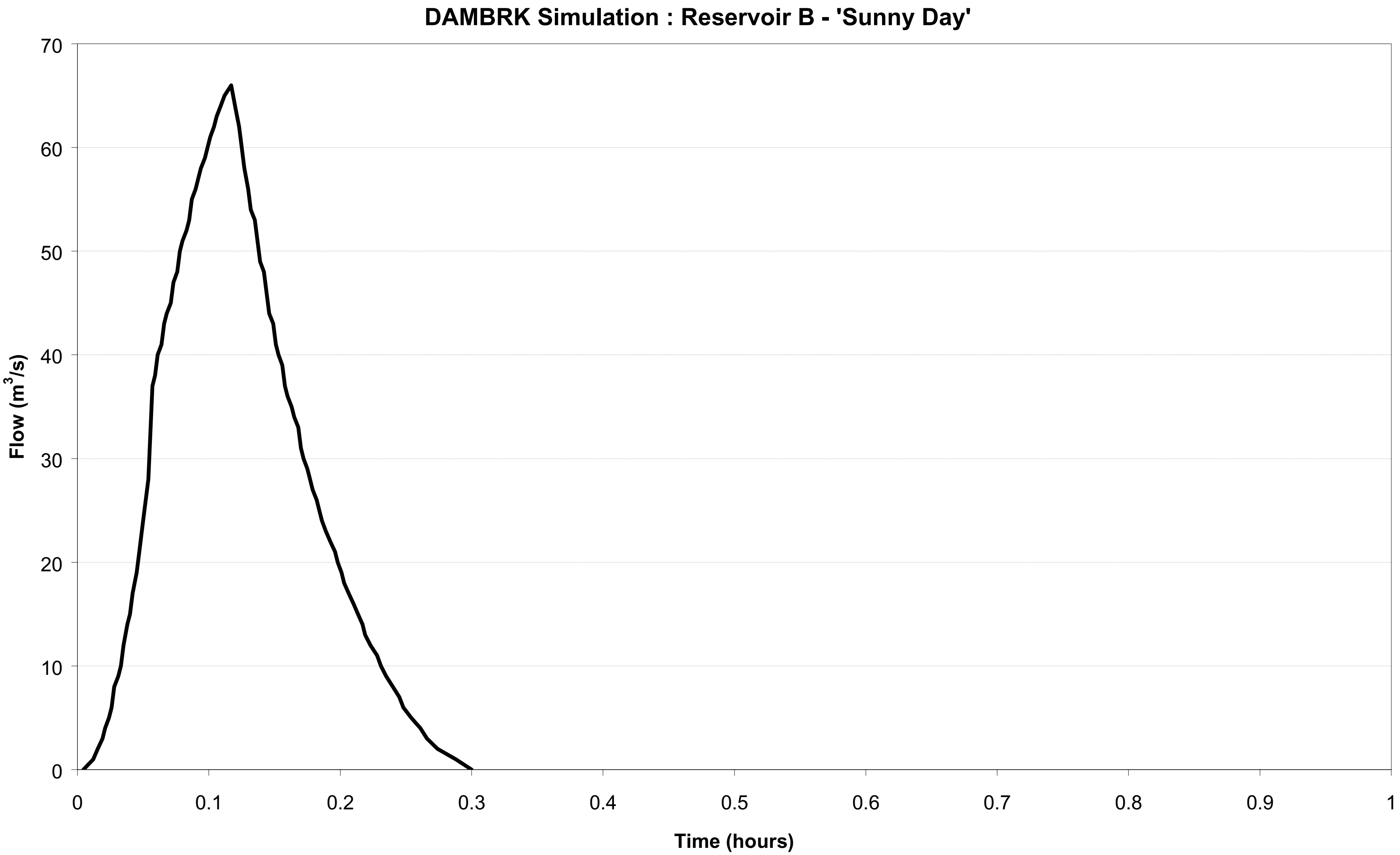


Figure 6.4

Figure 6.5

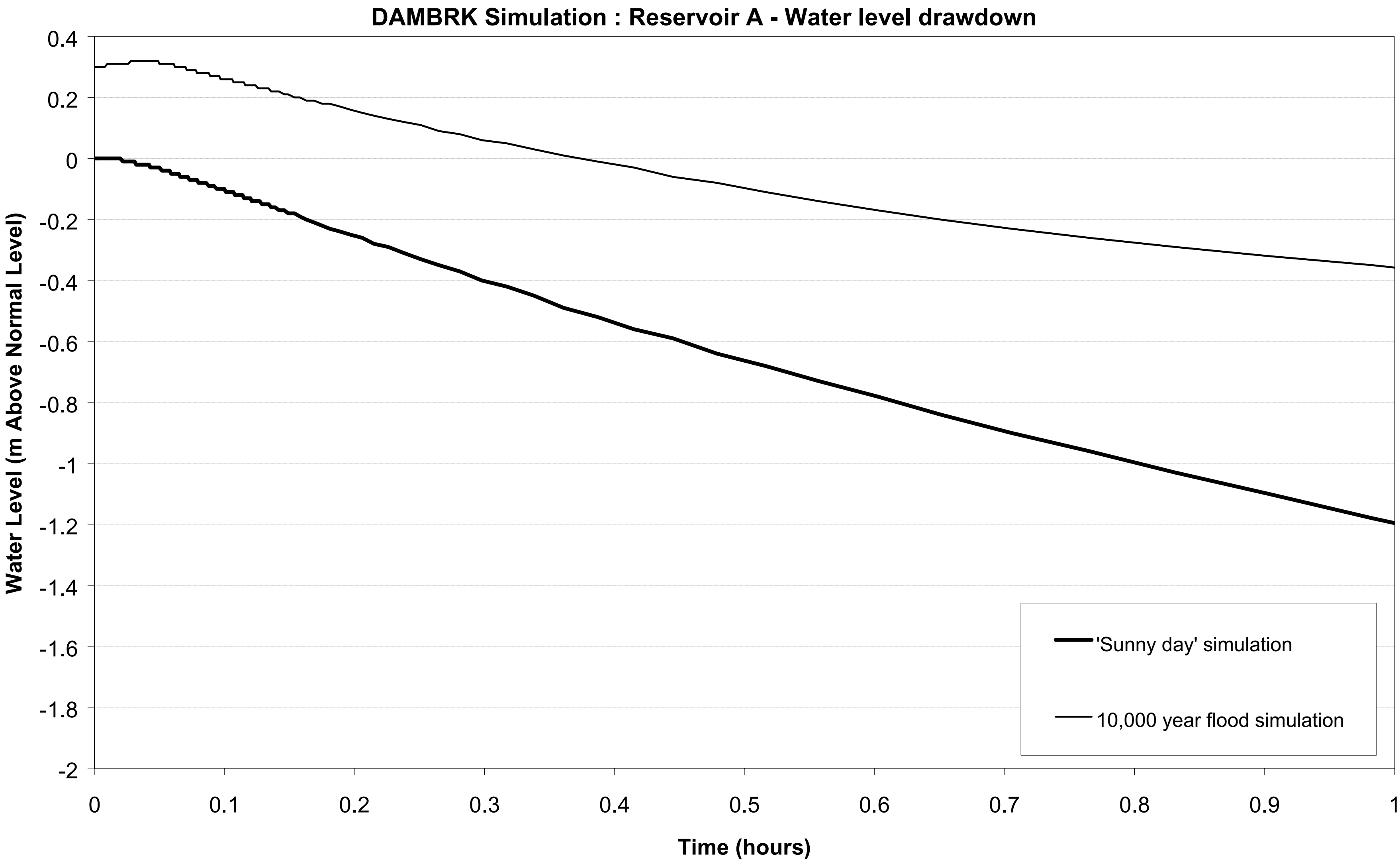
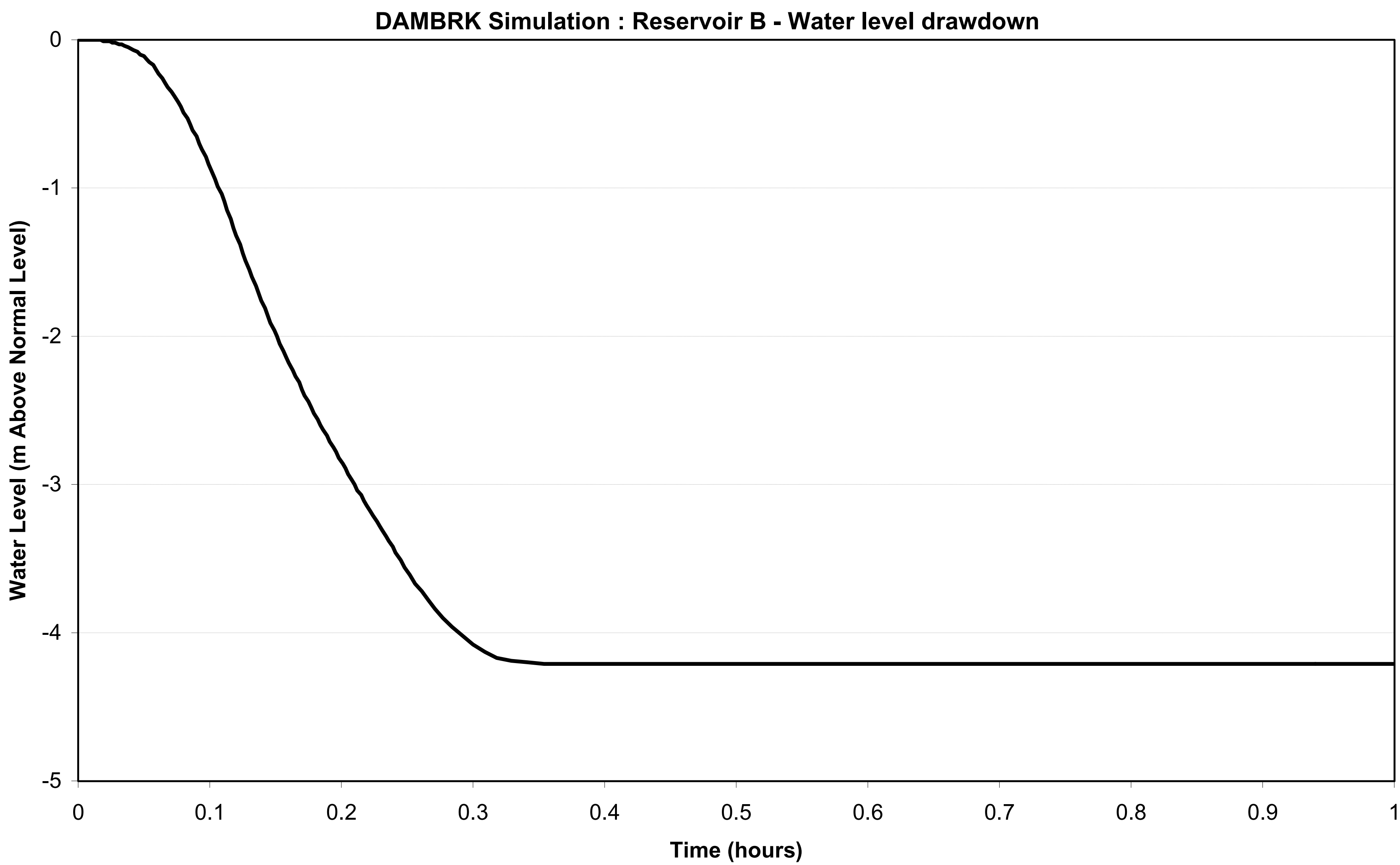


Figure 6.5

Figure 6.6



DAMBRK Simulation : Reservoir B - Water level drawdown
Water Level (m Above Normal Level)
0
-1
-2
-3
-4
-5
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Time (hours)

Figure 6.7 Reservoir A Dambreak - Development of Bed Shear Stress (N/m^2) with 'Sunny Day' Inflow Conditions

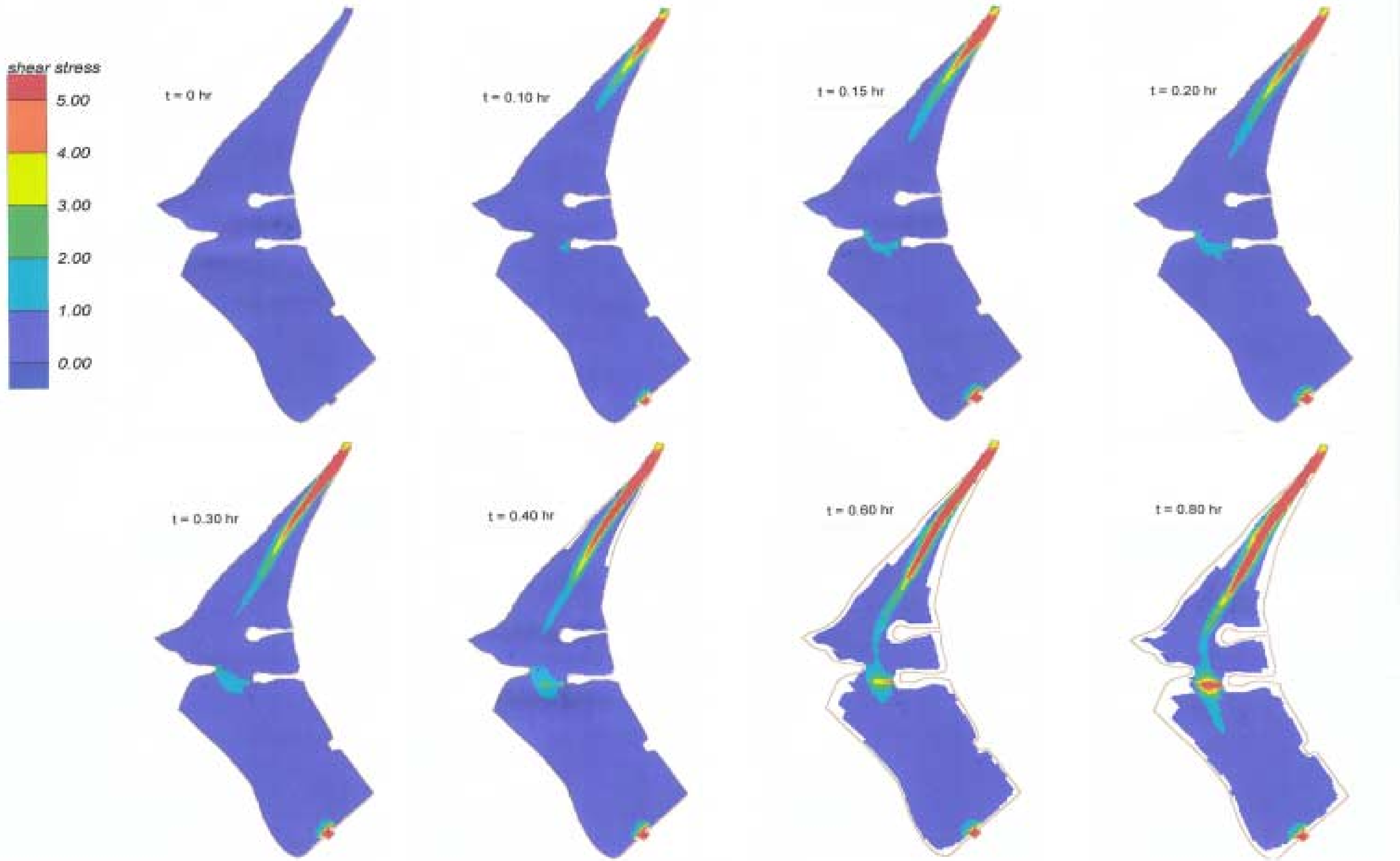


Figure 6.8 Reservoir A Dambreak - Development of Bed Shear Stress (N/m^2) with 10,000-year Flood Inflow Conditions

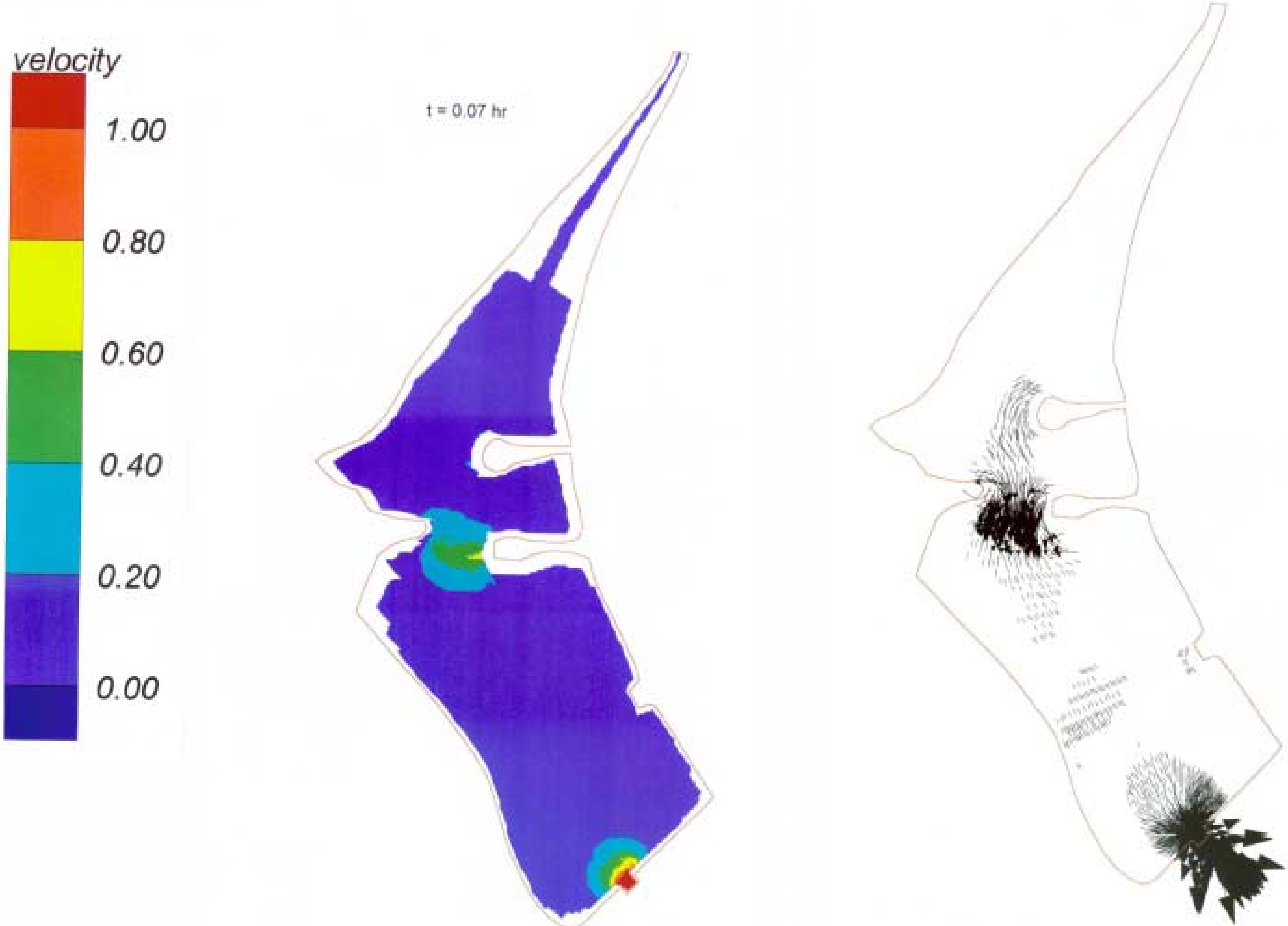


Figure 6.9 Reservoir A Dambreak - Velocity Contours (m/s) and Vectors with 'Sunny Day' Inflow Conditions

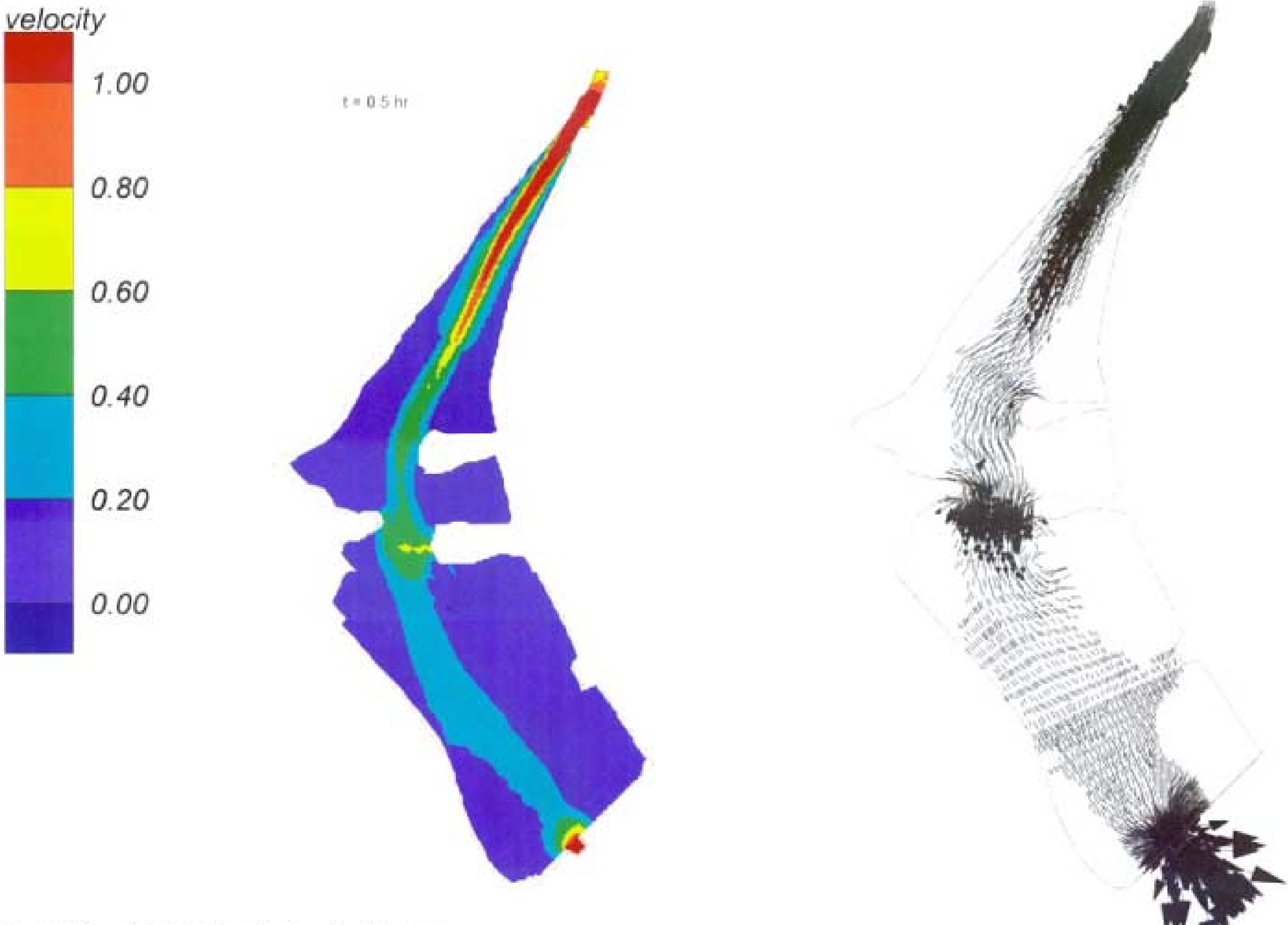


Figure 6.10 Reservoir A Dambreak - Velocity Contours (m/s) and Vectors with 10,000-year Flood Inflow Conditions

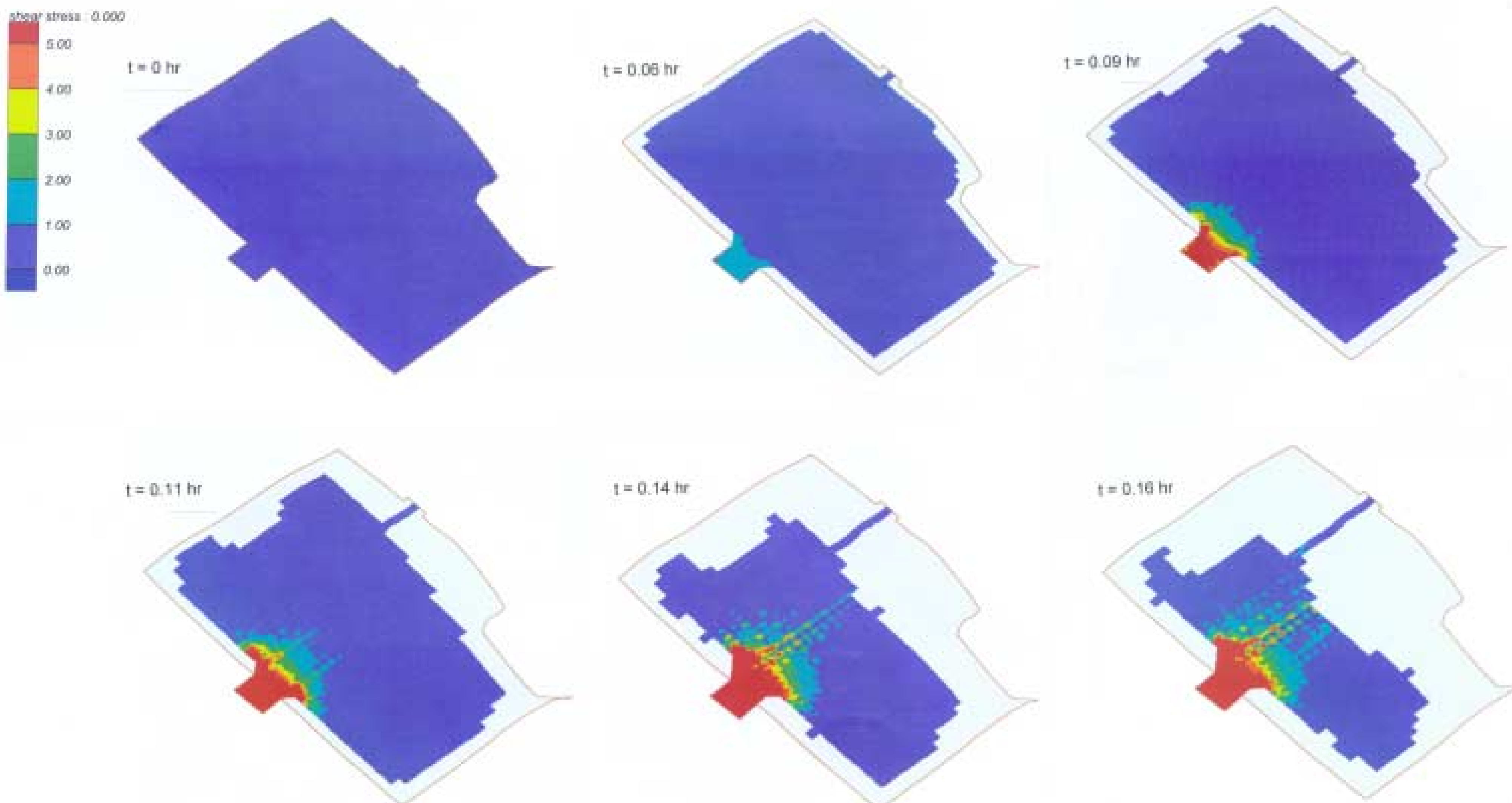


Figure 6.11 Reservoir B Dambreak - Development of Bed Shear Stress (N/m^2) with 'Sunny Day' Inflow Conditions

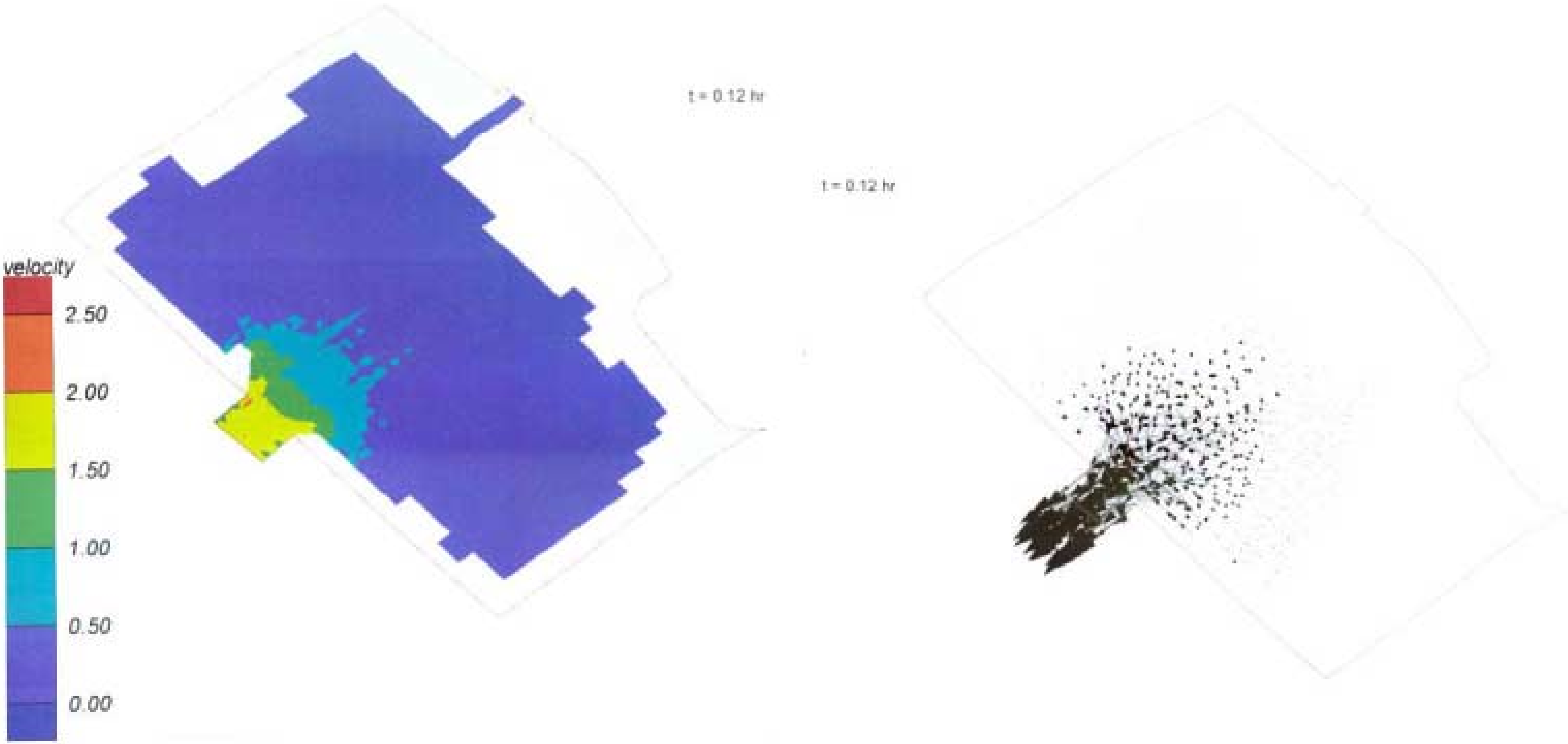


Figure 6.12 Reservoir B Dambreak - Velocity Contours (m/s) and Vectors with 'Sunny Day' Inflow Conditions

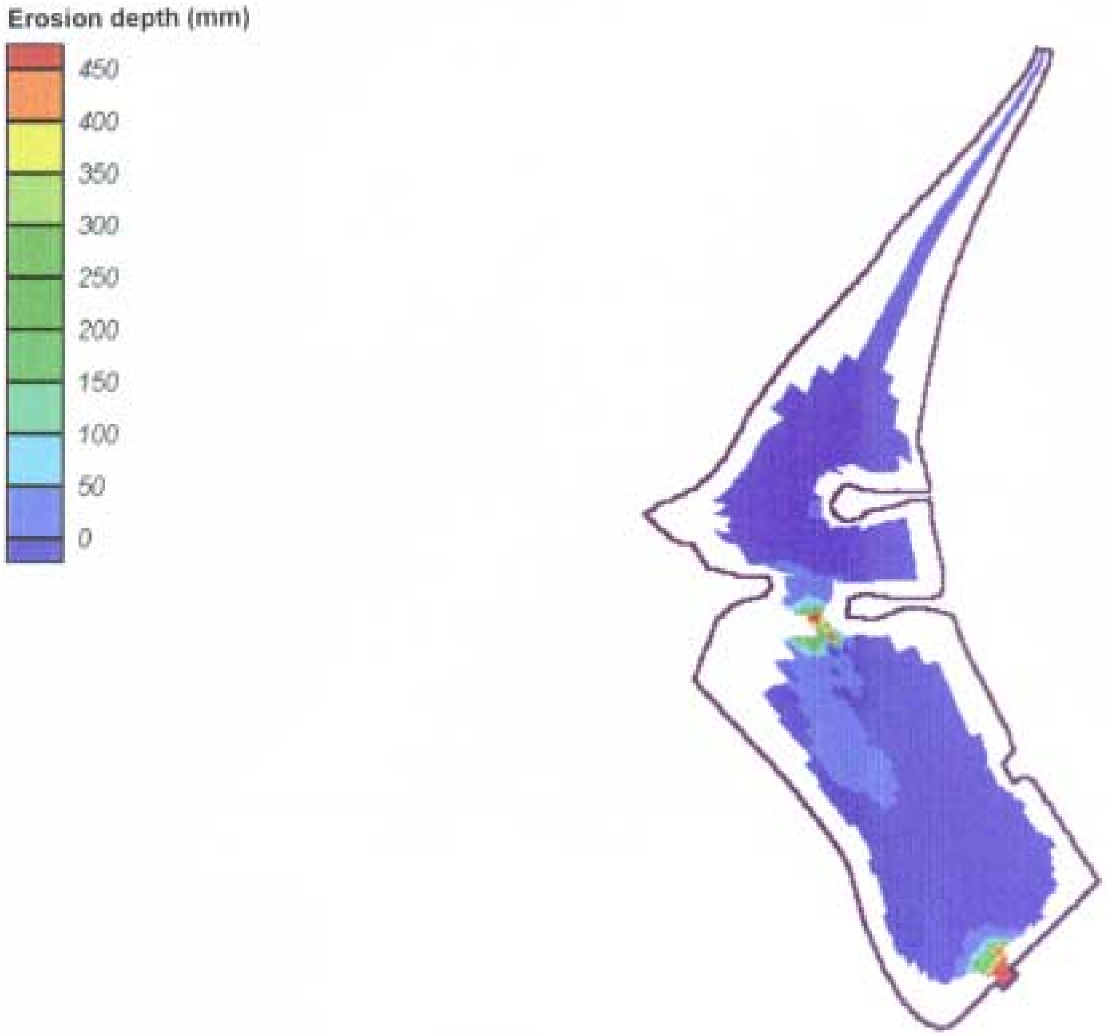


Figure 6.13 **Reservoir A** Dambreak – Total erosion depth with 'Sunny Day' Inflow Conditions

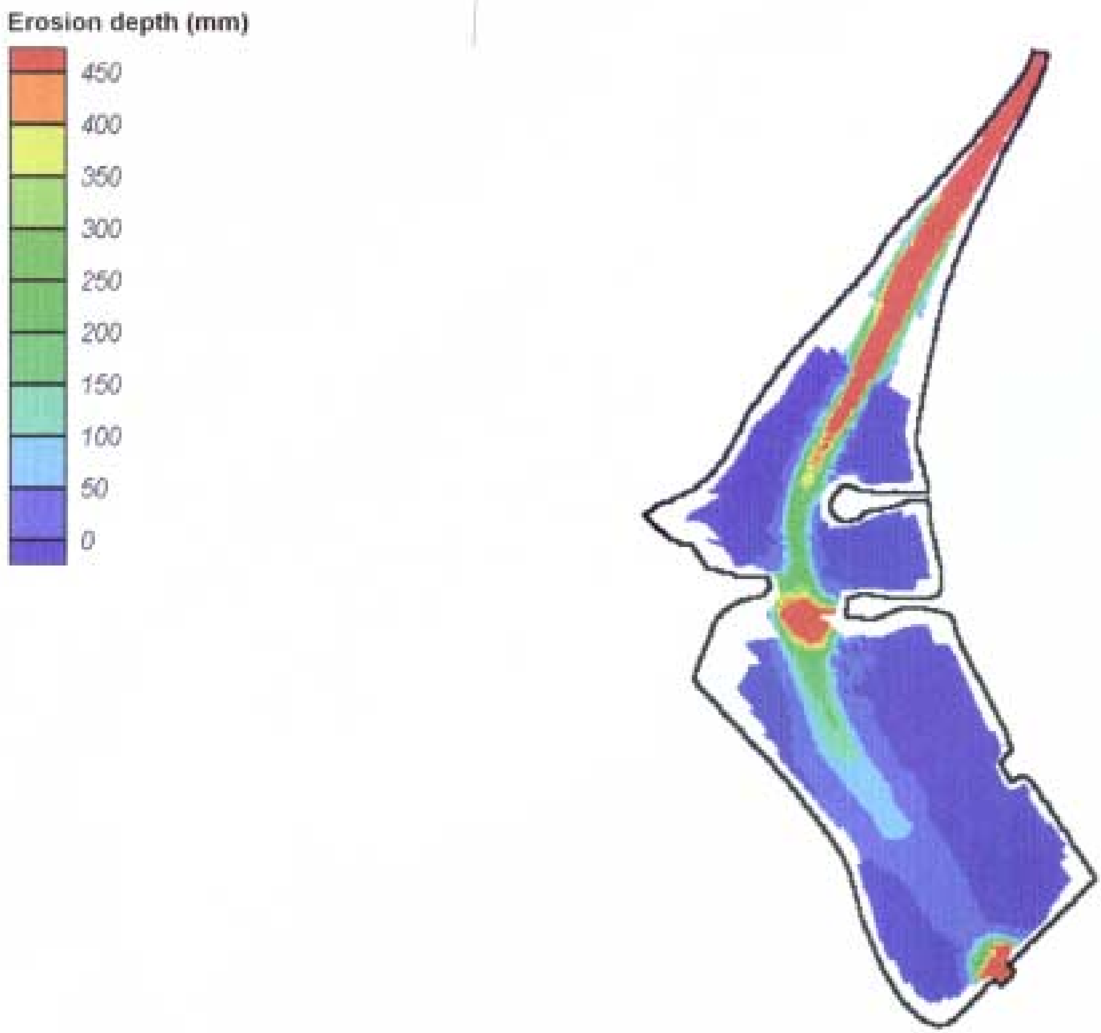


Figure 6.14 Reservoir A Dambreak – Total erosion depth with 10,000-year Flood Inflow Conditions

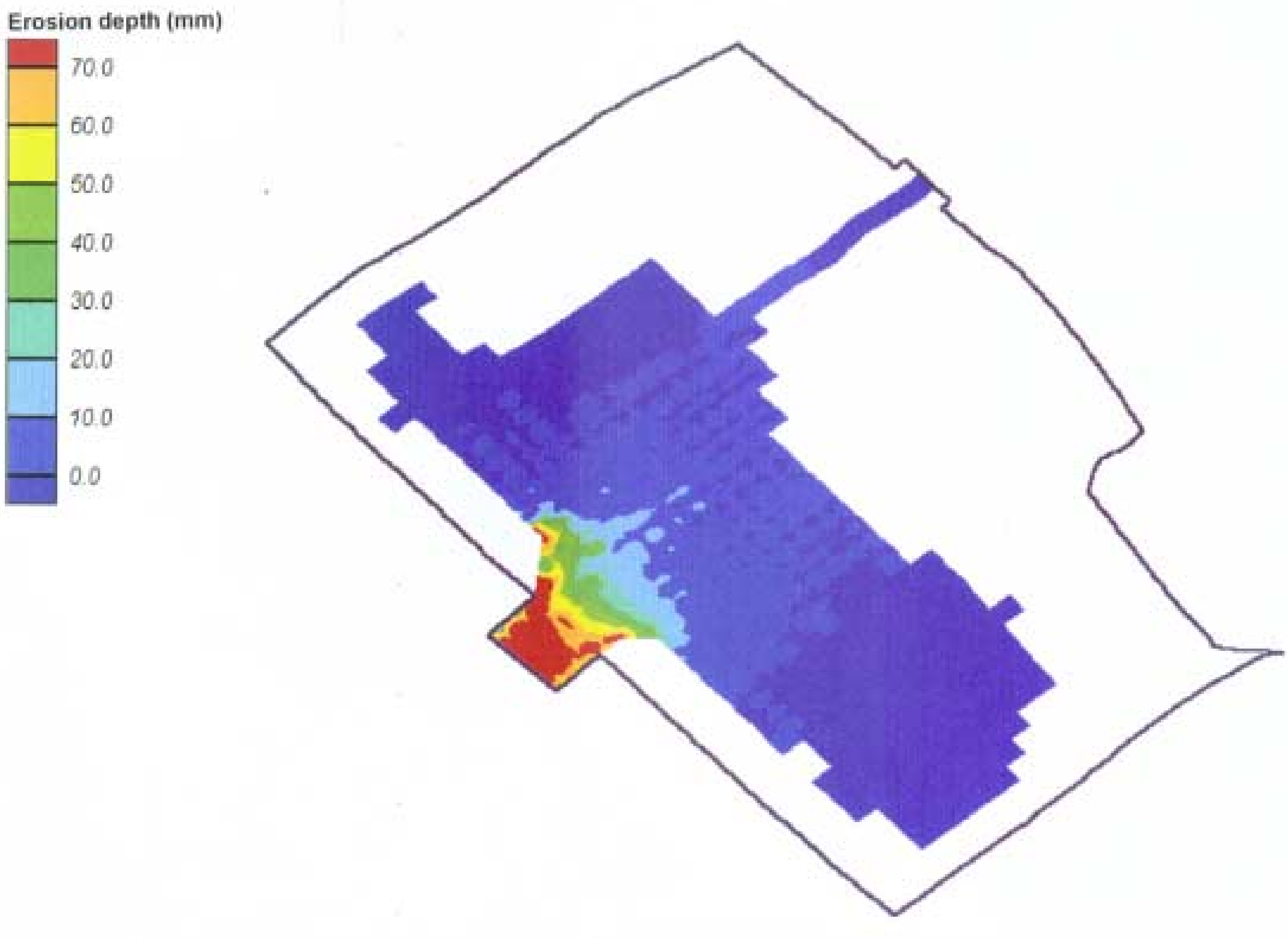
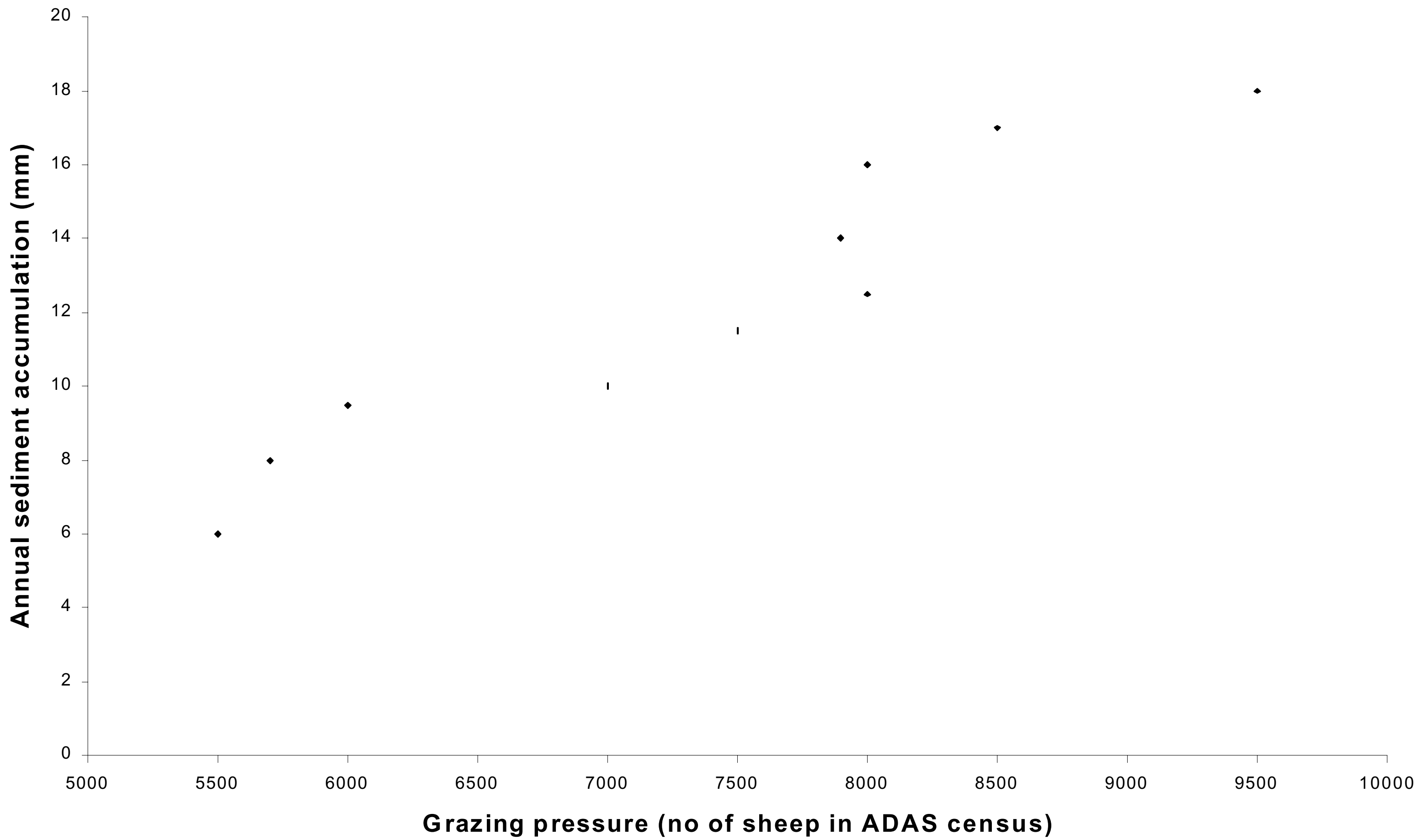


Figure 6.15 **Reservoir B** Dambreak – Total erosion depth with 'Sunny Day' Inflow Conditions

Figure 7.1



Correlation between annual rate of sediment accumulation in Blelham Tarn and total number of sheep in adjacent parishes (after Van der Post *et al*, 1997).

Figure 7.1

Figure 7.2

Progress of Scour valve test, Blakeley Reservoir, October 1985

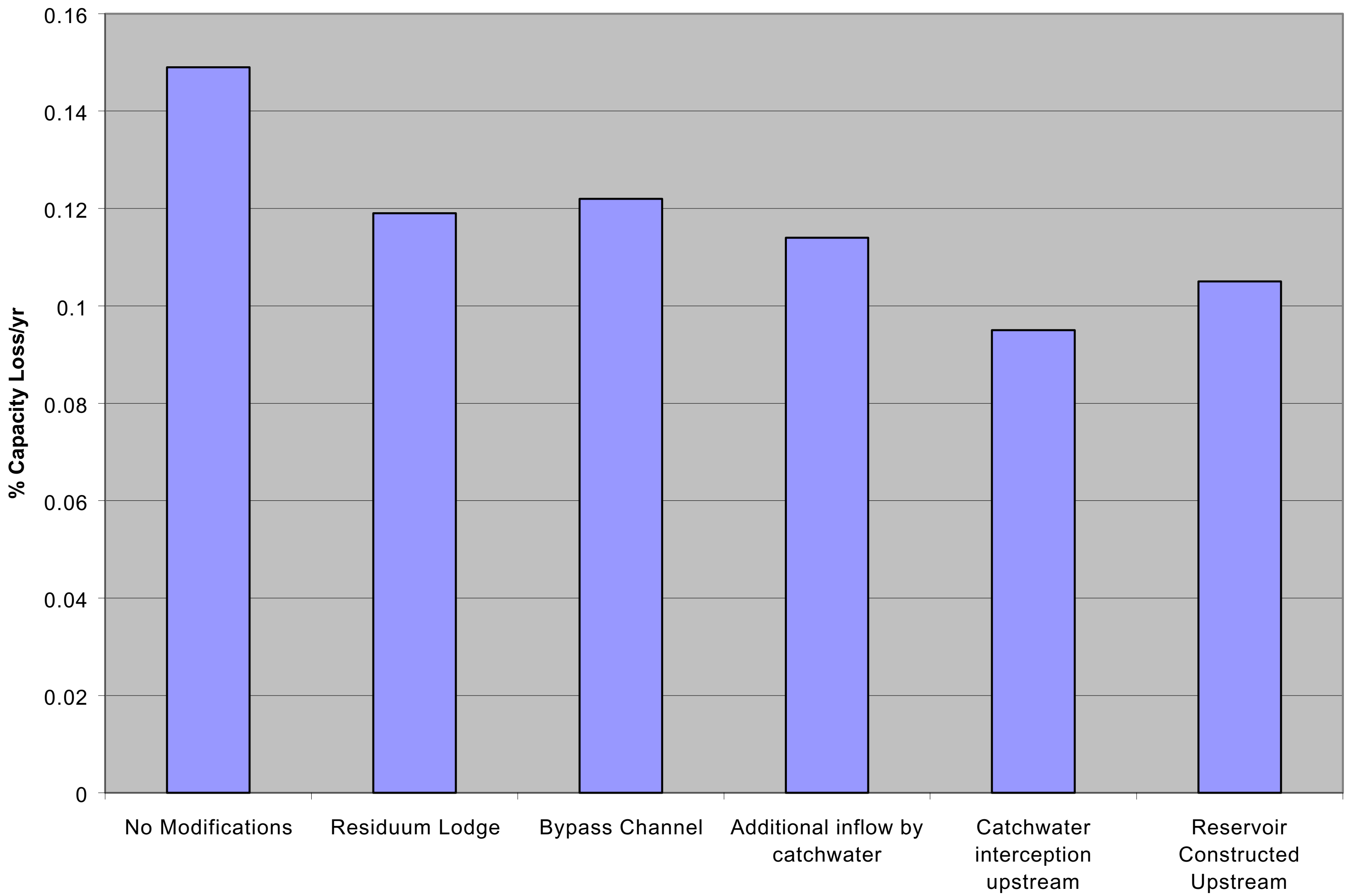
Figure 7.3

Settling Basin– Longendale Reservoir

Figure 7.4

Clearance of a silt trap

Figure 7.5



Measurements of long term siltation rates with different sediment control methods

Figure 7.5

Figure 9.1

Sediment Concentrations Measured at Various River Locations during Test Opening of Bottom Outlet Valve at Holmestyes Dam 28 May 1986 (after Pemberton 1987)

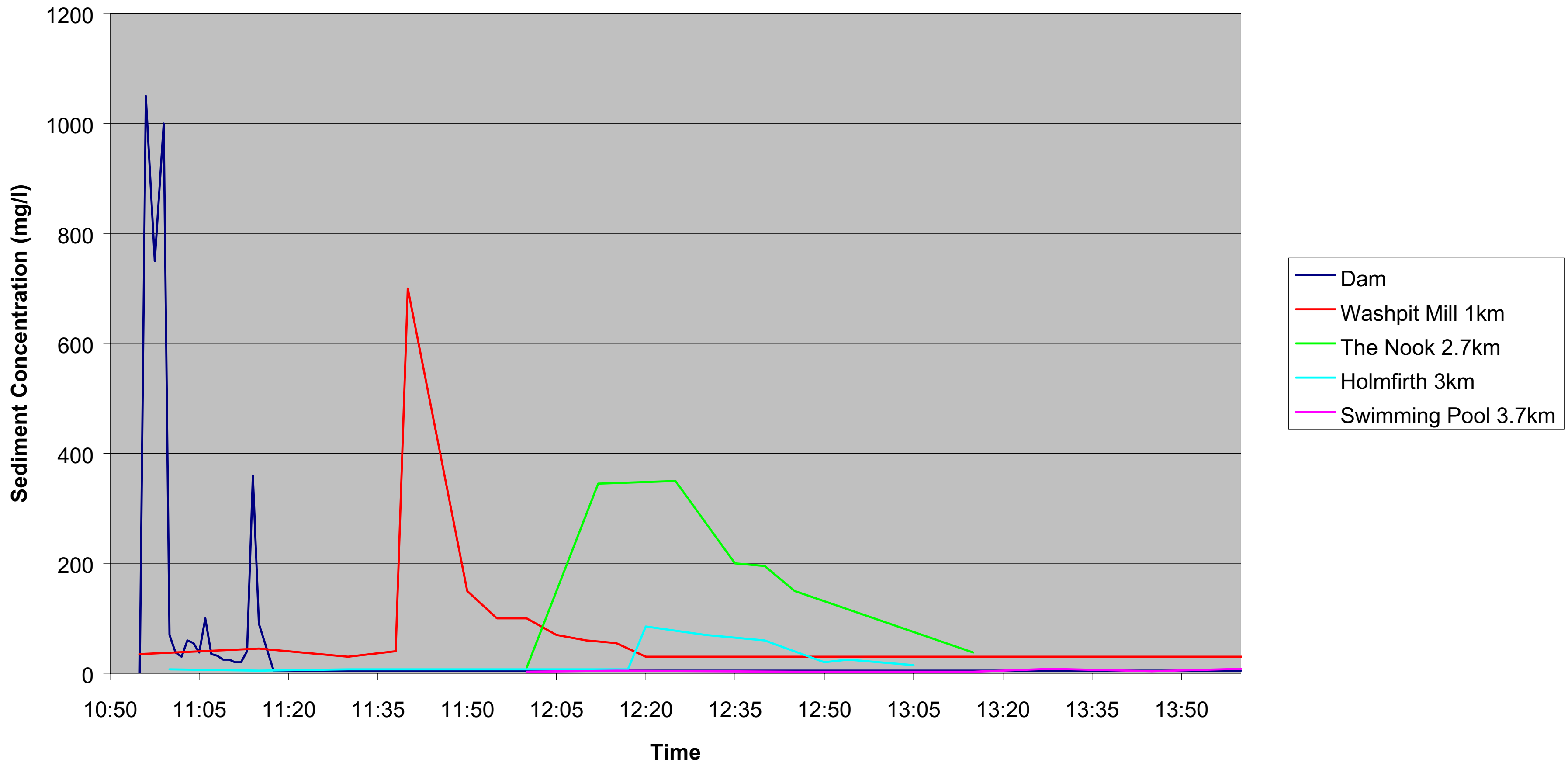


Figure 9.1

Plate 1 In situ Vane test and Sediment Sampling at Reservoir A

Plate 2 Makereth Sediment Sampling Equipment

Plate 3 Makereth Sampling Tubes

Plate 4 Sediment Sampling at Reservoir B

Plate 5 Reservoir C

Plate 6 Removing Sediment from around low level outlet (reservoir in peat catchment)

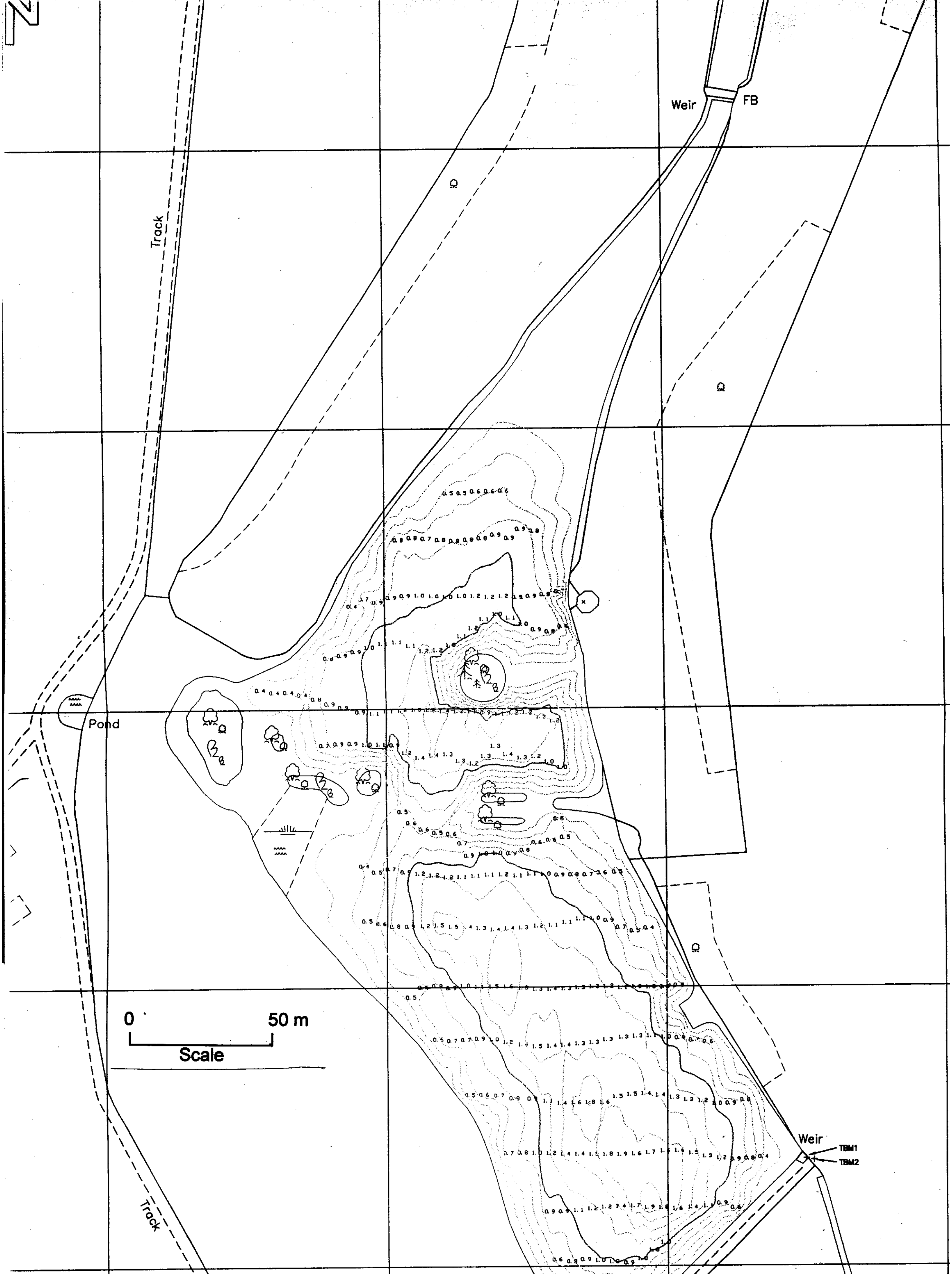
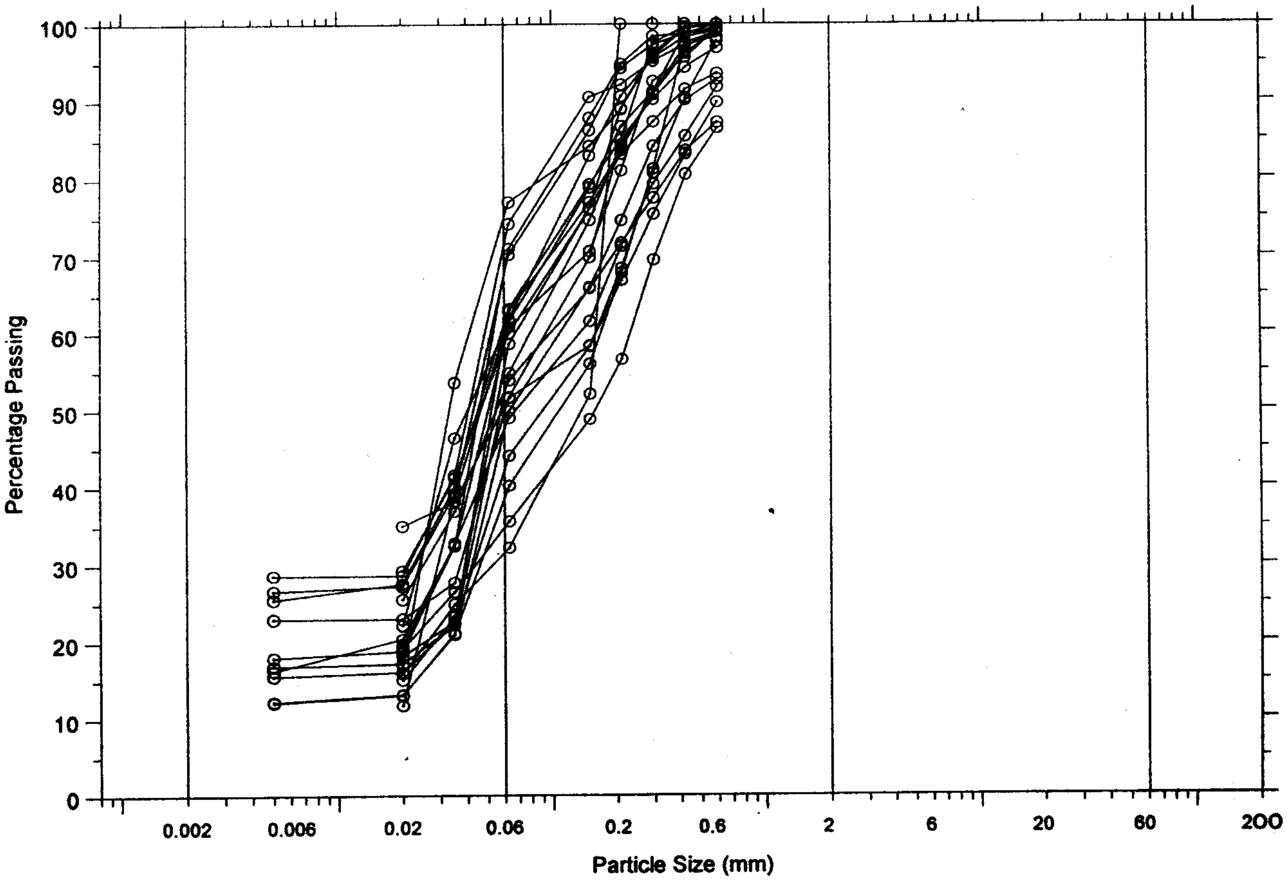


Figure A1.1a Plan of Reservoir A showing Depth to Top of Sediment below Water Level

Figure A1.1b Plan of Reservoir A showing Depth to Bottom of Sediment below Water Level



CLAY	SILT			SAND			GRAVEL			COBBLES
	Fine	Medium	Coarse	Fine	Medium	Coarse	Fine	Medium	Coarse	

Legend

DETR	UK RESERVOIR SEDIMENTATION	Halcrow
SOIL PARTICLE SIZE DISTRIBUTION **Reservoir A**		Report No: Figure No: **Figure A1.2**

178/0
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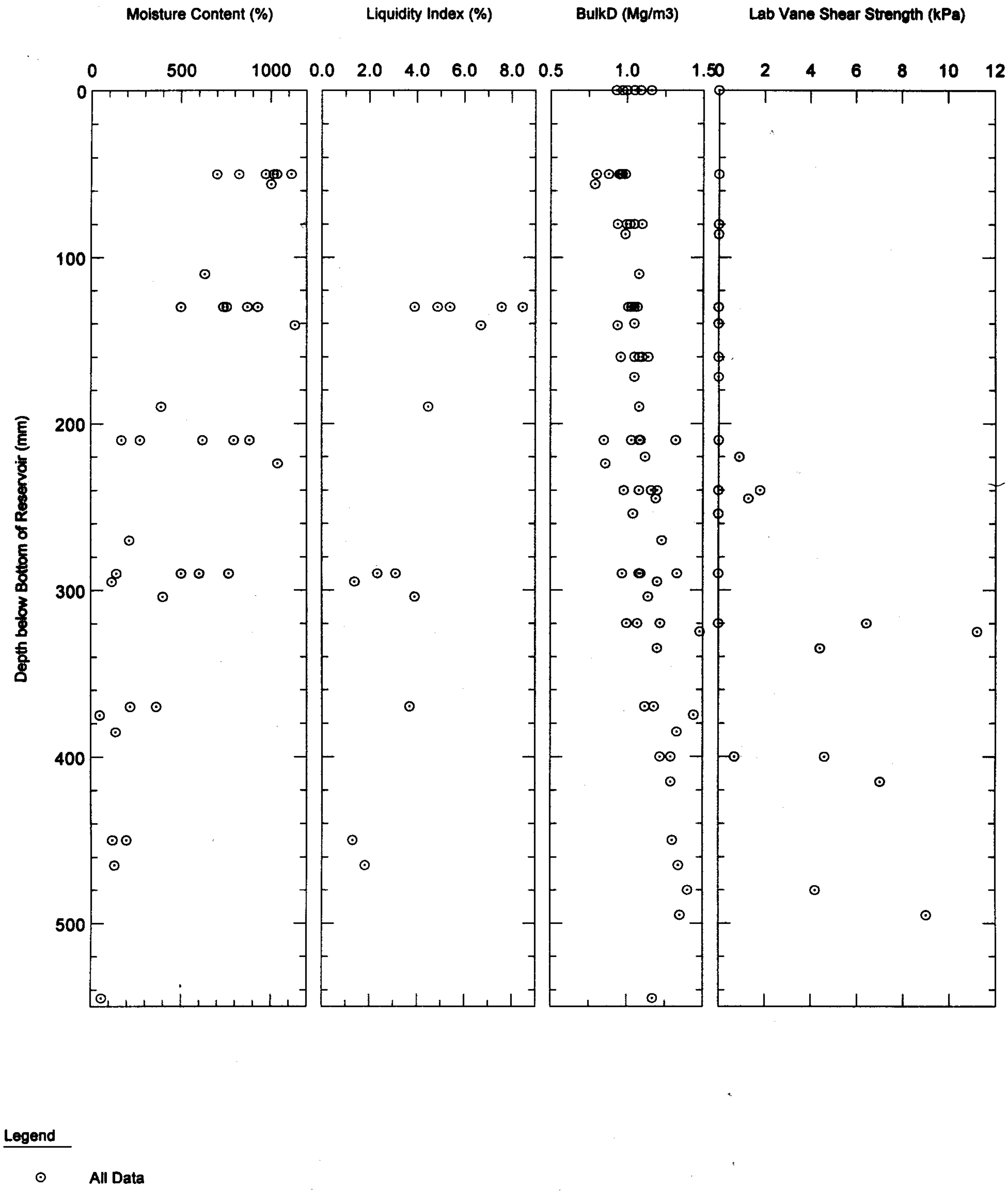
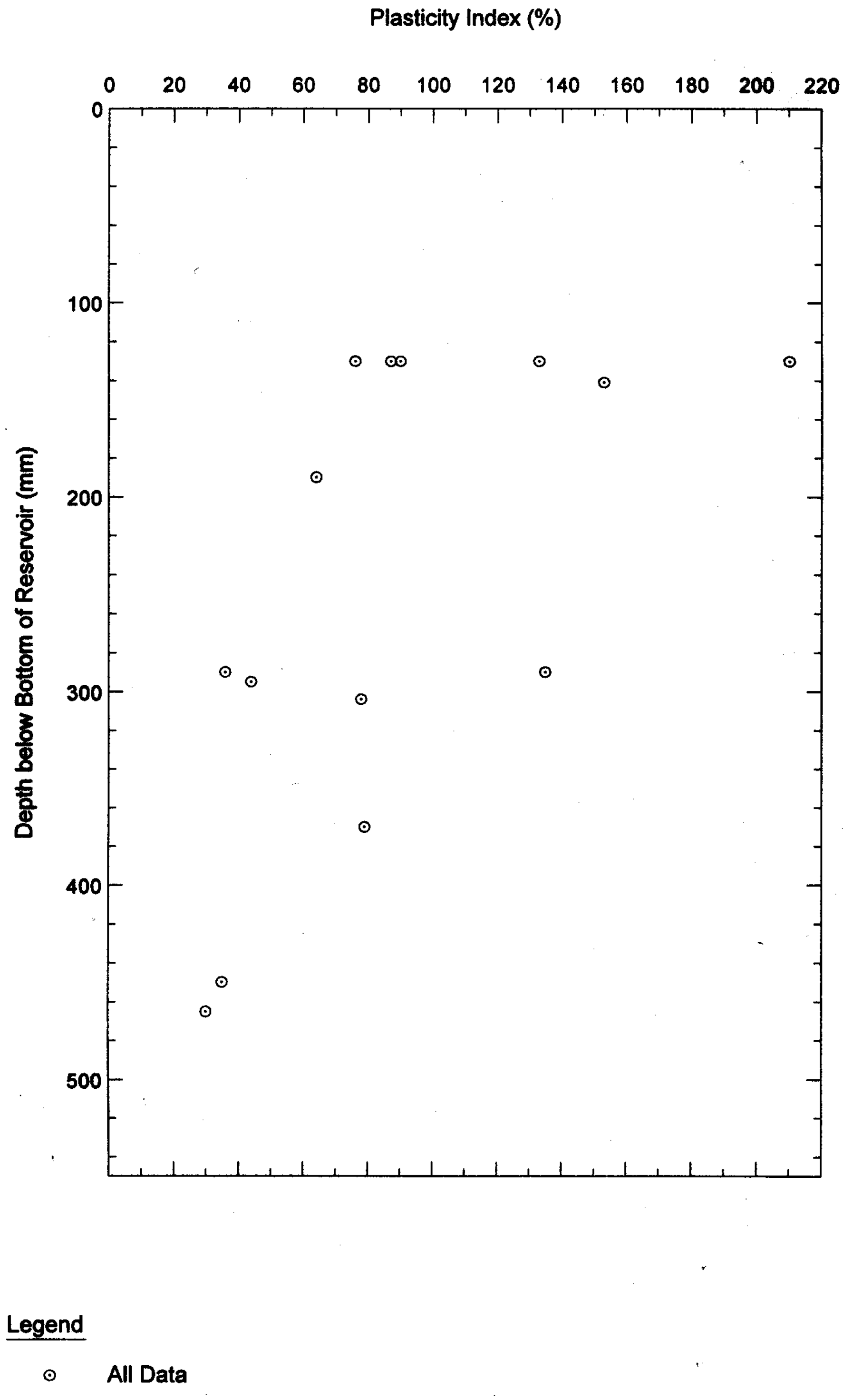
AGS



DETR	UK RESERVOIR SEDIMENTATION	Halcrow
PHYSICAL PARAMETERS v DEPTH		Report No:
Reservoir A		Figure No: **Figure A1.3**



DETR	UK RESERVOIR SEDIMENTATION	Halcrow
PLASTICITY INDEX v DEPTH **Reservoir A**		Report No: Figure No: **Figure A1.4**

Vorx 14/0

TABLE PRIORITY:caltes_hde

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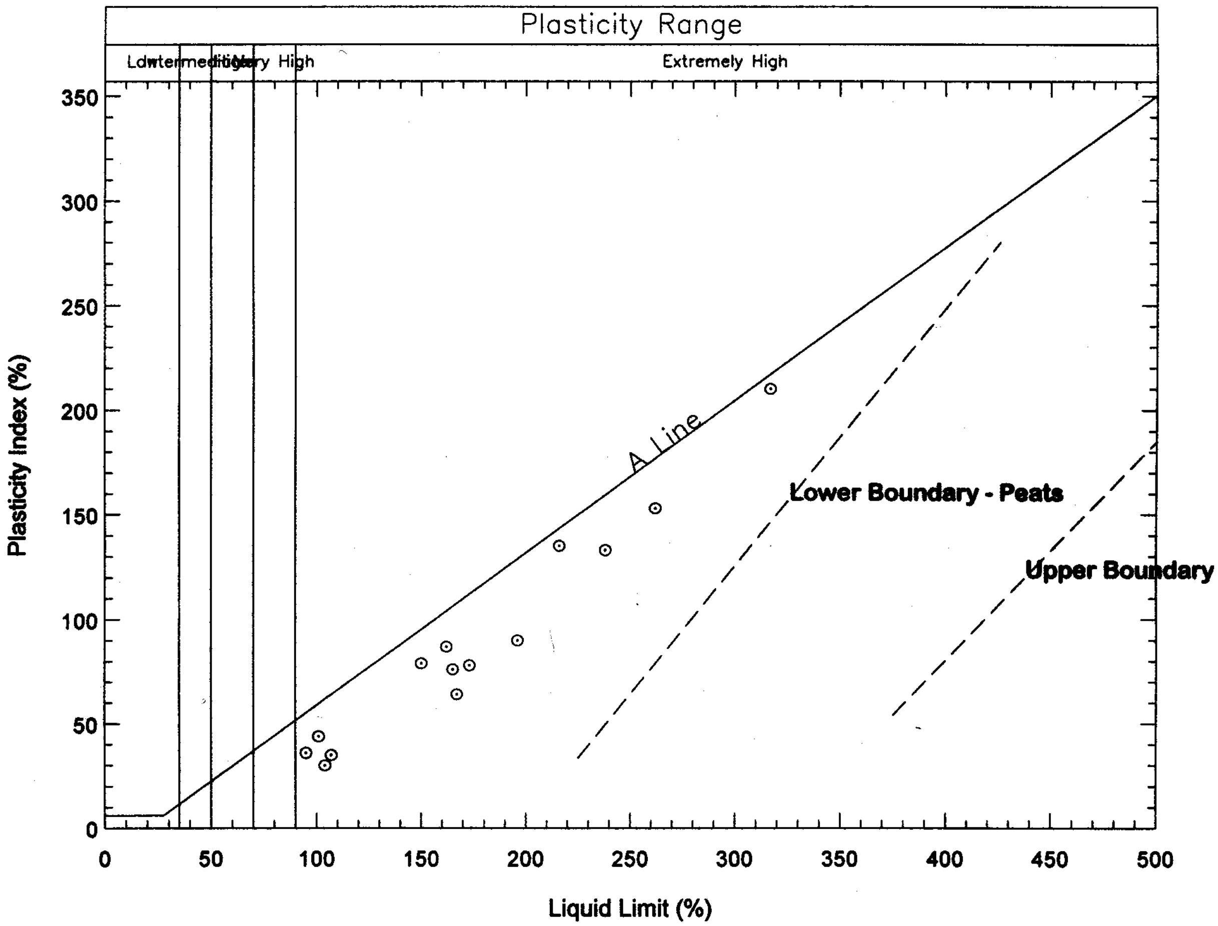
AGS



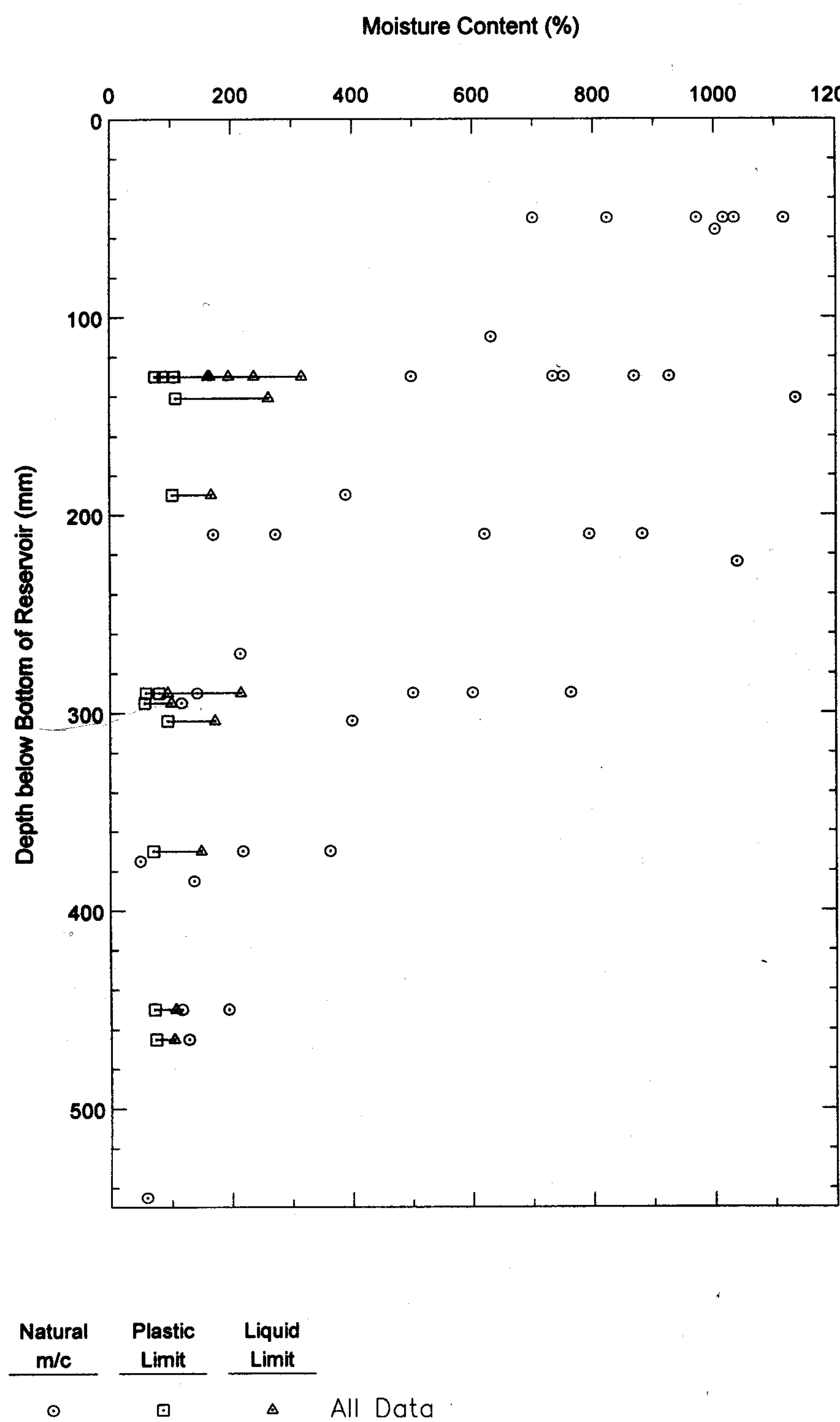
Legend

⊙ All Data

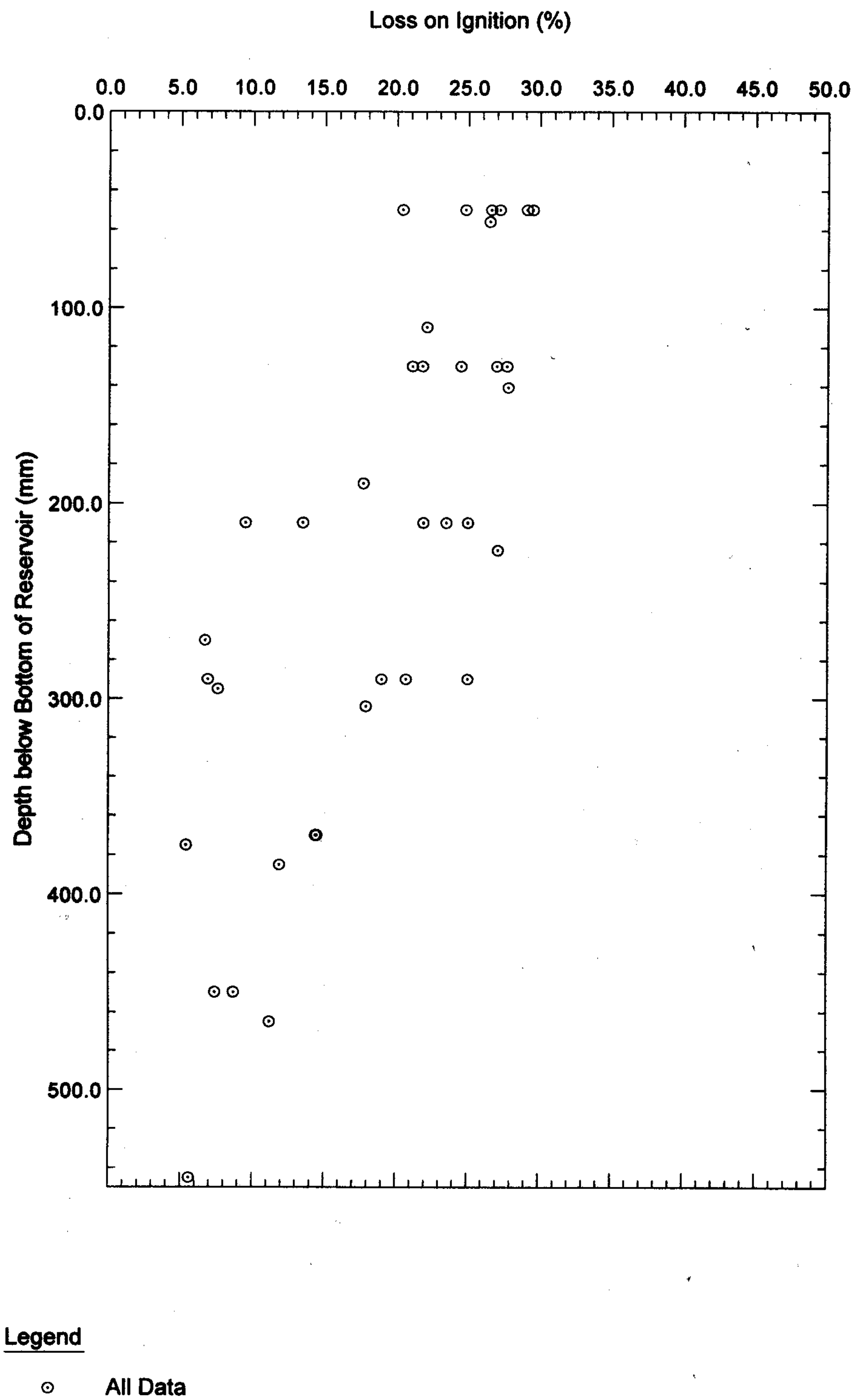
DETR	UK RESERVOIR SEDIMENTATION	Halcrow
PLASTICITY CHART Reservoir A		Report No: Figure No: Figure A1.5

pl___gre.met ads scales in units/cm 2000/06/19 10:43 xCLSS_LL 35.714 y:clss_pi 35.700 ⊙ TABLE PRIORITY:clss_hole Vor:x 14/0

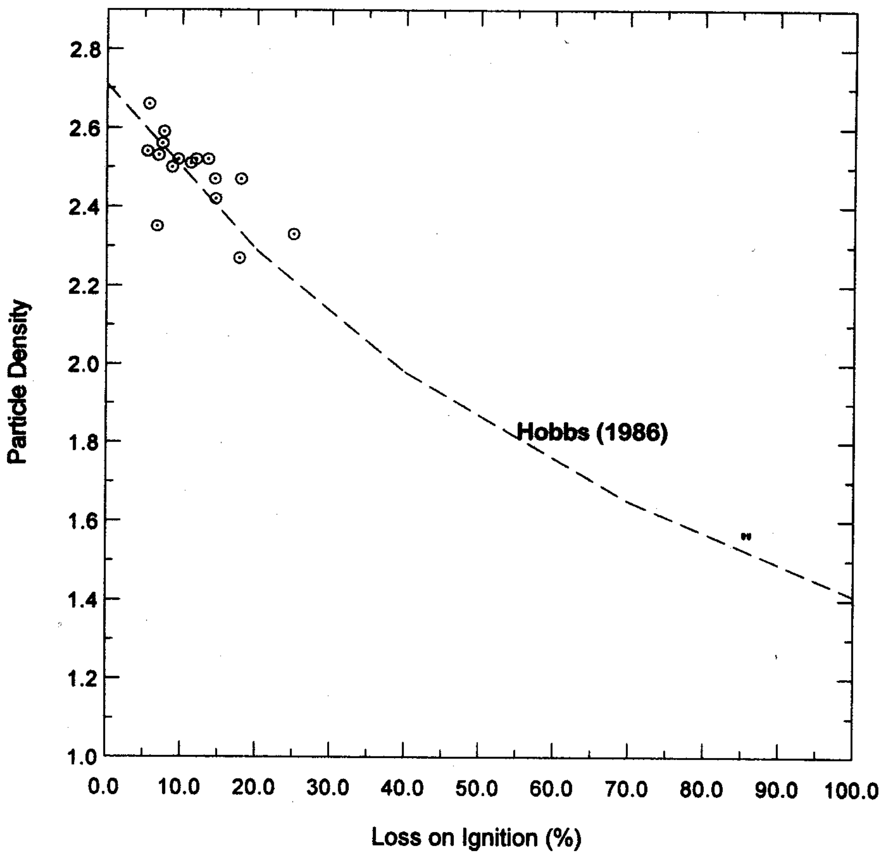
AGS



DETR	UK RESERVOIR SEDIMENTATION	Halcrow
MOISTURE CONTENT v DEPTH		Report No:
Reservoir A		Figure No: **Figure A1.6**



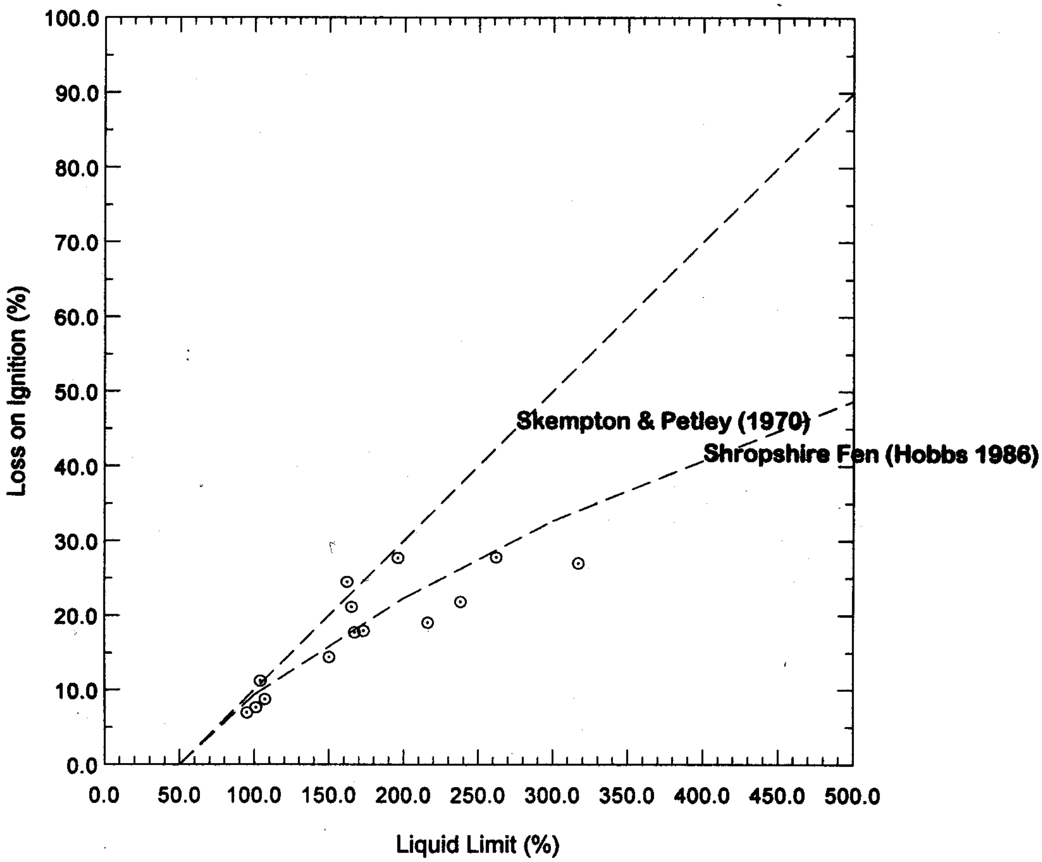
DETR	UK RESERVOIR SEDIMENTATION	Halcrow
LOSS ON IGNITION v DEPTH **Reservoir A**		Report No:
		Figure No: **Figure A1.7**



Legend

⊙ All Data

DETR	UK RESERVOIR SEDIMENTATION	Halcrow
LOSS ON IGNITION v PARTICLE DENSITY Reservoir A		Report No: Figure No: Figure A1.8



Legend

⊙ All Data

DETR	UK RESERVOIR SEDIMENTATION	Halcrow
LIQUID LIMIT v LOSS ON IGNITION		Report No:
Reservoir A		Figure No: **Figure A1.9**

Vor:x 14 / 0
pvp__gra.met axis scales in units/cm 2000/06/19 10:03 xCLSS_LL 50.000 y:clss_loig 10 ⊙ TABLE PRIORITY:CLSS
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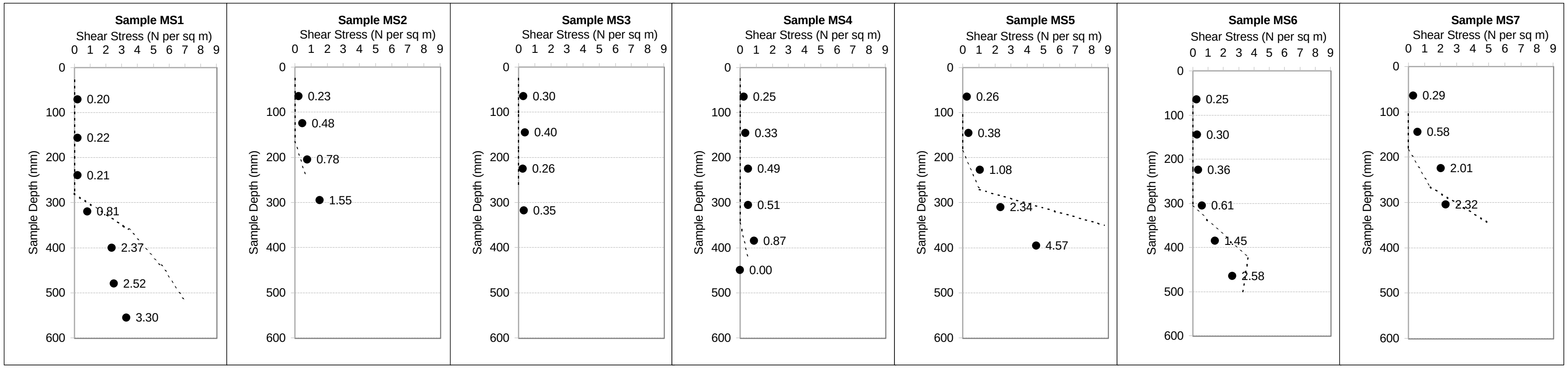


These graphs show calculated shear stress variation with depth for each of the seven Makareth sediment sample cores extracted from Reservoir A.

The dotted values are calculated from bulk density measurements using the HR Wallingford formula for critical bed shear stress in non-colloidal sediments.
The dashed lines represent shear stress variation based on laboratory shear vane results (Kamphuis and Hall, 1983)

Figure A1.10
Reservoir A - Estimation of Critical Bed Shear Stress derived from Laboratory Results

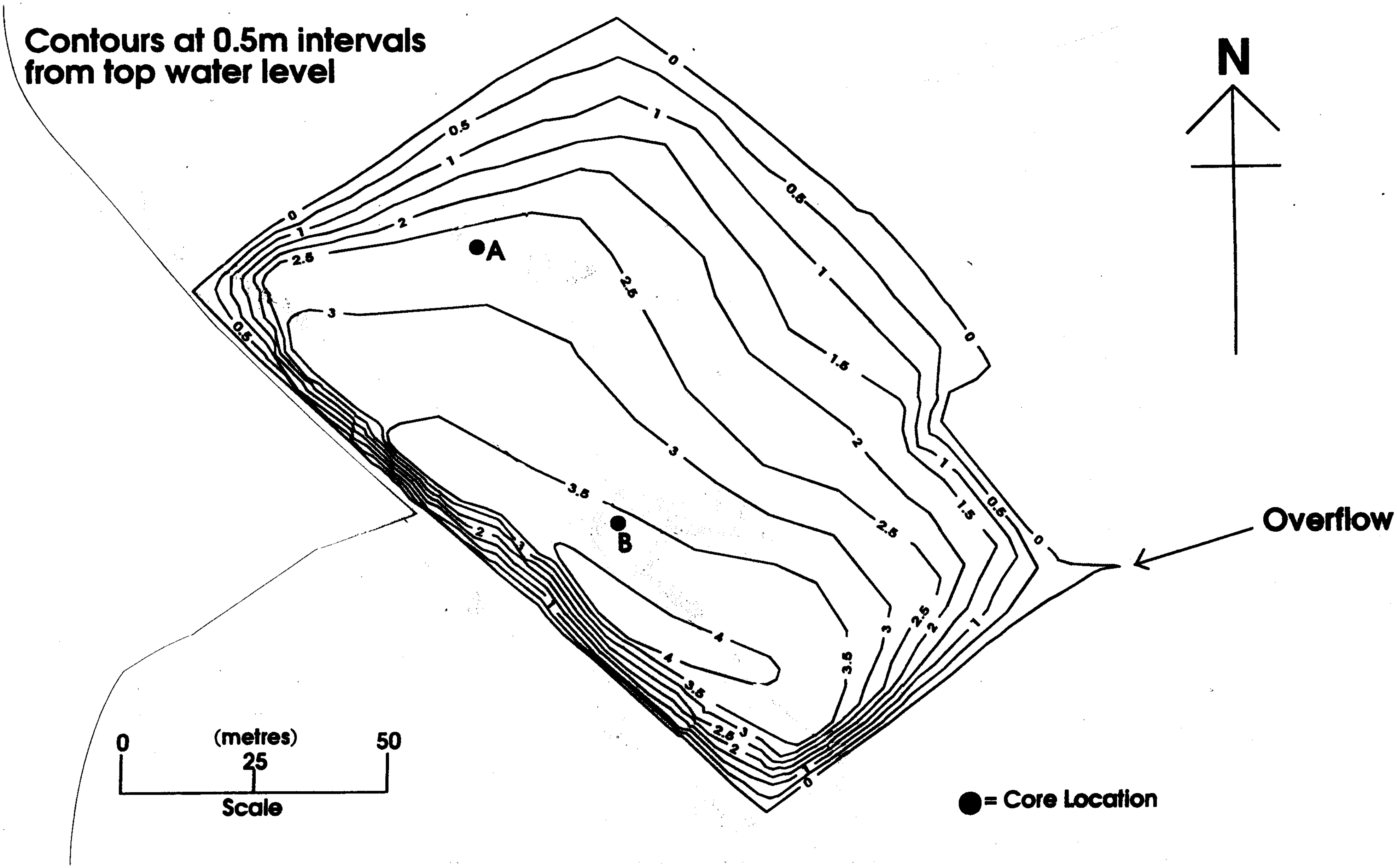
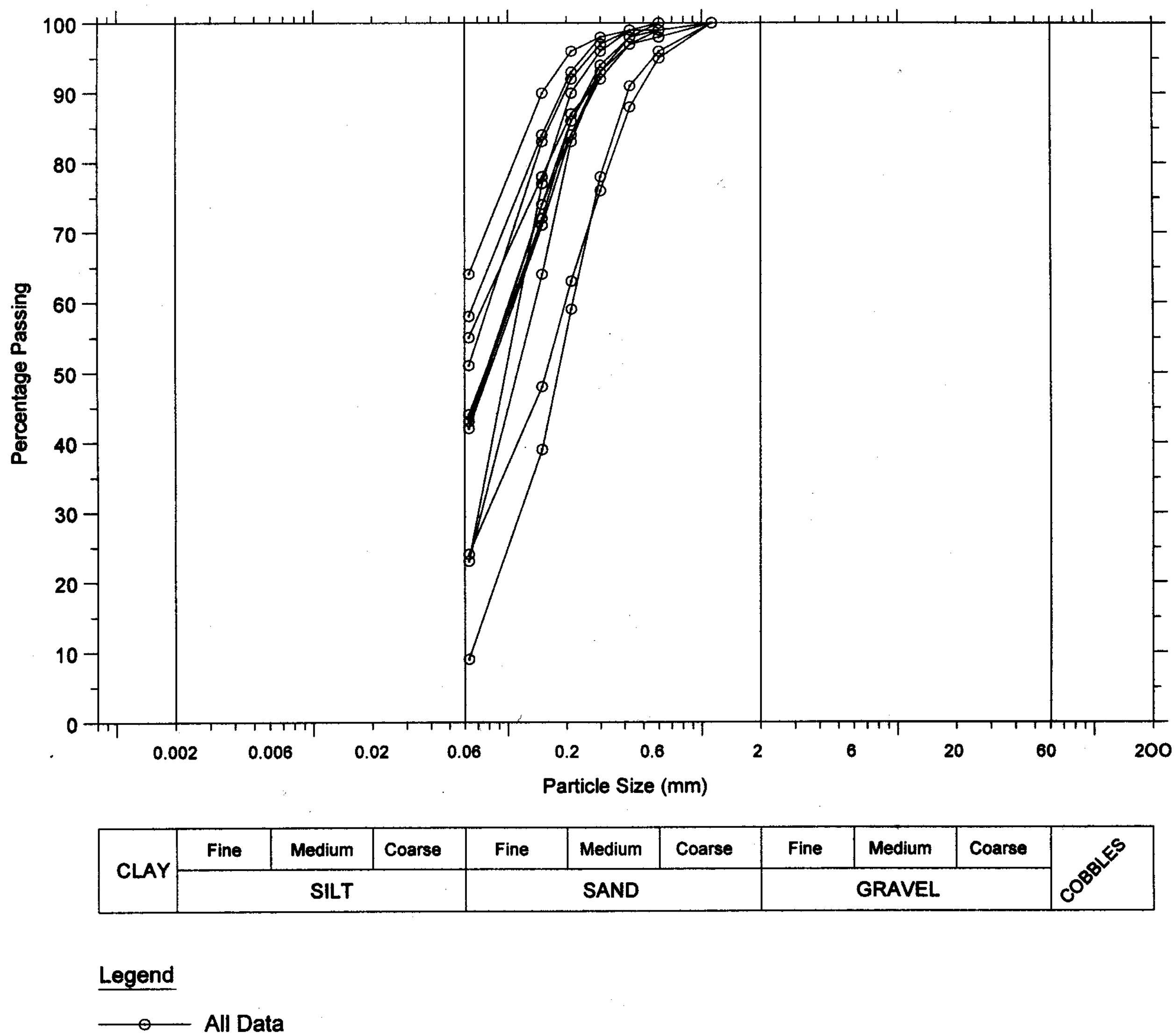


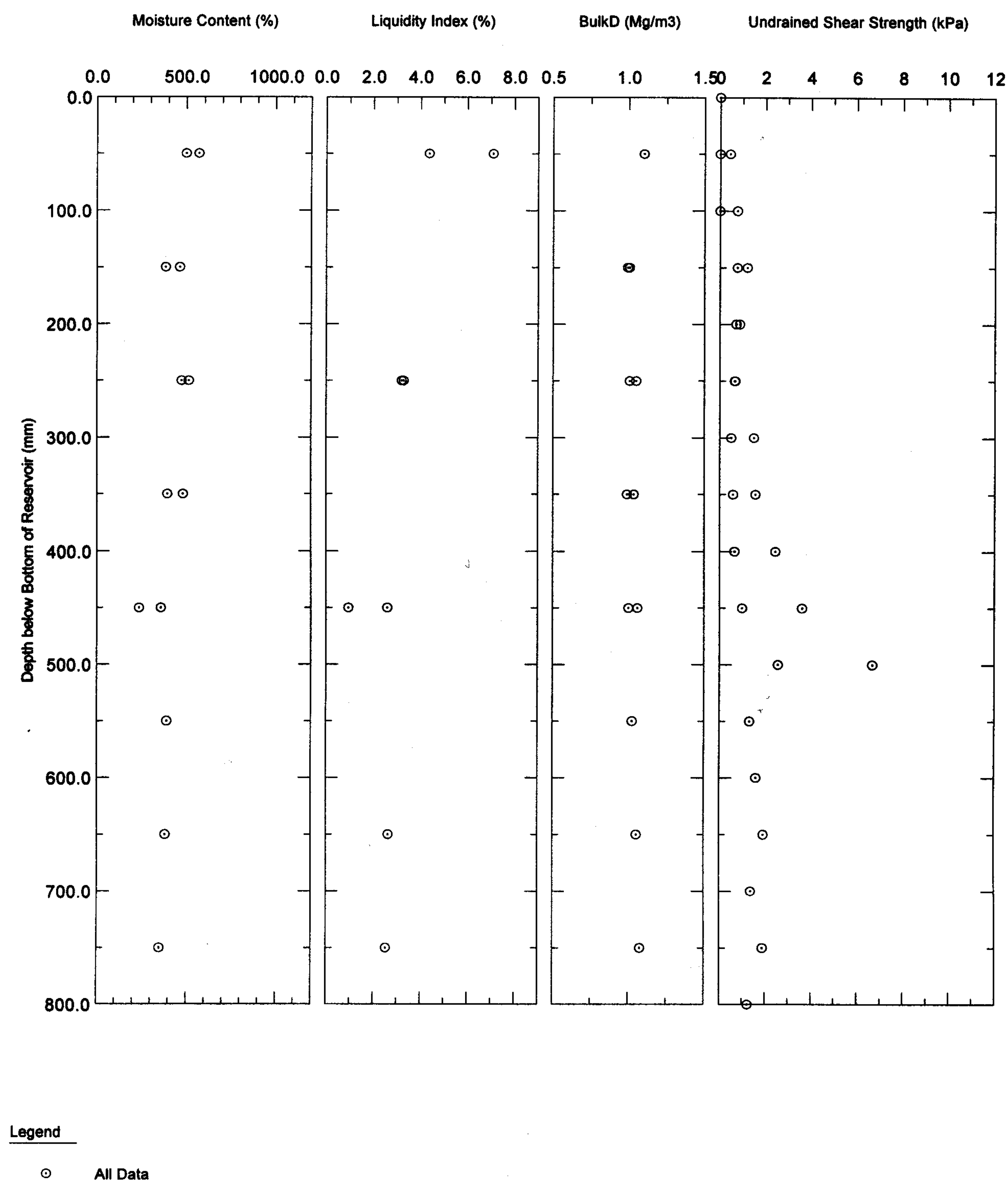
Figure A2.1 **Plan of Reservoir B showing Results of Bathymetric Survey and Position of Sediment Sampling Cores**



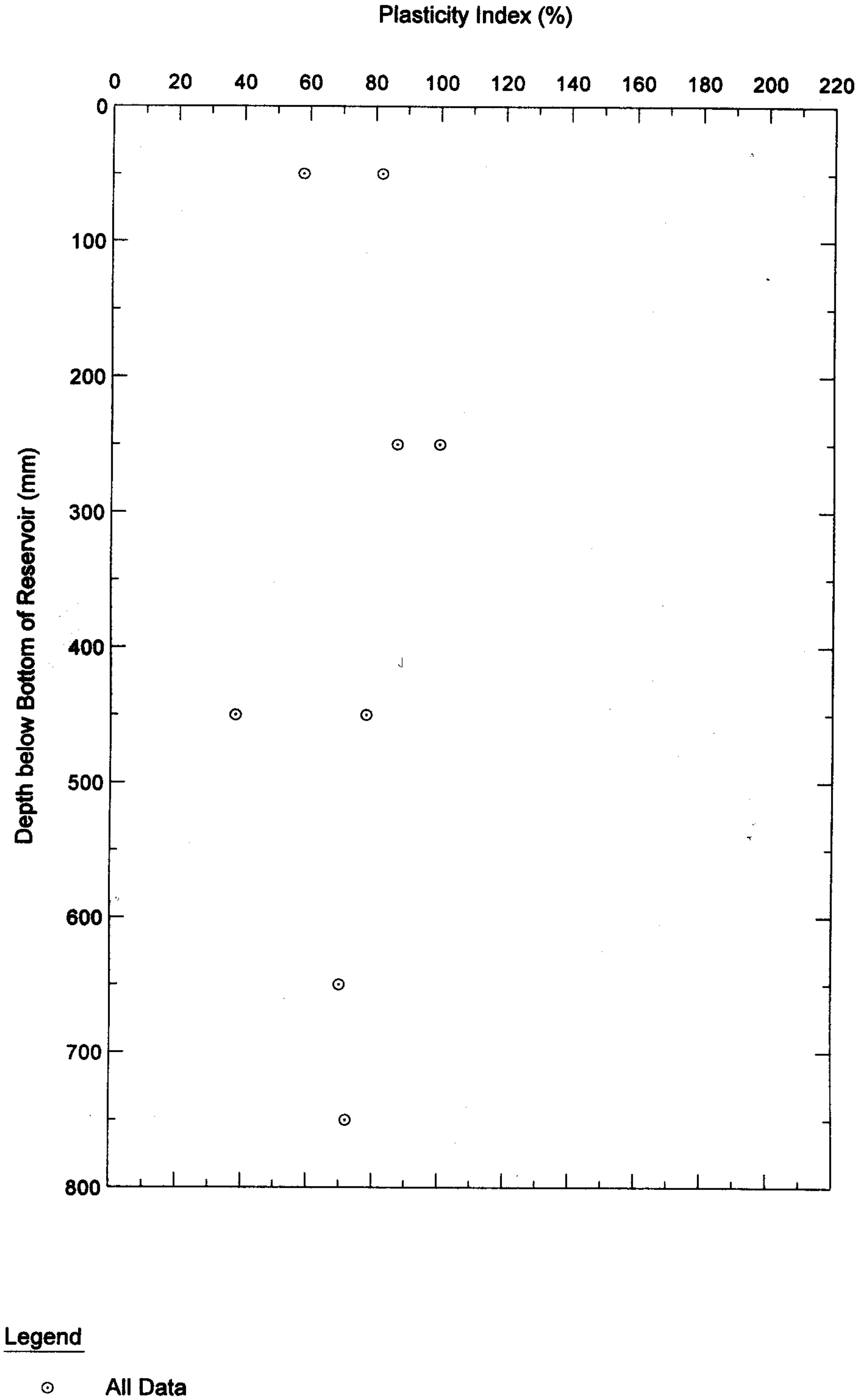
DETR	UK RESERVOIR SEDIMENTATION	Halcrow
SOIL PARTICLE SIZE DISTRIBUTION **Reservoir B**		Report No:
		Figure No: **Figure A2.2**

psd_gra.met axis scales in units/cm slsr 2000/07/19 16:48 x:grad_sizefig LOG y:GRAD_PERP 10.000 ⊙ TABLE PRIORITY:grifcifisa_h HOLE_ID () BC 91/0

AGS



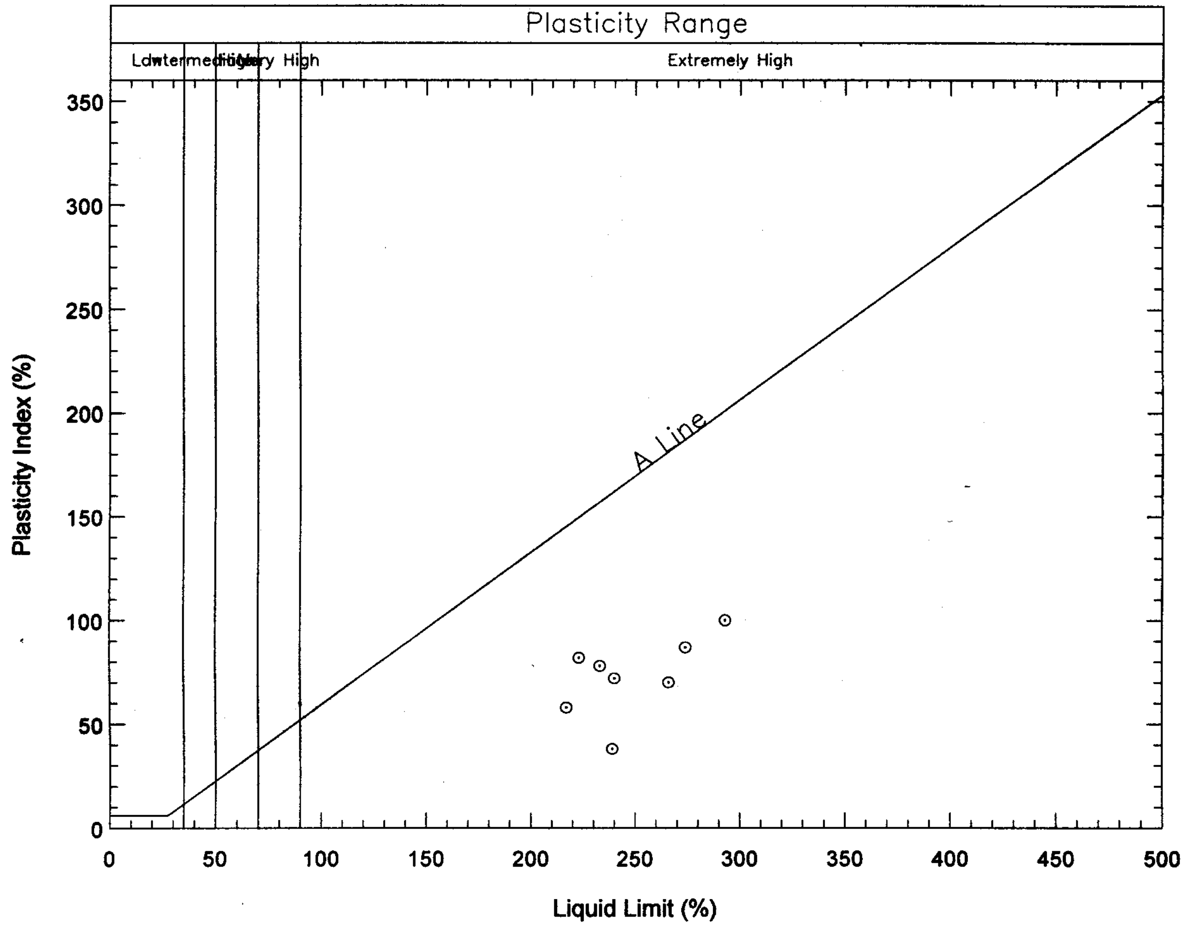
DETR	UK RESERVOIR SEDIMENTATION	Halcrow
PHYSICAL PARAMETERS v DEPTH **Reservoir B**		Report No: Figure No: **Figure A2.3**



DETR	UK RESERVOIR SEDIMENTATION	Halcrow
PLASTICITY INDEX v DEPTH		Report No:
Reservoir B		Figure No: **Figure A2.4**

pi___gre.met axis scales in units/cm 2000/07/19 16:43 xCLSS_PI 22.000 y:SAMP_TOP 53.333 ⊙ TABLE PRIORITY:clifes_hole HOLE_ID () BC

Vor.x 8/0



Legend

⊙ All Data

DETR	UK RESERVOIR SEDIMENTATION	Halcrow

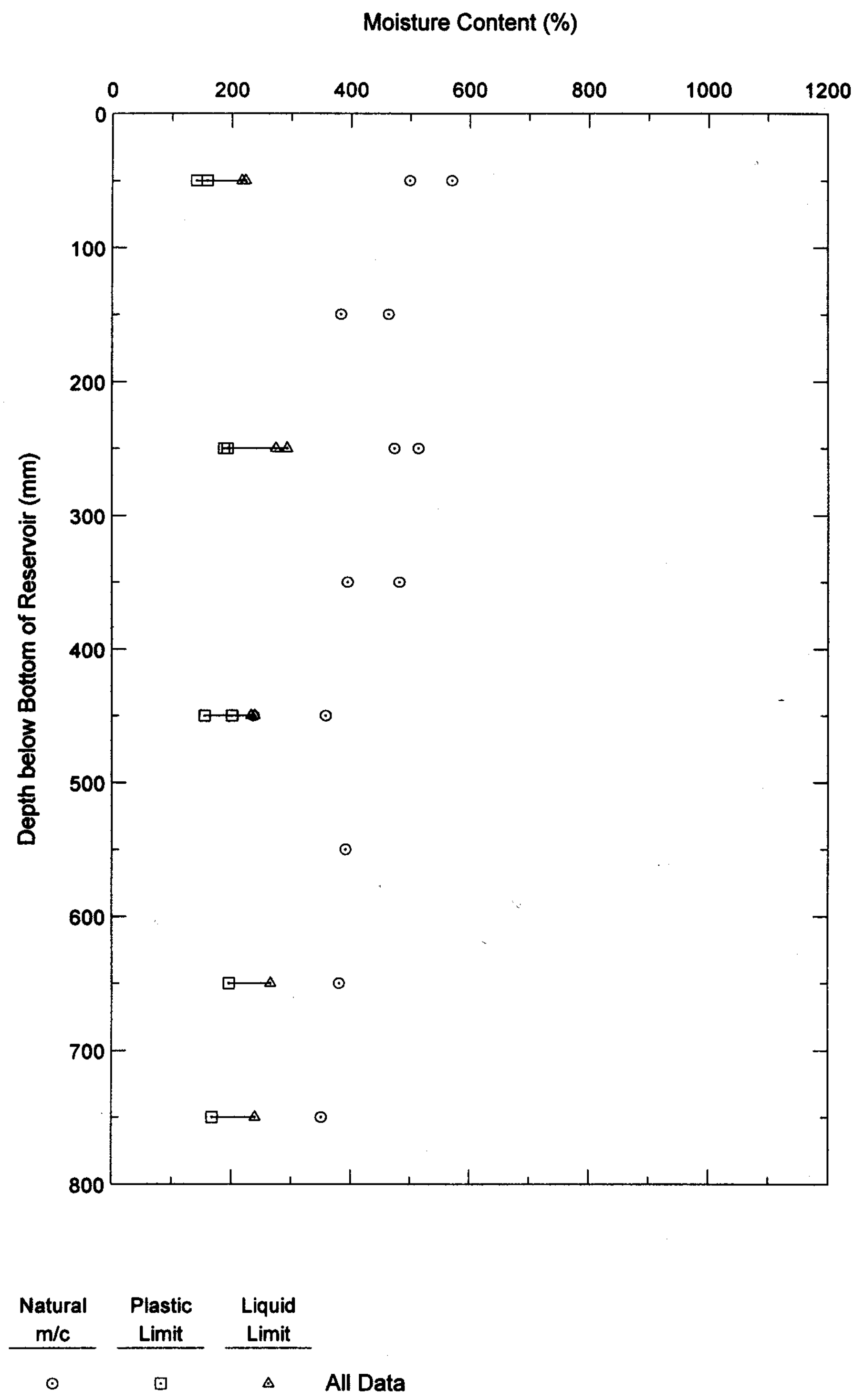
PLASTICITY CHART

Reservoir B

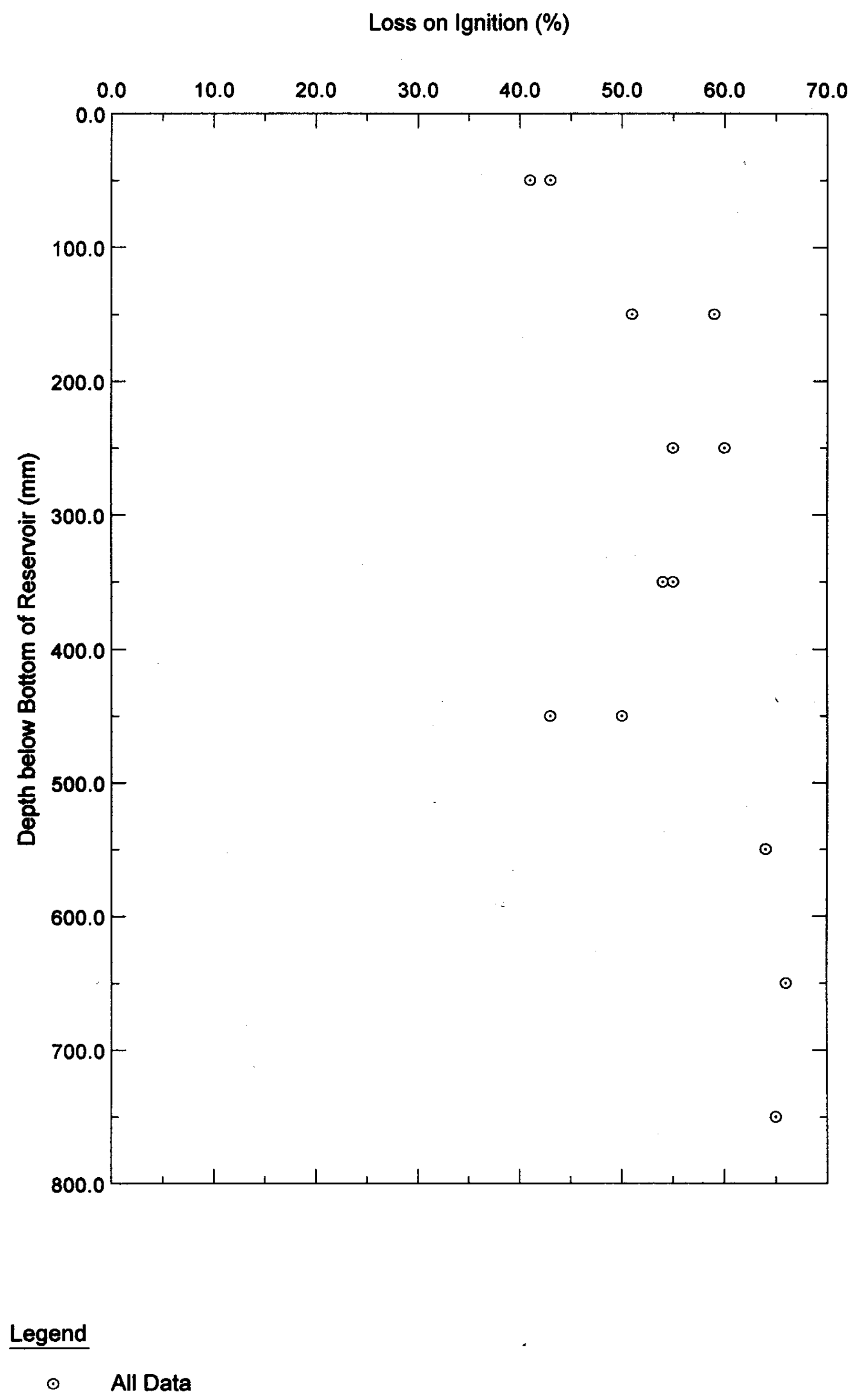
Report No:

Figure No: **Figure A2.5**

⊙ TABLE PRIORITY:clfea_hole HOLE_ID () BC xCLSS_LL 35.714 yclss_pl 36.000 2000/07/19 15:34 axis scales in units/cm pl__gre.met Vor:x 8/0 AGS

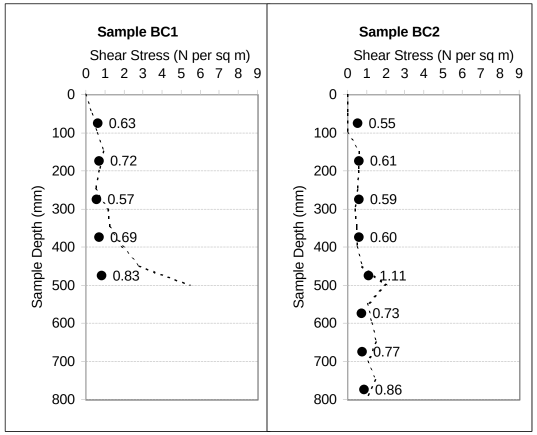


DETR	UK RESERVOIR SEDIMENTATION	Halcrow
MOISTURE CONTENT v DEPTH		Report No:
Reservoir B		Figure No: **Figure A2.6**



DETR	UK RESERVOIR SEDIMENTATION	Halcrow
LOSS ON IGNITION v DEPTH **Reservoir B**		Report No: Figure No: **Figure A2.7**

pvd_gre.met axis scales in units/cm sisr 2000/07/19 16:38 x:class_loig 7 y:SAMP_TOP 53.333 ⊙ TABLE PRIORITY:class_hole HOLE_ID () BC Vorx 13/0



These graphs show calculated shear stress variation with depth for each of the two Makareth sediment sample cores extracted from Reservoir B.

The dotted values are calculated from bulk density measurements using the HR Wallingford formula for critical bed shear stress in non-colloidal sediments.
The dashed lines represent shear stress variation based on laboratory shear vane results (Kamphuis and Hall, 1983)

Figure A2.8
Reservoir B - Estimation of Critical Bed Shear Stress derived from Laboratory Results

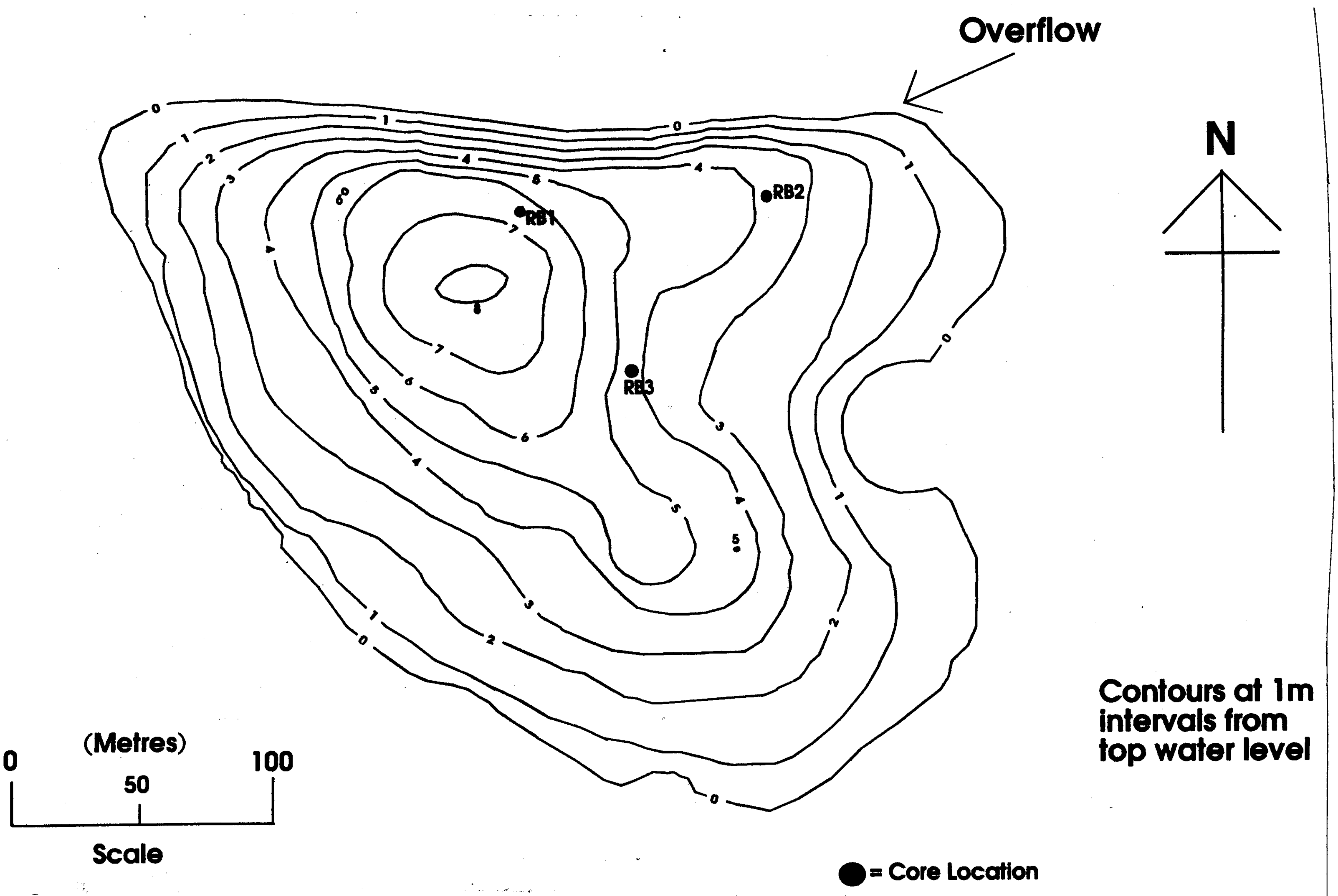
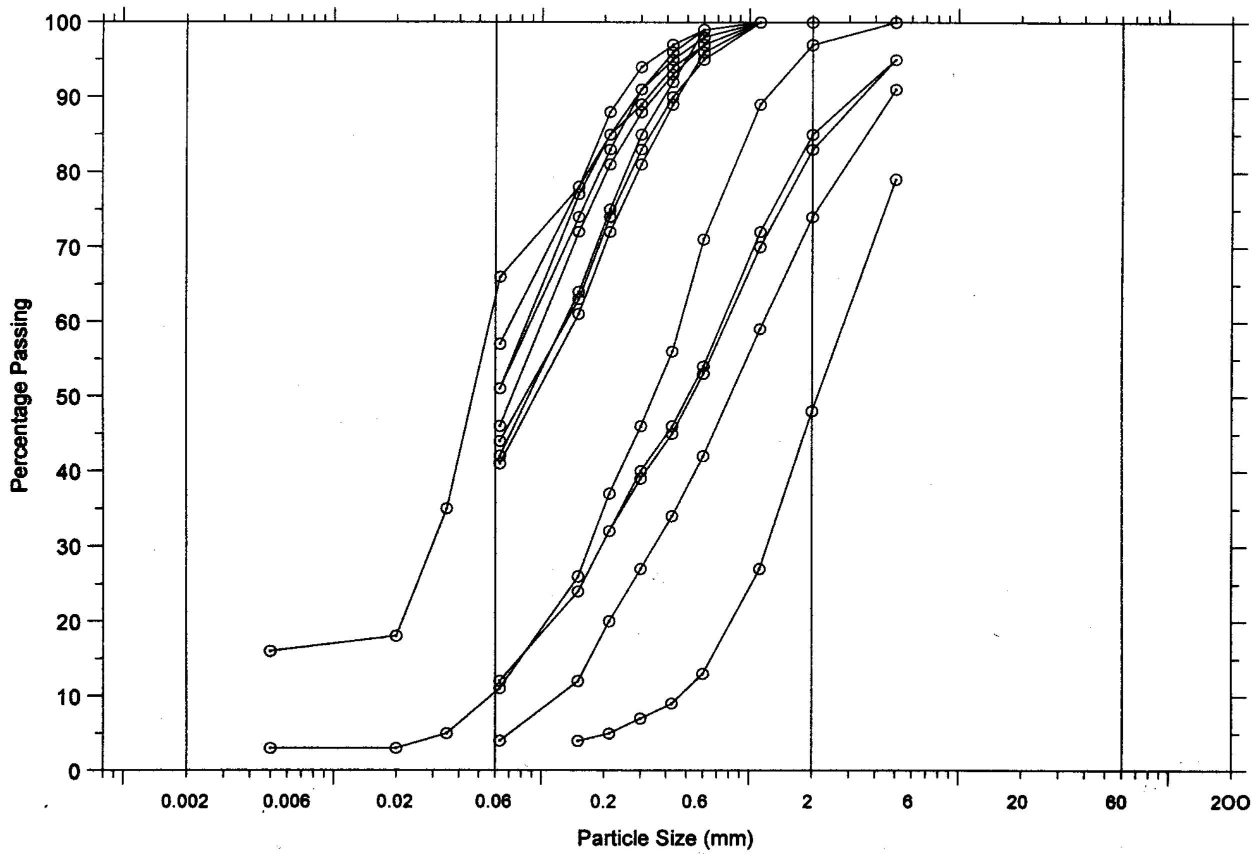


Figure A3.1 Plan of Reservoir C showing Results of Bathymetric Survey and Position of Sediment Sampling Cores

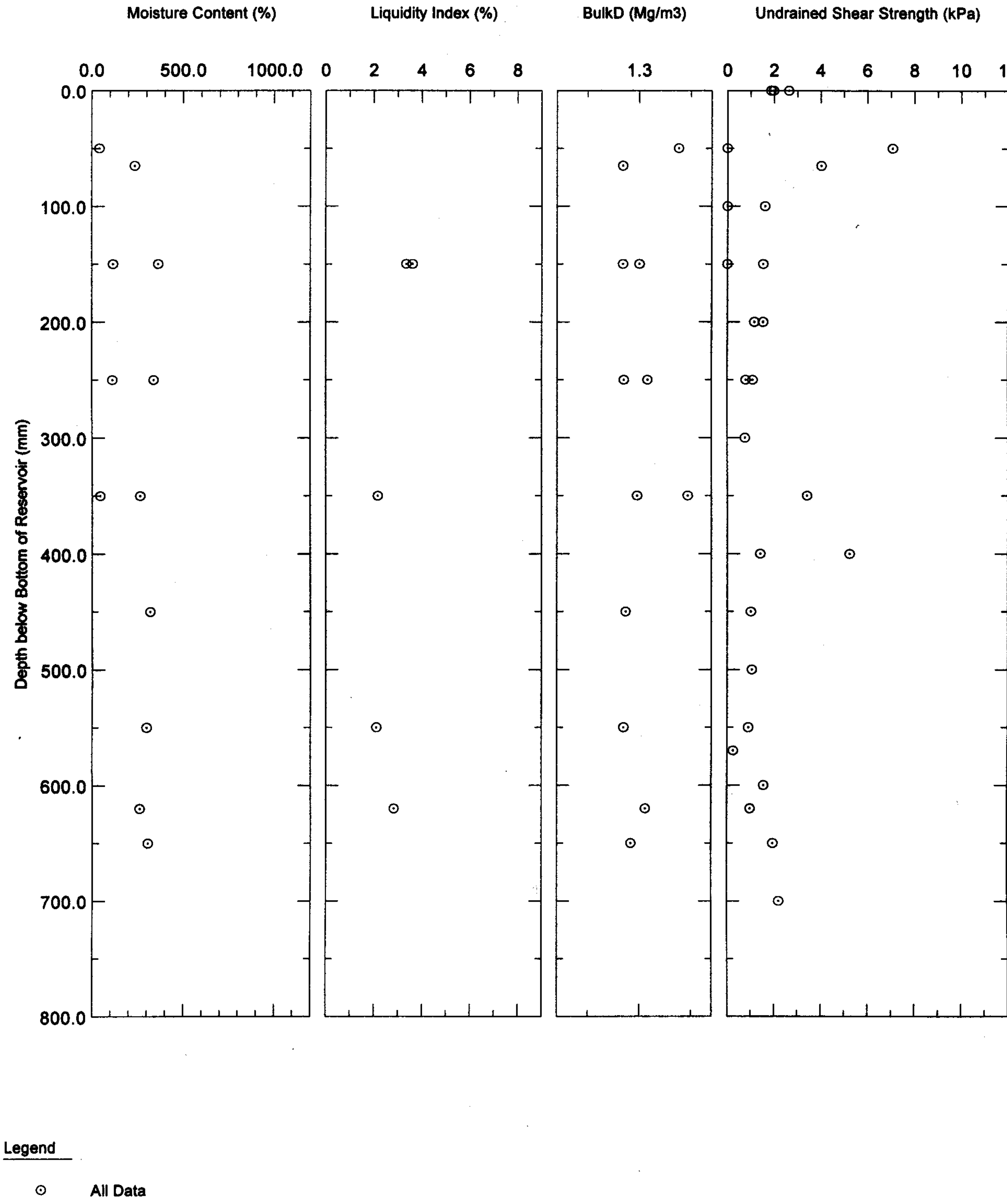


CLAY	Fine	Medium	Coarse	Fine	Medium	Coarse	Fine	Medium	Coarse	COBBLES
	SILT			SAND			GRAVEL			

Legend

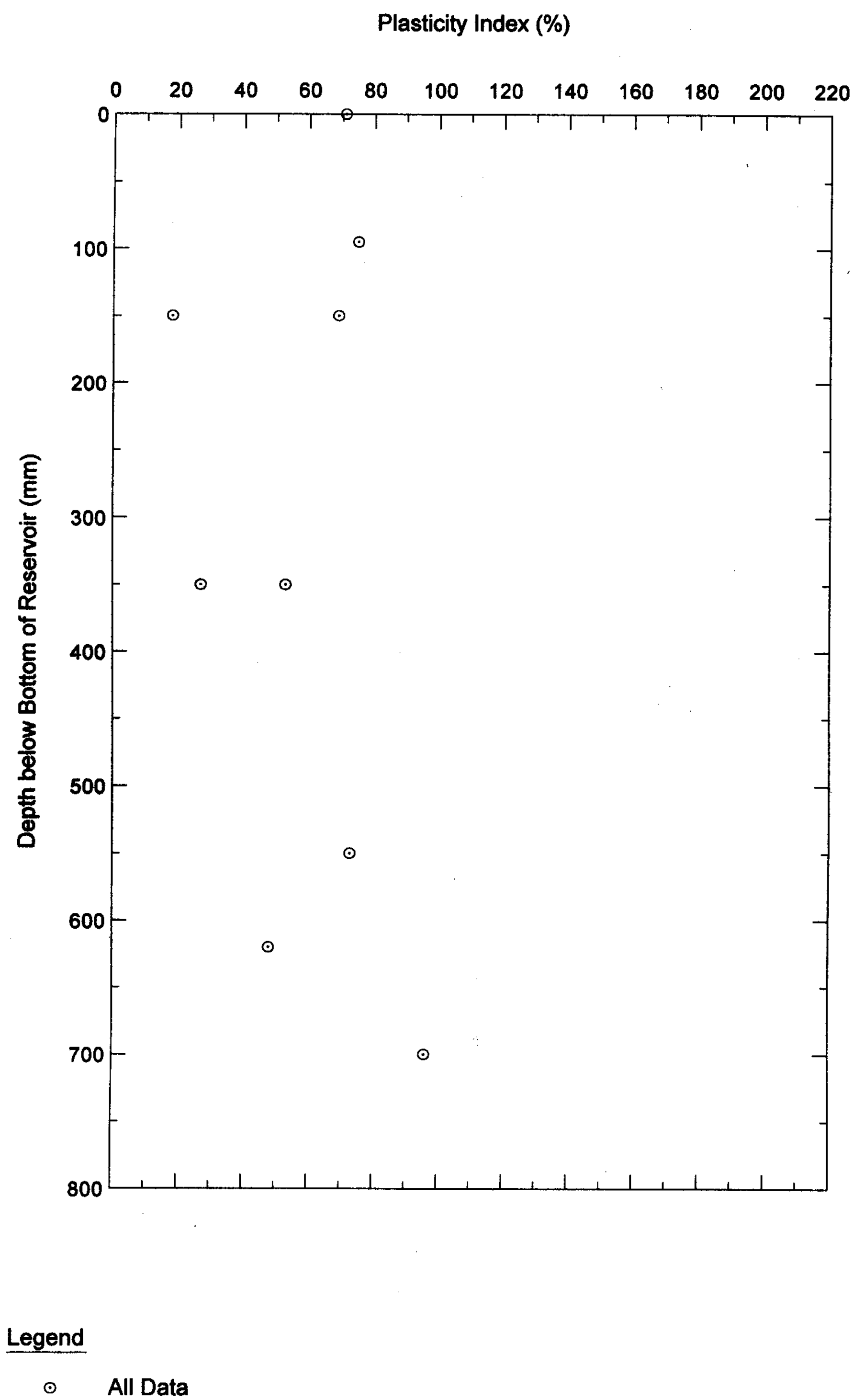
All Data

DETR	UK RESERVOIR SEDIMENTATION	Halcrow
SOIL PARTICLE SIZE DISTRIBUTION **Reservoir C**		Report No: Figure No: **Figure A3.2**



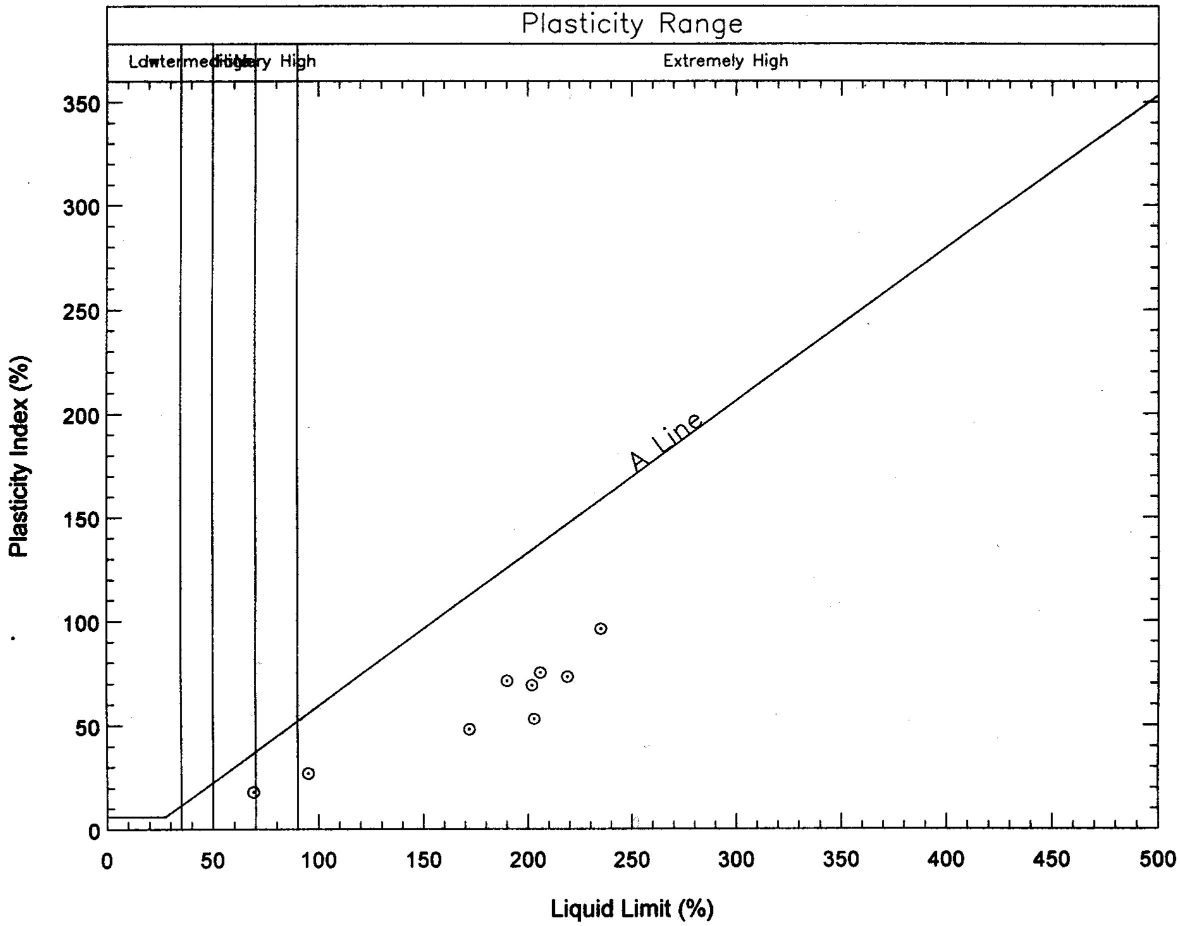
xCLSS_VNPK 2.667 y:SAMP_TOP 53.333 ⊙ TABLE PRIORITY:cliffes_hole HOLE_ID () RB Vorx 26 / 0
xCLSS_BDEN 0.600 y:SAMP_TOP 53.333 ⊙ TABLE PRIORITY:cliffes_hole HOLE_ID () RB Vorx 12 / 0
xCLSS_LI 2.571 y:SAMP_TOP 53.333 ⊙ TABLE PRIORITY:cliffes_hole HOLE_ID () RB Vorx 5 / 1
xCLSS_NMC 342.857 y:SAMP_TOP 53.333 ⊙ TABLE PRIORITY:cliffes_hole HOLE_ID () RB Vorx 12 / 0
mb__gre.met axis scales in units/cm 2000/07/19 16:28 ster
AGS

DETR	UK RESERVOIR SEDIMENTATION	Halcrow
PHYSICAL PARAMETERS v DEPTH		Report No:
Reservoir C		Figure No: **Figure A3.3**



DETR	UK RESERVOIR SEDIMENTATION	Halcrow
PLASTICITY INDEX v DEPTH **Reservoir C**		Report No: Figure No: **Figure A3.4**

Ver.x 9/0 ⊙ TABLE PRIORITY:cl#ss_hole HOLE_ID () RB x:CLSS_PI 22.000 y:SAMP_TOP 53.333 2000/07/19 16:45 axis scales in units/cm pl___gre.met AGS



Legend

⊙ All Data

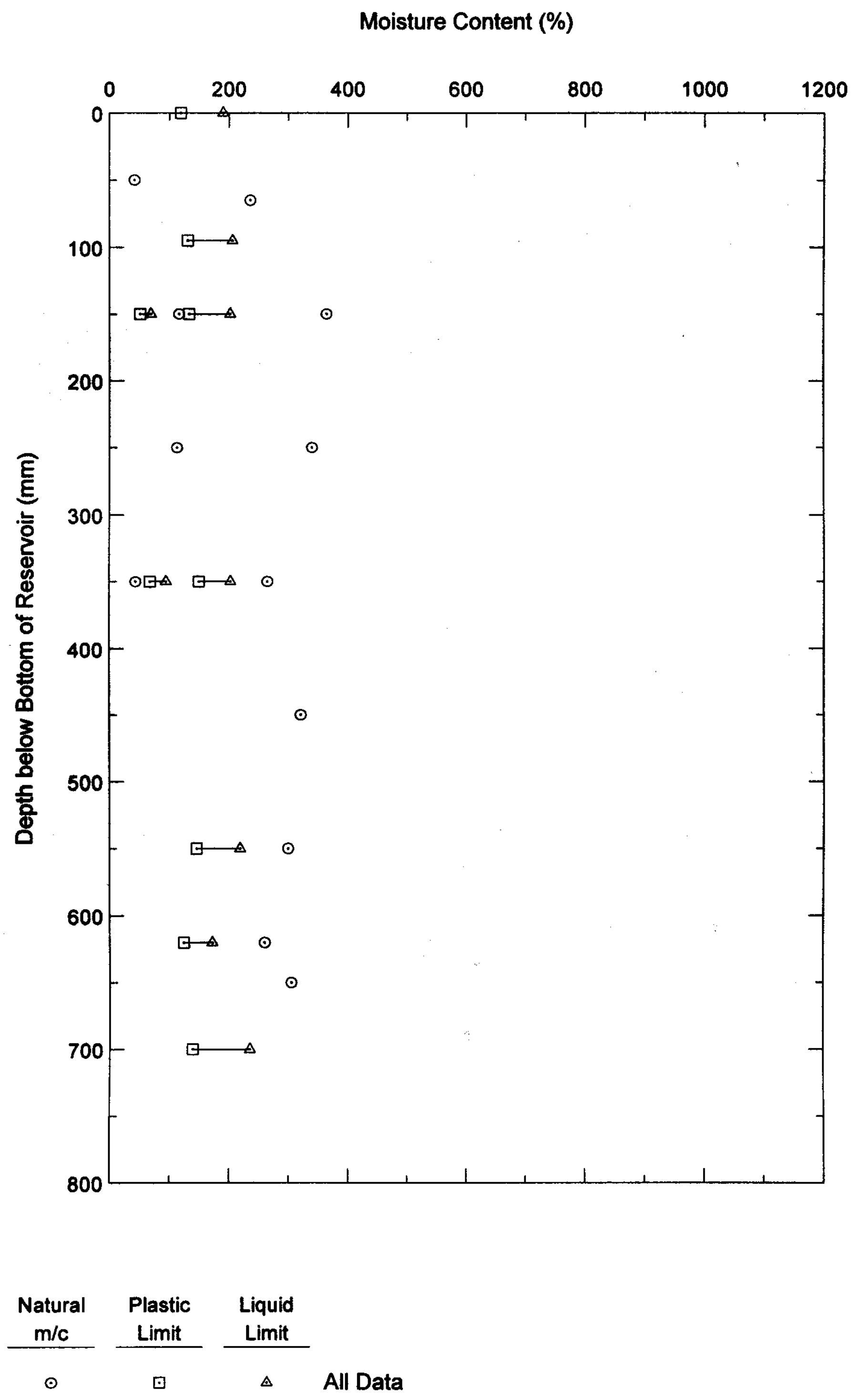
DETR	UK RESERVOIR SEDIMENTATION	Halcrow
PLASTICITY CHART **Reservoir C**		Report No: Figure No: **Figure A3.5**

Vorx 9/0

xCLSS_LL 35.714 yclss_pl 36.000 ⊙ TABLE PRIORITY:clss_hole HOLE_ID () RB

pl_gra.met axis scales in units/cm 2000/07/19 15:31 stsr

AGS

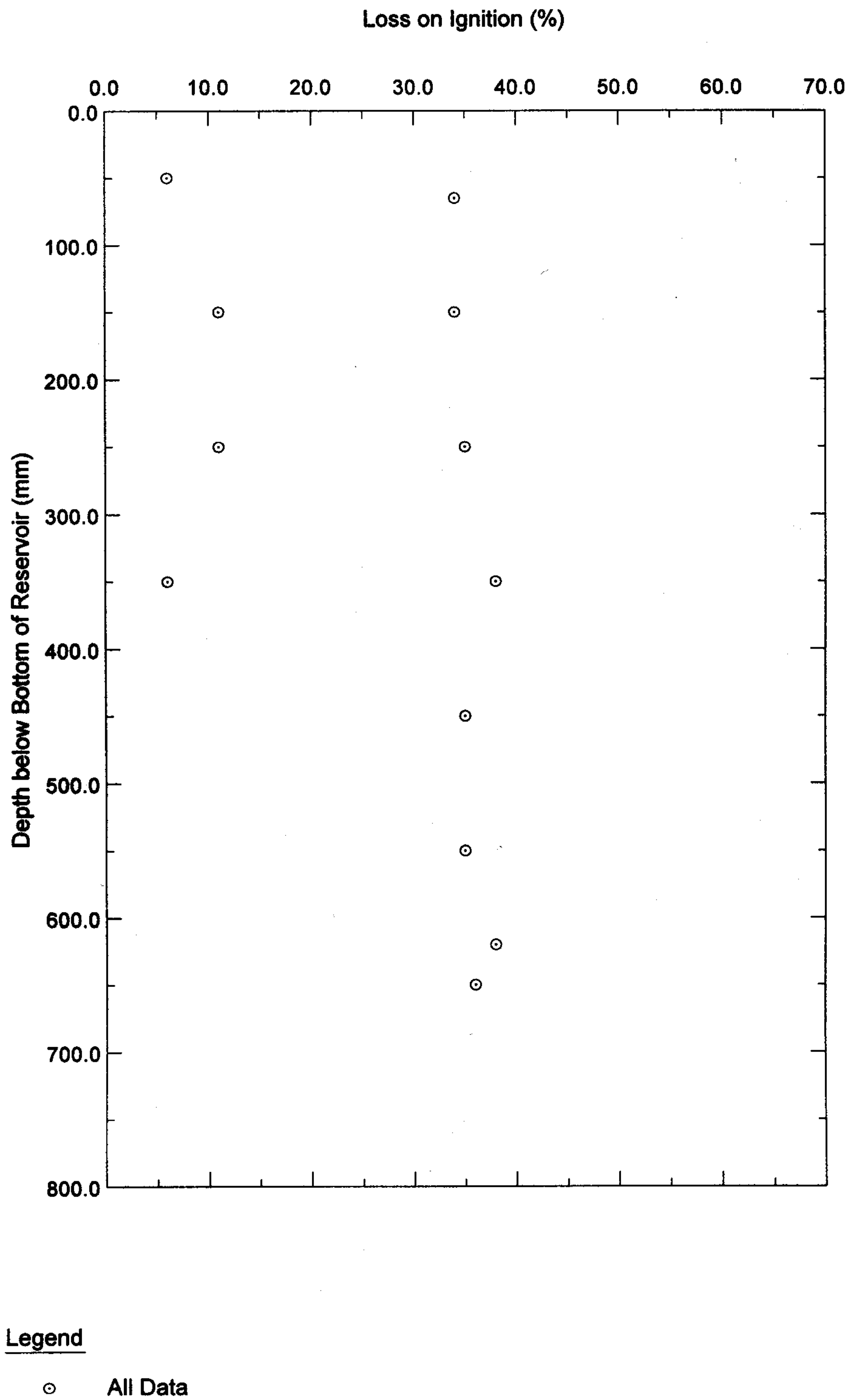


Vorx 12/0

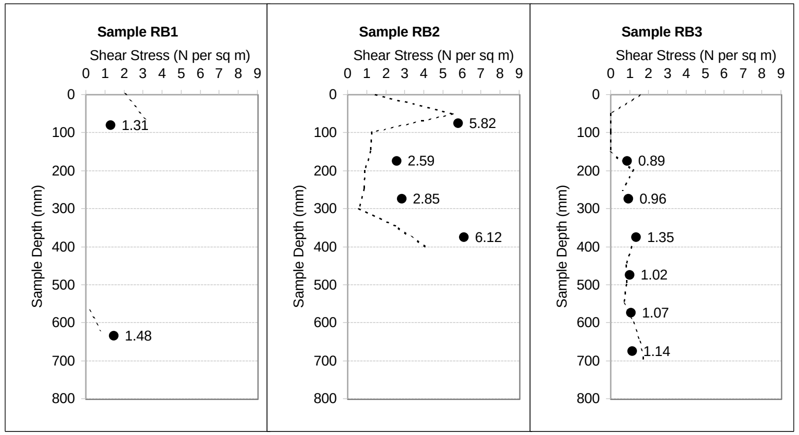
xCLSS_NMC 120.000 y:SAMP_TOP 53.333 ⊙ TABLE PRIORITY:cliss_hole HOLE_ID () RB

DETR	UK RESERVOIR SEDIMENTATION	Halcrow
MOISTURE CONTENT v DEPTH **Reservoir C**		Report No: Figure No: **Figure A3.6**

mc__gre.met axis scales in units/cm 2000/07/19 15:26 AGS



DETR	UK RESERVOIR SEDIMENTATION	Halcrow
LOSS ON IGNITION v DEPTH **Reservoir C**		Report No: Figure No: **Figure A3.7**



These graphs show calculated shear stress variation with depth for each of the three Makareth sediment sample cores extracted from Reservoir C.

The dotted values are calculated from bulk density measurements using the HR Wallingford formula for critical bed shear stress in non-colloidal sediments.
The dashed lines represent shear stress variation based on laboratory shear vane results (Kamphuis and Hall, 1983)

Figure A3.8
Reservoir C - Estimation of Critical Bed Shear Stress derived from Laboratory Results

Table B1 - Sedimentation rates observed in British Lakes and Reservoirs:

Landuse etc	Impounding reservoirs with sediment control or another reservoir upstream	Impounding reservoirs with no sediment control or other reservoir upstream	Indicative sediment yields suggested in previous report to DETR ($t.km^{-2}.yr^{-1}$)
Lowland pasture		**Blagdon** = 121 $m^3.km^{-2}.yr^{-1}$ but no sediment density available (Bristol Water). **Chard** , Somerset= 29 $t.km^{-2}.yr^{-1}$ but catchment is 25% urban (He et al, 1996). **Chew Valley** = 314 $m^3.km^{-2}.yr^{-1}$ but no sediment density available (Bristol Water) **Elleron Lake,** Yorks = 9.46 $t.km^{-2}.yr^{-1}$ (Foster & Lees, 1999). **Furnace Pond,** Kent = 11.6 $t.km^{-2}.yr^{-1}$ but 20% cultivated (He et al, 1996). **Seeswood Pool,** Warwickshire at end of 19th century = 8 $t.km^{-2}.yr^{-1}$ (Foster et al, 1990). **Stourton Lake,** Somerset = 29.6 $t.km^{-2}.yr^{-1}$ (He et al, 1996, says catchment undisturbed but doesn't give precise landuse). **Wadhurst Park,** Kent = 72.3 $t.km^{-2}.yr^{-1}$, catchment 95% undisturbed (He et al, 1996).	**Low 0-10**
Mixed arable, channels <1:1000		**Slapton Lea,** Devon = 16 $t.km^{-2}.yr^{-1}$ (Heathwaite, 1993). **Thoresby Lake**, Notts = 6.4 $t.km^{-2}.yr^{-1}$ (Butcher, Labadz and White, unpublished survey for British Coal, 1989).	**Low 0-25**
Upland less erodible soils or established forest		**Boltby,** Yorks = 19.57 $t.km^{-2}.yr^{-1}$ (Foster & Lees, 1999). **Fontburn** Northumbria= 12.46 $t.km^{-2}.yr^{-1}$ (Foster & Lees, 1999). **Merevale Lake,** Warwickshire = average 9.45 $t.km^{-2}.yr^{-1}$, varying 5-20. Deciduous woodland catchment (Foster et al , 1985). **Ponsonby Tarn,** Cumbria = 7 $t.km^{-2}.yr^{-1}$ before clear felling (Oldfield et al, 1999). **Trentabank,** Macclesfield Forest = 22.9-34 $t.km^{-2}.yr^{-1}$ (Stott, 1985, 1987).	**Low 10-25**

Table B1 Sedimentation rates observed in British Lakes and Reservoirs (continued):

Landuse etc	Impounding reservoirs with sediment control or another reservoir upstream	Impounding reservoirs with no sediment control or other reservoir upstream	Indicative sediment yields suggested in previous report to DETR ($t.km^{-2}.yr^{-1}$)
Lowland intensive agriculture or upland poor vegetation	**Holl** = 72.3 $t.km^{-2}.yr^{-1}$ (Duck & McManus, 1990).	**Barnes Loch,** Northumbria = 23.62 $t.km^{-2}.yr^{-1}$, mostly moorland (Foster & Lees, 1999). **Cameron,** Fife = 70 $t.km^{-2}.yr^{-1}$ (Al-Jibburi & McManus, 1993). **Catcleugh,** Northumbria = 43.1 $t.km^{-2}.yr^{-1}$ (Hall, 1967). **Cropston,** Leics. = 45.6 $t.km^{-2}.yr^{-1}$ (Cummins & Potter, 1967 and 1972). **Drumain,** Fife = 3.9 $t.km^{-2}.yr^{-1}$ (Duck & McManus, 1994). **Fillingham Lake,** Lincs. = arable, 16.49 $t.km^{-2}.yr^{-1}$ (Foster & Lees, 1999). **Glenfarg,** Tayside = 52 $t.km^{-2}.yr^{-1}$ (Duck & McManus, 1994). **Glenquey,** Tayside = 15.1 $t.km^{-2}.yr^{-1}$ (Duck & McManus, 1994). **Hopes,** East Lothian = 25 $t.km^{-2}.yr^{-1}$ (Ledger et al, 1974). **Kelly,** Renfrewshire/Ayrshire = 41 $t.km^{-2}.yr^{-1}$ (Ledger et al, 1980). **Llyn Geirionydd,** N. Wales = 6-18 $t.km^{-2}.yr^{-1}$, with higher values being due to mining rather than afforestation (Dearing, 1992). **Llyn Peris,** N. Wales = 5 -42 $t.km^{-2}.yr^{-1}$, increase associated with overgrazing, construction etc (Dearing *et al*, 1981). **March Ghyll,** Yorks. = 19.47 $t.km^{-2}.yr^{-1}$, mostly moorland (Foster & Lees, 1999). **Newburgh Priory Pond,** Yorks.= mixed agricultural, 52.38 $t.km^{-2}.yr^{-1}$ (Foster & Lees, 1999). **North Esk,** Midlothian = 26 $t.km^{-2}.yr^{-1}$ (Ledger et al, 1974). **Old Mill Reservoir,** Devon = mean 54 $t.km^{-2}.yr^{-1}$ increasing from 20 to 90 $t.km^{-2}.yr^{-1}$ as agriculture intensified (Foster and Walling, 1994). **Pinmacher,** Ayrshire = 50.9 $t.km^{-2}.yr^{-1}$ (Duck & McManus, 1994). **Ponsonby Tarn,** Cumbria = 39.8 $t.km^{-2}.yr^{-1}$ after trees felled (Oldfield et al, 1999). **Seeswood Pool,** Warwickshire = 36 $t.km^{-2}.yr^{-1}$ after agricultural intensification. Effectiveness of grass buffer strip for reducing input from cultivated land was noted. (Foster et al, 1990). **Strines,** Yorks. = 113.4 $m^3. km^{-2}.yr^{-1}$ according to Young, 1958, but no sediment density given. Later surveys suggest 70.1 to 115.6 $t.km^{-2}.yr^{-1}$ (White et al , 1997). **Strinesdale Upper**, Lancs.= 39 $t.km^{-2}.yr^{-1}$ (Labadz, Butcher & White , unpublished survey for North West Water, 1993). **Wyresdale,** Lancs = 41.5 $t.km^{-2}.yr^{-1}$ (Price et al, 2000). **Yetholm Loch,** Northumbria = arable, 22.01 $t.km^{-2}.yr^{-1}$ (Foster & Lees, 1999).	**Medium 25-100**

Table B1 Sedimentation rates observed in British Lakes and Reservoirs (continued):

Landuse etc	Impounding reservoirs with sediment control or another reservoir upstream	Impounding reservoirs with no sediment control or other reservoir upstream	Indicative sediment yields suggested in previous report to DETR ($t.km^{-2}.yr^{-1}$)
Upland peat/ moorland	**Southern Pennine Reservoirs:** in a study of 77 reservoirs, those with residuum lodges or bywash channels in place experienced mean rates of capacity loss approximately 166-188 $m^3.km^{-2}.yr^{-1}$ compared to 213-219 $m^3.km^{-2}.yr^{-1}$ for unmodified reservoirs, although variance within the samples was high (Labadz et al, 1995, White et al , 1996). Effects of reservoirs upstream and catchwater interception were less clear. It is possible that any difference in the average rates is confounded by the preferential siting of chains of reservoirs in moorland areas with relatively high erosion rates.	**Abbeystead,** Lancs = 192 $t.km^{-2}.yr^{-1}$ (Rowan et al , 1995). **Chew Reservoir,** Lancashire = 212.7 $t.km^{-2}.yr^{-1}$ (Labadz, 1988). **Carron Valley,** Stirlingshire = 141.9 $t.km^{-2}.yr^{-1}$ (Duck & McManus, 1990). **Earlsburn,** Stirlingshire =68.2 $t.km^{-2}.yr^{-1}$ (Duck & McManus, 1990). **Howden,** Peak District = 35.7 $t.km^{-2}.yr^{-1}$ from Severn Trent survey data, but 127.7 $t.km^{-2}.yr^{-1}$ suggested by Hutchinson (1995) from sediment cores. **North Third,** Stirlingshire = 205.4 $t.km^{-2}.yr^{-1}$ (Duck & McManus, 1990). **Southern Pennine reservoirs** 77 reservoirs = mean 124.5 $t.km^{-2}.yr^{-1}$ but with median value 77 $t.km^{-2}.yr^{-1}$ (Labadz et al, 1995, White et al , 1996). **Wessenden Valley chain,** Yorks. = average for 4 reservoirs 203.7 $t.km^{-2}.yr^{-1}$ (Labadz et al, 1991).	**High (>100)**

Table B2 - Correlations coefficients for sedimentation in British reservoirs:

- Correlation Coefficients - -

	M3KM2YR	M3YEAR	ANNPERC	SY
CARATIO	.6949	.3910	.066	.2769
	(96)	(113)	(113)	(93)
	P= .000	**P= .000**	P= .487	**P= .007**
CATCHMNT	.0866	.4352	.3871	.0013
	(98)	(115)	(114)	(104)
	P= .397	**P= .000**	**P= .000**	P= .990
DATEORIG	.2673	.3446	.0020	.1799
	(100)	(124)	(123)	(103)
	P= .007	**P= .000**	P= .983	P= .069
HEIGHT	.0976	.2052	-.0804	.3267
	(99)	(123)	(122)	(104)
	P= .336	**P= .023**	P= .379	**P= .001**
LENGTH	.5947	.3244	-.1431	-.0522
	(84)	(106)	(105)	(88)
	P= .000	**P= .001**	P= .145	P= .629
RAIN	-.2573	-.2627	.2322	.3011
	(66)	(78)	(77)	(68)
	P= .037	**P= .020**	**P= .042**	**P= .013**
SAREA	.5502	.9147	.1632	.0177
	(94)	(118)	(117)	(99)
	P= .000	**P= .000**	P= .079	P= .862

(Coefficient / (Cases) / 2-tailed Significance)
" . " is printed if a coefficient cannot be computed

Table B3 - Regression (curve-fitting) for prediction of sedimentation rates in British reservoirs:

Independent: CARATIO

Dependent	Mth	Rsq	d.f.	F	Sigf	Upper bound	b0	b1	b2	b3
SY	POW	.162	91	17.61	.000		4.1666	.5028		
ANNPERC	LOG	.110	111	13.75	.000		.4068	-.0526		
M3KM2YR	**LIN**	**.483**	**94**	**87.77**	**.000**		**145.882**	**.5706**		
M3KM2YR	LOG	.266	94	34.07	.000		-2104.1	478.797		
M3YEAR	LIN	.153	111	20.03	.000		2143.51	6.5353		
M3YEAR	LOG	.129	111	16.42	.000		-29909	6626.98		
M3YEAR	**QUA**	**.495**	**110**	**53.93**	**.000**		**-6752.7**	**44.8196**	**-.0039**	
M3YEAR	**CUB**	**.516**	**109**	**38.73**	**.000**		**-10097**	**61.3512**	**-.0090**	**3.4E-07**

Independent: RAIN

Dependent	Mth	Rsq	d.f.	F	Sigf	Upper bound	b0	b1	b2	b3
M3YEAR	LIN	.069	76	5.63	.020		29692.9	-20.613		
M3YEAR	LOG	.094	76	7.86	.006		186542	-25753		
M3YEAR	INV	.117	76	10.03	.002		-20347	2.8E+07		
M3YEAR	**QUA**	**.150**	**75**	**6.59**	**.002**		**112307**	**-174.50**	**.0670**	
M3YEAR	CUB	.158	74	4.62	.005		202165	-443.48	.3193	-7.E-05
ANNPERC	LIN	.054	75	4.27	.042		-.0226	.0001		
ANNPERC	QUA	.093	74	3.80	.027		.3978	-.0007	3.5E-07	
SY	LIN	.091	66	6.58	.013		-9.0833	.0785		
SY	LOG	.101	66	7.38	.008		-617.77	99.5782		
SY	INV	.098	66	7.18	.009		180.171	-107046		
SY	QUA	.118	65	4.37	.017		-148.88	.3058	-9.E-05	
SY	**CUB**	**.146**	**64**	**3.66**	**.017**		**235.232**	**-.6117**	**.0006**	**-2.E-07**
M3KM2YR	INV	.112	64	8.05	.006		-888.03	1380315		
M3KM2YR	QUA	.136	63	4.96	.010		5396.85	-8.1821	.0031	

Independent: HEIGHT

Dependent	Mth	Rsq	d.f.	F	Sigf	Upper bound	b0	b1	b2	b3
M3YEAR	LIN	.042	121	5.32	.023		-2077.1	324.385		
M3YEAR	CUB	.075	119	3.20	.026		11463.3	-1677.9	76.8543	-.7541
SY	COM	.114	102	13.09	.000		25.6525	1.0359		
SY	**POW**	**.131**	**102**	**15.32**	**.000**		**6.5337**	**.7267**		
ANNPERC	INV	.063	120	8.05	.005		.0682	.9678		

Independent: LENGTH

Dependent	Mth	Rsq	d.f.	F	Sigf	Upper bound	b0	b1	b2	b3
ANNPERC	INV	.052	60	3.30	.074		.0608	16.6323		

Independent: SAREA

Dependent	Mth	Rsq	d.f.	F	Sigf	Upper bound	b0	b1	b2	b3
M3YEAR	LIN	.372	67	39.75	.000		640.313	3.1026		
M3YEAR	QUA	.380	66	20.20	.000		404.369	4.7633	-.0005	
M3YEAR	**CUB**	**.621**	**65**	**35.57**	**.000**		**-565.53**	**14.3651**	**-.0117**	**2.4E-06**
ANNPERC	LIN	.335	67	33.71	.000		.0800	.0001		
ANNPERC	**QUA**	**.423**	**66**	**24.18**	**.000**		**.1215**	**-.0001**	**8.3E-08**	
ANNPERC	**CUB**	**.427**	**65**	**16.15**	**.000**		**.1279**	**-.0002**	**1.6E-07**	**-2.E-11**

Table B4 - Stepwise multiple regression to predict volumetric sedimentation for British reservoirs:

```
          * * * *   M U L T I P L E   R E G R E S S I O N   * * * *


Listwise Deletion of Missing Data

Equation Number 1    Dependent Variable..   M3KM2YR

Block Number  1.  Method:  Stepwise     Criteria   PIN  .0500   POUT  .1000
   CARATIO  CATCHMNT DATEORIG HEIGHT   LENGTH   ORIGCAP  RAIN     SAREA


Variable(s) Entered on Step Number
   1..    CARATIO


Multiple R           .98913
R Square             .97838
Adjusted R Square    .97796
Standard Error    195.38919

Analysis of Variance
                    DF      Sum of Squares      Mean Square
Regression           1      88122901.97958   88122901.97958
Residual            51       1947023.70796      38176.93545

F =    2308.27595       Signif F =  .0000


------------------ Variables in the Equation ------------------

Variable              B        SE B       Beta         T  Sig T

CARATIO        1.500435     .031230    .989133    48.045  .0000
(Constant)  -131.383827   29.277236               -4.488  .0000


------------- Variables not in the Equation -------------

Variable     Beta In  Partial  Min Toler         T  Sig T

CATCHMNT     .018206  .122646    .981028      .874  .3864
DATEORIG    -.007598 -.048578    .883663     -.344  .7324
HEIGHT       .006739  .045609    .990166      .323  .7482
LENGTH      -.003922 -.020137    .569704     -.142  .8873
ORIGCAP      .023306  .122634    .598500      .874  .3864
RAIN         .028854  .185518    .893602     1.335  .1879
SAREA        .037234  .208682    .679003     1.509  .1376


End Block Number   1   PIN =     .050 Limits reached.
```

Table B5 - Stepwise multiple regression to predict annual percentage loss of capacity for British reservoirs:

```
           * * * *   M U L T I P L E   R E G R E S S I O N   * * * *


Listwise Deletion of Missing Data

Equation Number 1    Dependent Variable..   ANNPERC

Variable(s) Entered on Step Number
   3..    RAIN


Multiple R           .66746
R Square             .44551
Adjusted R Square    .41731
Standard Error       .10029

Analysis of Variance
                    DF      Sum of Squares      Mean Square
Regression           3              .47681           .15894
Residual            59              .59346           .01006

F =      15.80114       Signif F =  .0000


------------------ Variables in the Equation ------------------

Variable              B        SE B       Beta         T  Sig T

ORIGCAP    -1.14575E-05  2.1066E-06  -1.466550    -5.439  .0000
RAIN        1.02860E-04  4.8445E-05    .220346     2.123  .0379
SAREA       1.16777E-04  1.8220E-05   1.700382     6.409  .0000
(Constant)     -.035140     .058193               -.604  .5483


------------- Variables not in the Equation -------------

Variable     Beta In  Partial  Min Toler         T  Sig T

CARATIO      .066856  .068955    .114688      .526  .6006
CATCHMNT    -.212939 -.183916    .088792    -1.425  .1595
DATEORIG    -.011050 -.013077    .128238     -.100  .9210
HEIGHT       .137908  .166225    .107697     1.284  .2043
LENGTH      -.054171 -.058969    .122870     -.450  .6545


End Block Number   1   PIN =     .050 Limits reached.
```

Table B6 - Stepwise multiple regression to predict sediment yield for British reservoirs:

```
* * * *   M U L T I P L E   R E G R E S S I O N   * * * *
Listwise Deletion of Missing Data

Equation Number 1    Dependent Variable..   SY

Block Number  1.  Method:  Stepwise     Criteria   PIN  .0500   POUT  .1000
   CARATIO  CATCHMNT DATEORIG HEIGHT   LENGTH   ORIGCAP  RAIN SAREA

Variable(s) Entered on Step Number
   1..    RAIN
Multiple R           .35757
R Square             .12785
Adjusted R Square    .11108
Standard Error     80.31189

Analysis of Variance
                    DF      Sum of Squares      Mean Square
Regression           1         49168.25618      49168.25618
Residual            52        335399.99350       6449.99988
F =       7.62299       Signif F =  .0079

------------------ Variables in the Equation ------------------
Variable              B        SE B       Beta         T  Sig T
RAIN            .122325     .044305    .357566     2.761  .0079
(Constant)   -53.656884   54.585794                -.983  .3302

------------- Variables not in the Equation -------------

Variable     Beta In  Partial  Min Toler         T  Sig T
CARATIO      .255964  .272630    .989418     2.024  .0483
CATCHMNT     .061282  .065468    .995380      .469  .6414
DATEORIG     .248033  .265054    .995953     1.963  .0551
HEIGHT       .281410  .297873    .977176     2.228  .0303
LENGTH       .043942  .046308    .968612      .331  .7420
ORIGCAP      .203303  .217695    .999995     1.593  .1174
SAREA       -.063874 -.066697    .950948     -.477  .6351

Variable(s) Entered on Step Number
   2..    HEIGHT
Multiple R           .45303
R Square             .20524
Adjusted R Square    .17407
Standard Error     77.41415

Analysis of Variance
                    DF      Sum of Squares      Mean Square
Regression           2         78927.80434      39463.90217
Residual            51        305640.44534       5992.94991
F =       6.58505       Signif F =  .0029

------------------ Variables in the Equation ------------------
Variable              B        SE B       Beta         T  Sig T
HEIGHT         1.984722     .890649    .281410     2.228  .0303
RAIN            .107781     .043202    .315051     2.495  .0159
(Constant)   -80.646267   53.992244               -1.494  .1414

------------- Variables not in the Equation -------------

Variable     Beta In  Partial  Min Toler         T  Sig T
CARATIO      .205023  .223331    .931367     1.620  .1115
CATCHMNT    -.082464 -.082206    .775358     -.583  .5623
DATEORIG     .153476  .153304    .778038     1.097  .2779
LENGTH       .068456  .075300    .951061      .534  .5957
ORIGCAP      .019517  .015751    .505839      .111  .9118
SAREA       -.042658 -.046529    .925397     -.329  .7433
End Block Number   1   PIN =     .050 Limits reached.
```

APPENDIX C RESEARCH CONTRACT - SEDIMENTATION IN STORAGE RESERVOIRS: SPECIFICATION

1: It is recognised that water storage reservoirs are susceptible to gradual reduction of their actual water capacity by sedimentation, but there appears to be little information relevant to British conditions on rates of capacity reduction, how rates can be arrested, or how (if at all) scdimcnt already accumulated can be safely and economically removed.

2. This lack of information is troublesome for at least two distinct reasons. The first is that the long-term consequences for the operations which reservoirs were constructed are largely unknown. In the particular case of public water supply, it is conceivable that the reduction may lead to a significant reduction in water available for use, thus affecting, in the longer term, water company water resources plans. It is therefore appropriate to carry out some research with the aim of providing better quantification of the possible effects, particularly at a time when the Environment Agency is embarking uponthe preparation of new water resources strategies for England and Wales.

3. The second reason relates to the current provisions of the Reservoirs Act 1975, which requires a rigorous system of inspection for 'large raised reservoirs' capable of holding more than 25,000 m3 of water above the level of the surrounding ground. Some reservoirs, although designed with a capacity greater than that threshold, are now thought to hold less than 25,000 m3 of water because of sedimentation, and there have been calls from various bodies for these to be removed from the ambit of the Act. But there is a degree of uncertainty as to the nature of the sediment, and whether, in any likely British conditions, the sediment might itself present an inundation danger in the event of the failure of the dam retaining it.

3 It IS also recognised that sedimentation of reservoirs may have significant cnvironmcntal effects. Some may be regarded as beneficial, although potentially outweighed by the operational consequences - for example, the establishment of mud banks which provide valuable wildlife habitats. Other effects may bc clearly less desirable - for example, the progressive loss of recreational amenity provided by the water body.

Objectives

5. The proposed research there:fore has the following objectives:

(a) To devise a broad classification of British reservoirs according to the factors which are likely to determine their susceptibility to significant capacity loss through sedimentation.

(b)) To carry out site and historical record investigations at reservoirs representative of some or all of the broad classes identified in (a) to determine (i) the extent and rate of loss of water capacity, and (ii) the consequences for the operation with which each reservoir is associated.

To extrapolate the reservoir-specific findings in (b) to the reservoir class as a whole, with particular attention to reservoirs used for public water supply.

(d) To examine the physical nature of reservoir sediments in the reservoirs studied in (b) in sufficient detail to determine how they would behave in the event of dam failure, and to extrapolate those findings as far as possible to other reservoirs.

(e) To identify any actions which could be taken to reduce, if desirable, the sedimentation rates for (i) the specific reservoirs studied in (b), and (ii) other reservoirs in those reservoir classes.

(f) To consider whether there are options, in British circumstances, for the economic and environmentally acceptable removal of sediment from reservoirs.

(g) To consider, in broad terms, past and future environmental consequences of sedimentation at (i) the reservoirs studied in (b) and (ii) other reservoirs in those reservoir classes.

Programme of work

6. Prospective contractors shall devise a programme of work to address all the above objectives within a maximum of 20 **months from award of contract** (which is expected to be made no later than 1 June 1999). The programme should be structured so as to address each of the seven objectives in turn, so that outputs against each are delivered in that order at intervals during the overall contract. However, prospective contractors are free to propose alternative structures, provided these are fully explained and justified. In any event, the programme of work must have clearly identified milestones, corresponding at least to the seven objectives, with a clear statement of the date by which each will be reached and of the price for reaching it. The programme of work shall include at least outline details of the techniques, organisational and working methods which will be used to attain those objectives. The outputs shall be initially in the form of hard copy reports to the Department's Nominated Officer, combined, at the contractor's discretion, into a single volume. But the reports shall be in a state suitable for subsequent publication.

Publications

7. Proposed written papers or articles resulting from this research shall be submitted to the Department's Nominated Officer, allowing at least 10 working days for comment and clearance.

General information to be provided by prospective contractors

8. Prospective contractors shall submit tenders for a programme of work to meet all seven objectives, as described in paragraph 5. Full details of price for each milestone shall be provided. The breakdown of costs shall list separately those associated with staff, travel and subsistence, materials, sub-contracts and reports. The tender shall also include, as a separate item, a price for the publication of the reports within six months of the end of the contract. The contractor must also state whether VAT is applicable.

Department of the Environment, Transport and the Regions
Water Supply and Regulation Division
February 1999