Hydraulics Research
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RESERVOIR SEDIMENTATION
INTERIM REPORT

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This interim report describes work carried out under Contract No DGR/PECD 7/6/29-204/83, Hydraulics Structures and Alluvial Processes, funded by the Department of the Environment. The DoE nominated officer was Dr R P Thorogood. The work was carried out in the River Engineering Department of Hydraulics Research. Dr W R White, Head, River Engineering Department was the Company's nominated officer. The opinions expressed in this report are not necessarily those of the Department of the Environment.

ABSTRACT

This interim report describes work on numerical reservoir sedimentation models to improve the prediction of reservoir sedimentation. The study considers the problems of updating sections subject to erosion or deposition, the consolidation of deposited sediments and the definition required to model a combination of silts and sands. The purpose of the work is to enable improved predictions to be made of reservoir sedimentation and to enable methods of controlling sedimentation to be studied.

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1 INTRODUCTION

It is of the nature of reservoirs that they lead to a reduction of both the velocity of flow in a river and the water surface slope. This reduces the capacity of the river to transport sediment and encourages the deposition of sediment in the reservoir. The accumulation of sediment reduces the amount of water storage available and hence the utility of the reservoir. In extreme cases effectively all the useful storage may be lost due to sedimentation. The rate at which sediment accumulates has a major impact on the useful life of a reservoir and so is significant in assessing the economics of a proposed reservoir. There is, therefore, a need to be able to assess sedimentation when a reservoir is being planned.

A number of empirical methods have been developed based solely on two or three parameters such as the catchment size or run-off and reservoir storage (Churchill, 1948 and Brune, 1953). These can be criticised as they ignore obviously significant variables such as the type of sediment characteristic of the river. As a result of the inadequacies of this empirical approach the estimates of sedimentation which they provide can prove unreliable. There are instances of reservoirs filling with sediment within one or two years of construction. More recently with the availability of computers it has been possible to develop numerical models of reservoirs. These models calculate the water flow and sediment movement in detail throughout the reservoir. This interim report describes studies of how to develop these numerical reservoir models to make them more realistic so as to improve the accuracy of their predictions. If realistic reservoir models can be developed they will provide a more reliable and detailed estimate of the impact of sedimentation on a reservoir.

Reservoir sedimentation results from a complex interaction of a number of physical phenomena not all of which are we yet able to describe in detail. While the water flow can be described satisfactorily our understanding of the movement of the sediment, its distribution in plan and the process by which it settles and subsequently consolidates is incomplete and requires further work to elucidate the mechanisms involved. Despite our incomplete knowledge, however, it is certainly possible to improve the description of various of these processes in existing numerical models.

In the present study we have so far considered:

1) the way that cross-sections are up-dated following deposition or erosion;

2) the consoldiation of deposited sediments;

3) the amount of detail required to model a combination of silts and sands.

These ivestigations are described in the following sections.

2 UPDATING SECTIONS

The primary purpose of a numerical reservoir sedimentation model is to predict the extent and location of sediment deposition within a reservoir. In modelling the sediment movement the primary concern is deposition. Since, however, the water level in the reservoir fluctuates and the inflowing discharge varies, sediment that has previously been deposited may subsequently be eroded. It is necessary to be able to model both the deposition and erosion of sediment. In modelling deposition and erosion account must be taken of the effect that deposition and erosion have on the section. Numerical calculations can be made to predict the change in cross-section area at a section but the primary interest is in the resulting bed level. Thus the change in bed level must be derived from a change in cross-sectional area on the basis of some assumption about the distribution of deposition or erosion across the section. In the early mobile-bed numerical river it was simply assumed that the section was raised or lowered vertically by the deposition and erosion of sediments with no change in cross-section shape. This is satisfactory providing either the amount of deposition or erosion is small or that little change in cross-section shape is expected. In reservoir sedimentation neither of these conditions apply so more careful consideration must be given to the up-dating of cross-sections. Since deposition and erosion have different impacts on a cross-section we will consider them separately.

Deposition

There are three simple possible algorithms for modelling deposition (see Fig 1).

a) Raising the section bodily, without any change of shape. Unfortunately where changes in cross-sectional area are large this is not particularly realistic.

b) Fill in the section from the bottom.

c) Deposition is distributed across the total width of the section, the amount of deposition at each point assumed to be proportional to the depth so that most deposition takes place in the deepest parts of the section with proportionately less in the shallower areas.

Erosion

There are three simple possible algorithms for modelling erosion (see Fig 2).

a) Lowering the section bodily without any change of shape. Unfortunately this is not particularly realistic for reservoir sedimentation.

b) Erosion is simulated by calculating an equilibrium width of the river entering the reservoir and assuming that erosion is confined to that width.

c) Erosion takes place across the total width of the section and is taken to be proportional to the depth so that most erosion takes place in the deepest parts of the section.

To decide how realistic these algorithms are for reservoir sedimentation it was decided to look at cross-sections derived from reservoir surveys. The ODA unit at HR undertook an investigation of reservoir sedimentation in the Tana River Basin, Kenya funded by ODA in collaboration with the Tana and Athi Rivers Development Authority, the Ministry of Water Development, Kenya and the Kenya Power and Lighting Co Ltd. As part of the work cross-sections were surveyed on three reservoirs, Kindaruma, Kamburu and Masinga and the cross-sections compared with those derived from earlier surveys. (Wooldridge, 1984). Fig 3 shows Kindaruma reservoir and the comparison between some of the measured cross-sections. For the most part the sections appear to demonstrate a gradual filling up from the bottom most akin to (b) of Fig 1. Fig 4 shows Kamburu reservoir and the comparison of some of the measured cross-sections. In the sections from the upper part of the reservoir the original section is almost completely silted but the inflow of water has maintained a much smaller, almost trapezoidal section While some of the other sections demonstrate a gradual filling from the base, cf. (b) of Fig 1, others still demonstrate the locations of the original channel in the silted cross-section so that the pattern of sedimentation resembles (c) of Fig 1. The original investigators attribute the differences in the silting of the cross-sections of the two reservoirs to the way that the reservoirs are operated. Kindaruma is presently operated to maintain the water level at, or near, its maximum water level for long periods resulting in even sedimentation across the section. Kamburu reservoir, however, is subjected to a large range of water levels and this, it is claimed, leads to the preservation of low water channels due to the re-working of sediment when the water level is drawn down (Wooldridge 1983).

Evidence from Chinese reservoirs suggests that the problem is more complex. Comparison of cross-sections from Guanting reservoir before and after a period of drawdown demonstrated that a deep channel was formed by sediment re-erosion, see Fig 5. Unfortunately there is no indication of whether this channel corresponded with the original river channel. Cross-sections from Sanmenxia reservoir show deposition followed by erosion taking place across approximately the full width of the cross-section. Thus erosion does not necessarily imply the development of a deep, narrow channel. All this evidence suggests that of the latter two algorithms described above for modelling erosion and deposition each is realistic in certain circumstances but possibly less so in others and at the moment it is not possible to decide a priori which is the most appropriate.

2.1 Analysis of section updating

It should be noted that the differences between the methods of up-dating the sections depends upon the shape of the original cross-section. For an initially rectangular section all the methods for deposition are the same. For a triangular section large differences may occur between the three methods. It can be observed, however, that methods (2) and (3) under deposition tend to make the section appear more rectangular so that as deposition continues the differences between the methods become less. These are really specific examples of the more general observation that the methods are equivalent if the area of the cross-section is proportional to the depth and that the differences become more accentuated the further one goes from a linear function.

Methods (1), (2) and (3) for deposition have been programmed and the results have been compared for a triangular-shaped reservoir to accentuate the differences. Fig 6 is a longitudinal profile down the reservoir centre-line and shows the differences in bed level that may arise. By choosing a sufficiently wide initial section the differences may be made arbitarily large.

3 COMPACTION OF SEDIMENTS

In performing calculations of sediment transport the quantity normally calculated is the weight of sediment being transported. Deposition or erosion is represented by the rate of change of sediment transport with distance and is thus expressed in terms of weight of sediment. To determine the loss of storage, however, this weight has to be converted to a volume using a value of density for the deposited sediment. The value of the density with which sediment is initially deposited on the bed is a function of the composition of the material. The density of the material once it has been deposited may also vary depending upon the time and the amount of overburden to which it is subjected. As the variation in density may be up to a factor of 2 it can be significant in the determination of storage loss. We, therefore consider information available on the density of sediment deposits in reservoirs.

Various measurements of in-situ density of sediment deposits in reservoirs have been taken. The chief problem in interpreting this data, however, has been that there has been no way of assessing the age of the deposit. Thus though intuitively both age and overburden should be significant it is not possible from the available data to quantify the effect of either.

Evidence suggests that sands do not consolidate but achieve their ultimate density immediately. The initial density of silts and clays, however, depends upon their composition, as does the rate at which they consolidate. Heinemann (1962) measured sediment bed densities in Sabetha Lake, Kansas, using a gamma probe and a piston-type sampler. He showed that the density varied with the clay content, see Fig 7. The scatter is presumably due to the varying age and amount of overburden. Work by Burt and Parker (1984) demonstrates the effect of both time and overburden on the compaction of mud bed but their results seem to indicate that the ultimate density achieved is independant of both.

Lane and Koelzer (1943) collected a large quantity of data on sediment bed densities. Despite the fact that there was little firm data on the age of the deposits concerned, Lane and Koelzer postulated an equation of the form

$$W = W_1 + k \log_{10} T \quad , \qquad (1)$$

where

W is the bed density in lbs/cu ft after time T
W_1 is the bed density in lbs/cu ft after 1 year
K is a constant
T is the age of the bed in years.

The constant W_1 depends upon the size of the material and the parameter K on the size of the sediment and the type of operation of the reservoir, see Table 1. As even Lane and Koelzer point out the form of equation (1) is clearly wrong since according to the equation the density of silts and clays increases indefinitely with time. It is much more realistic to suppose that it asymptotes to some ultimate density. The values of W_1 for the case of reservoirs kept nearly empty were selected on the basis of field data and K was assumed to be zero, ie it was assumed that the deposits dried quickly to their ultimate density. The values of K for the other cases were chosen so that the density attained the reservoir nearly empty value after 1000 years. Thus it can be seen that while there is reasonable evidence to support the initial W_1 values the choice of K is arbitary. The equation does not take account of the effect of overburden.

Much work has been done on the self-weight consolidation of silts (Gibson, England and Hussey, 1967 and Been and Sills 1981). Attention has been chiefly directed at the initial development of soft soil beds. Under certain simplifying assumptions the process can be described by the equation

$$\frac{\partial e}{\partial t} = C_F \frac{\partial^2 e}{\partial z^2} \qquad (2)$$

where e is the voids ratio, C_F is the coefficient of consolidation, t is time and z is the vertical coordinate. Descriptions are being sought for the development of a consolidated bed in typically the first 1000 hours. In modelling reservoir sedimentation, however, timescales of 20 to 50 years are frequently considered. On such a timescale rapid consolidation is restricted to the very topmost layers of the bed. For the remainder of the bed only a small rate of change with time can be expected due to the slowly increasing overburden so that over a small timespan conditions can be assumed to be well approximated by steady relationships. We will, therefore, assume that in any small time interval conditions can be regarded as steady but that changes can be expected in the various quantities involved over a sufficiently long time interval. This assumes that the rapidly consolidating part of the bed is small in comparison with the total deposited depth of sediment. This should be true except in the early stages of the life of a reservoir.

If one assumes that the rate of increase of overburden is sufficiently small so that the majority of the soil column is in quasi-equilibrium then one can ignore the theory on the rate of consolidation and just look at the relationship between the void ratio e and the overburden pressure p. For soils this takes the form

$$e = e_o - C_c \log_{10} \left(\frac{p_o + \Delta p}{p_o}\right) \qquad (3)$$

(Terzaghi and Pec, 1967, p72), where C_c is the compression index.

For a soil with a void ratio of e then the density of a saturated soil and water combination is

$$\rho_{\text{soil}} = \frac{\rho_s + e\,\rho_w}{1 + e}, \qquad (4)$$

where ρ_s and ρ_w are the densities of the solids and water respectively.

Using equation (3) for the void ratio e we have

$$\rho_{\text{soil}} = \frac{\rho_s + (\rho_o - C_c \log_{10} \left[\frac{p_o + \Delta p}{p_o}\right] \rho w}{1 + \rho_o - C_c \log_{10} \left[\frac{p_o + \Delta p}{p_o}\right]} \qquad (5)$$

We will now consider the relationship between this equation and the Lane and Koelzer equation. Let us assume a uniform rate of sediment deposition so that the overburden pressure is of the form $p_o + KT$.

We can, therefore, replace $\frac{p_o + \Delta p}{p_o}$ by $1 + K^1T$,

where $K^1 = \frac{K}{p_o}$

Equation (5) then becomes

$$\rho_{\text{soil}} = \frac{\rho_s + (e_o - C_c \log_{10} [1 + k^1T]) \rho w}{1 + e_o - C_c \log_{10} 1 + K^1T} \qquad (6)$$

The form of equation (6) has similarities with that proposed by Lane and Koelzer,

$W = W_1 + K \log_{10} T$

We can see that the initial density W_1 is related to the initial void ration e_o and Lane and Koelzer quite rightly allow this to depend upon the nature of the material. It can be seen, however, that implicit in the use of the constant K is an arbitrarily assumed uniform rate of deposition. Equation (5) though more complicated than equation (1) has a number of advantages. It does not imply an indefinitely increasing density for large times and the constants may be obtained using well-known laboratory techniques.

4 MODELLING OF FINE SEDIMENTS

The behaviour of sediments depends upon, among other things, the sediment size. For sediments of sand size and larger (approximately D = 0.06 mm) the movement of the sediment depends only upon the local hydraulic conditions. As the sediment size decreases the speed with which the sediment concentration reacts to changes in the flow conditions diminishes and so for the smaller clay and silt fractions the sediment concentration depends not only upon the instantaneous local hydraulic conditions but also on the previous history of the flow. Because of this difference in behaviour when modelling reservoir sedimentation, it is necessary to treat the sand and silt fractions separately.

4.1 Modelling movement of sand fractions

The movement of non-cohesive sands is dependent upon the sediment diameter. For sediments which do not contain too broad a range of different sizes a representative sediment diameter is selected. In the case of Ackers and White theory for sediment movement the D_{35} size is chosen (Ackers and White, 1973). For widely graded sediments the range of sediment sizes may be divided into a number of different classes and a representative diameter used for each class (Day, 1980).

4.2 Modelling of silt fractions

The behaviour of the silt and clay fractions depends upon the fall velocity of the sediment. In the initial modelling of reservoir siltation a single representative fall velocity was used for calculating the movemnet of the silt fractions.

4.3 Observed distribution of sediment sizes in reservoir sediments

Heinemann (1962) took samples of sediment from Sabetha Lake, Kansas, USA and showed that the composition of the sediment deposited varied with distance upstream from the dam, see Fig 8. At each distance from the dam the points appear as a vertical series since a number of samples were taken at each cross-section, all being the same distance from the dam. The average percentage of clay of the volumetric samples obtained at each cross-section was also determined. The results show three separate relationships, the changes between each relationship coinciding with the entrance of a tributary. As expected the results verify the general picture that the more coarse sediment is deposited near the head of the lake and that the turbulence of the flow maintains the finer particles in suspension though as the level of turbulence falls progressively finer and finer material is deposited as the dam is approached. More careful study of the data, however, suggests that this distribution of sediment does not correspond to that typically obtained using a single representative silt size or fall velocity.

4.4 Numerical experiments

Numerical experiments were performed using 1 and 5 representative diameters for the silt sizes. After simulating two years of deposition in a reservoir a mean sediment size was calculated for the sediment deposited at each section. This was taken to be the mean of the sediment sizes weighted by the proportion of the material present on the bed. In Figure 9 this mean sediment diameter is plotted against distance upstream of the dam. The distribution of sediment and sediment sizes depend upon a number of factors such as variation of water level in the reservoir and the distribution of inflows throughout the year. It can be seen, however, that using one representative diameter for the sand and one for the silt gives a poor representation of the distribution of sediment sizes. Using fine silt diameters improves the modelling of the silt sizes but the use of only one representative diameter in the sand sizes leads to a loss of definition in that size range. It is, therefore, clear that whereas in calculating sediment transport in a river the use of a representative diameter such as D_{35} has been shown to be satisfactory (White et al, 1973) it is unable to simulate the process at the head of a reservoir whereby the different sand sizes are sorted according to the ability of the flow transport material.

5 CONCLUSIONS

This interim report discusses a number of developments to improve the accuracy with which predictions can be made of reservoir siltation. A number of methods of up-dating cross-sections have been discussed in the light of observed changes in reservoir sections. The consolidation of deposited sediments has been investigated and a new equation has been proposed to describe the change in density through time. This work should enable improvements to take place in the assessment of the impact of sedimentation in reservoirs. It should also enable a realistic assessment to be made of methods to relieve the problem of sedimentation, for example, the use of sediment flushing to maintain the storage of the reservoir.

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Table 1 Values of Lane and Koelzer parameters W_1 and K

		Sand		Silt		Clay	
	Reservoir Operation	W_1	K	W_1	K	W_1	K
a)	Sediment always submerged or nearly submerged	93	0	65	5.7	30	16.0
b)	Normally a moderate reservoir drawdown	93	0	74	2.7	46	10.7
c)	Normally considerable reservoir drawdown	93	0	79	1.0	60	6.0
d)	Reservoir normally empty	93	0	82	0.0	78	0.0

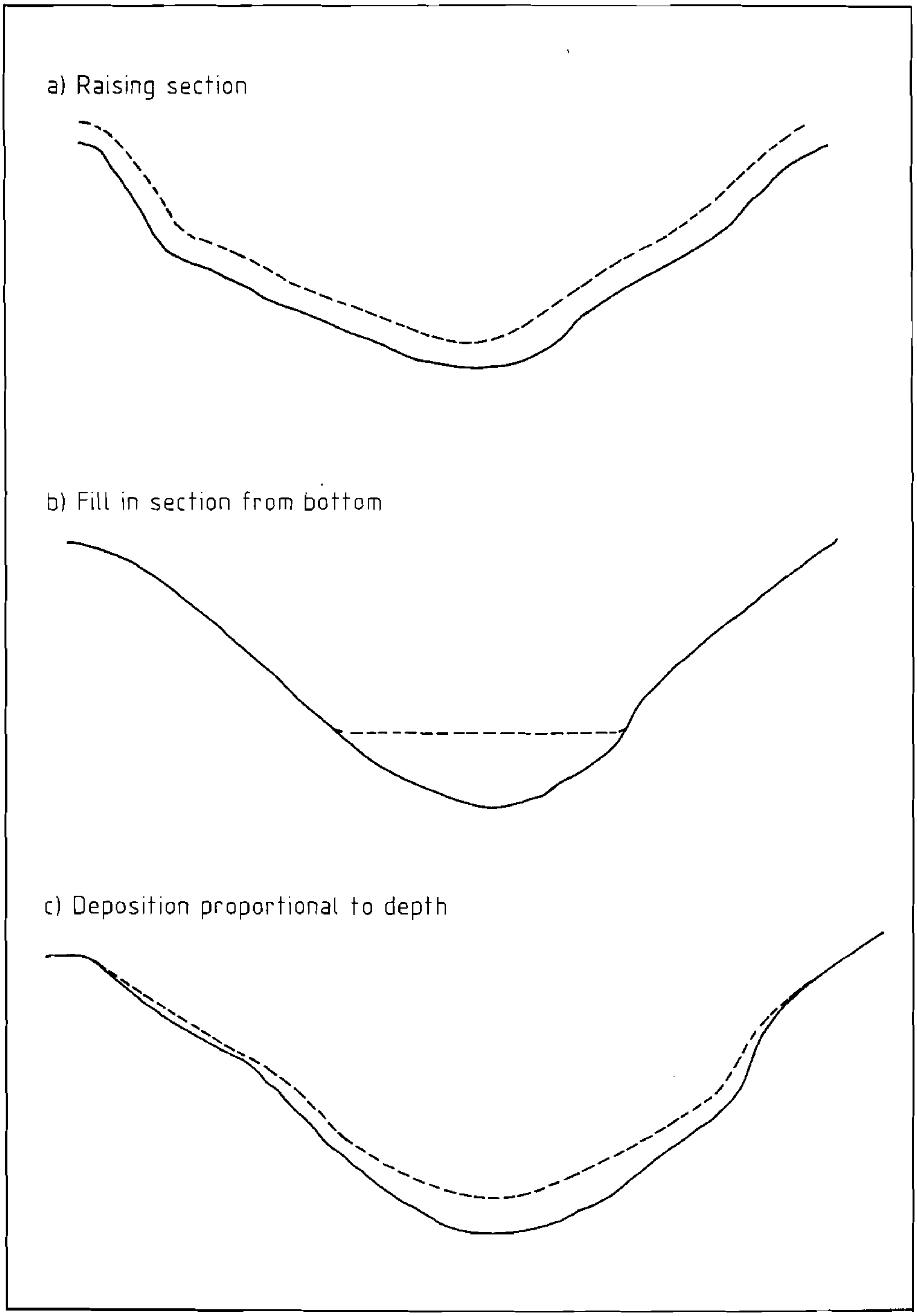


Fig 1 Algorithms for deposition

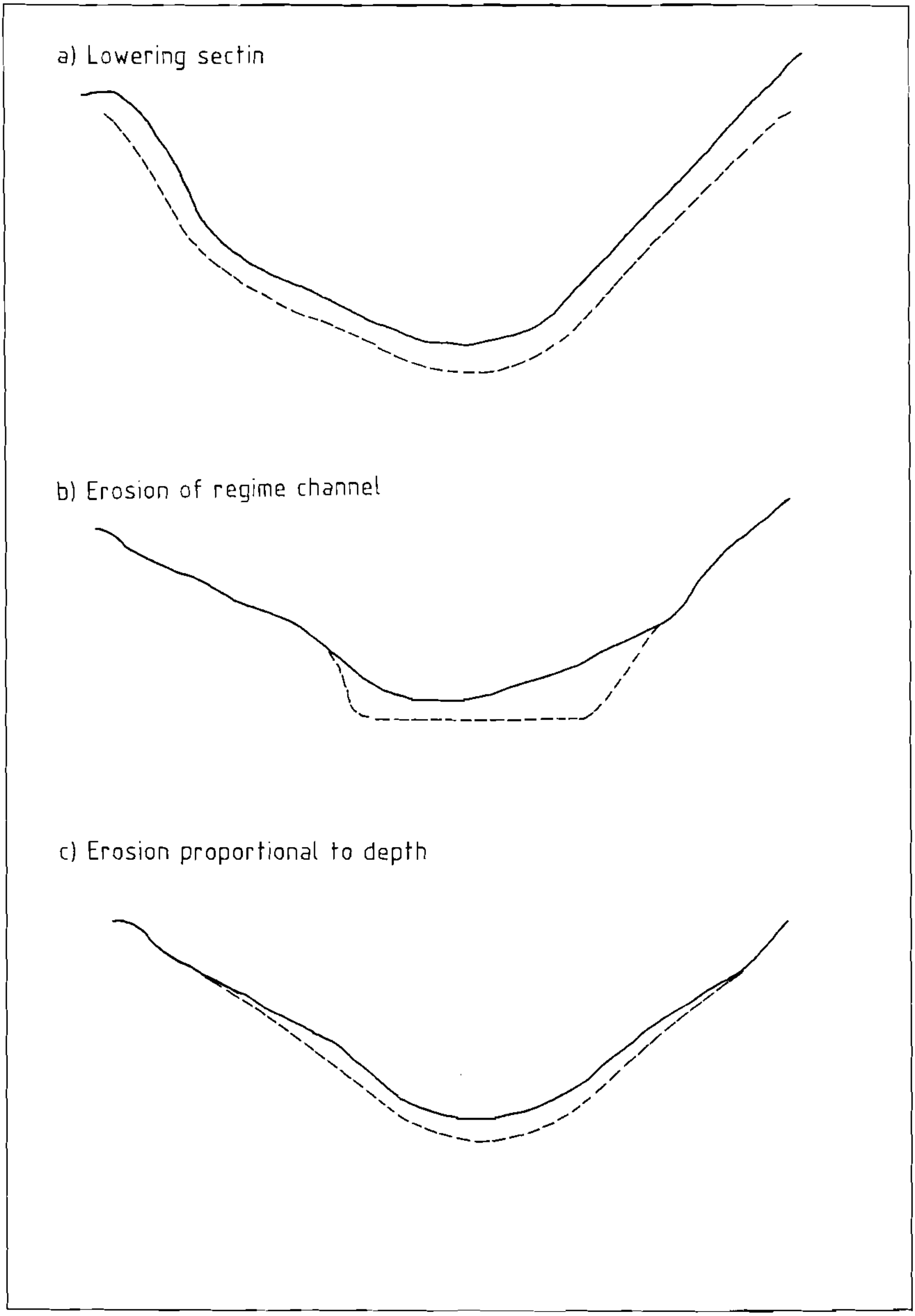
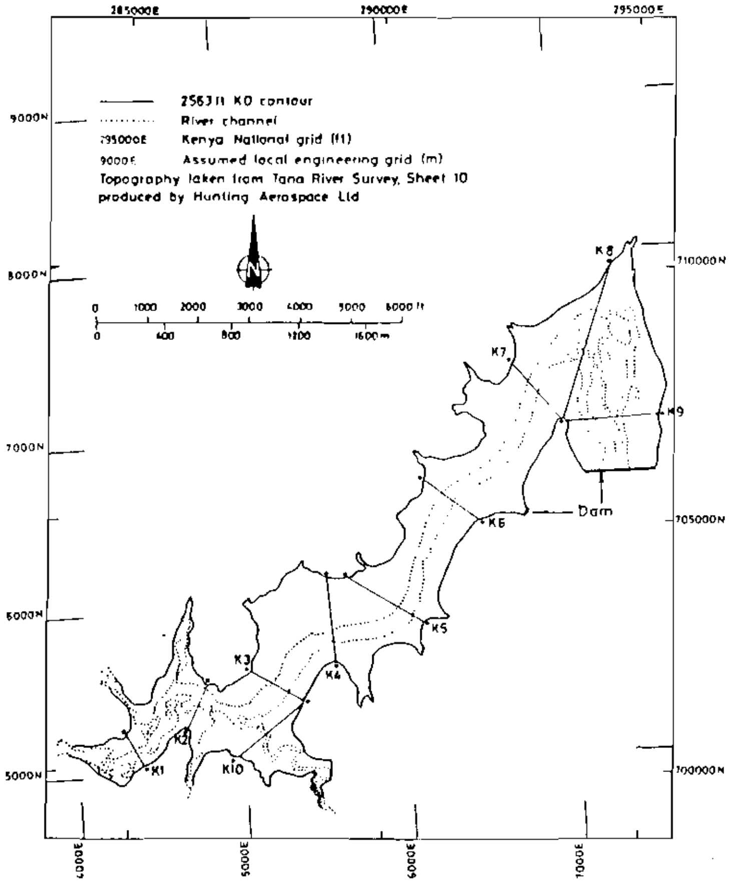


Fig 2 Algorithms for erosion



Kindaruma Reservoir

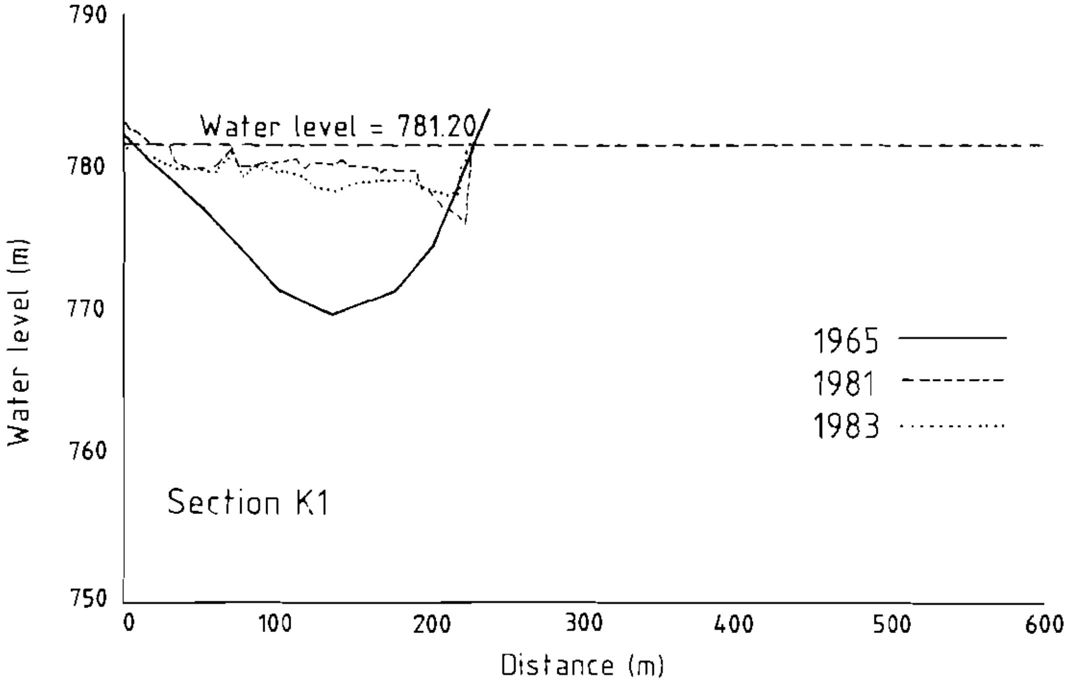


Fig 3A Kindaruma Reservoir cross-sections

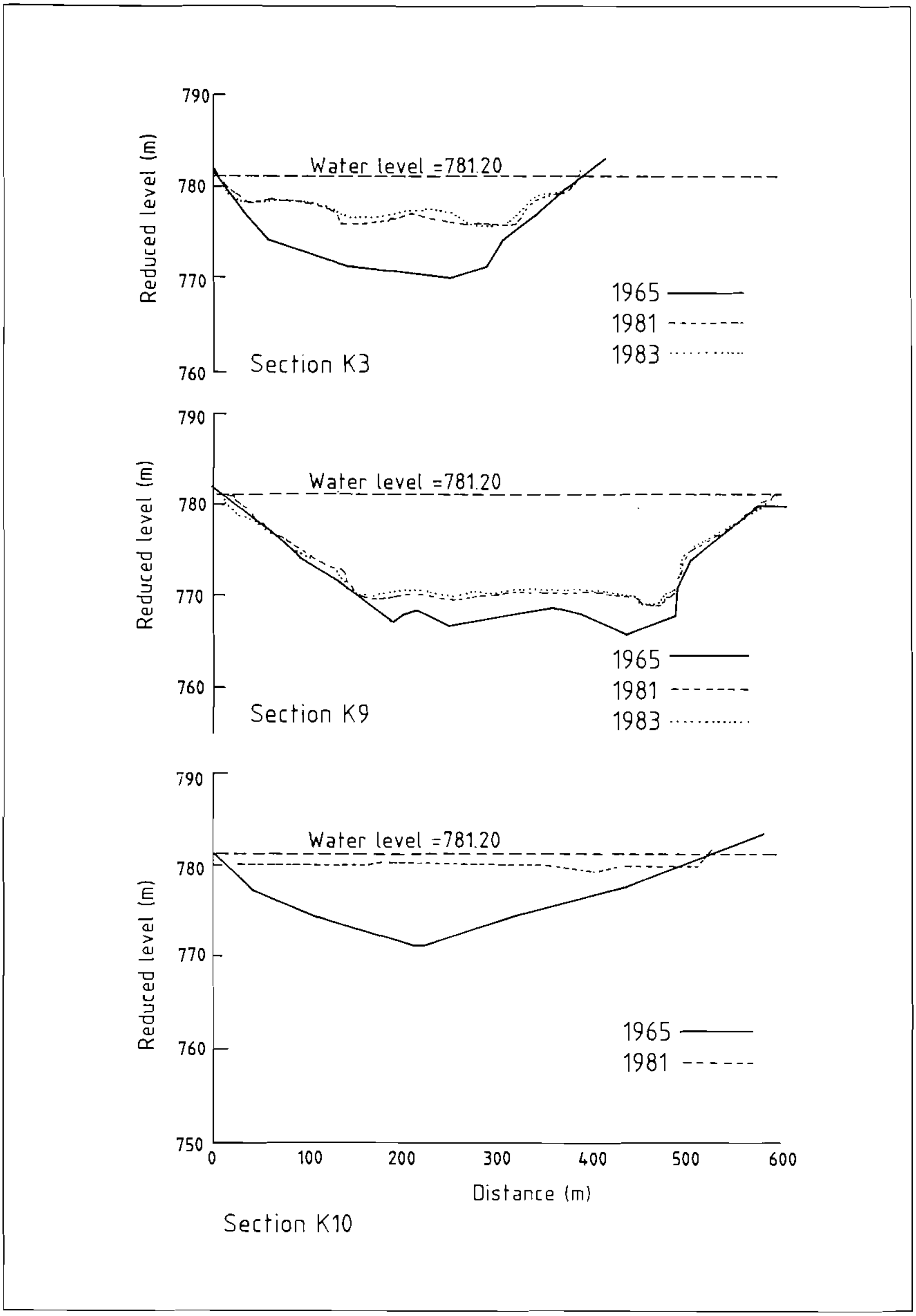
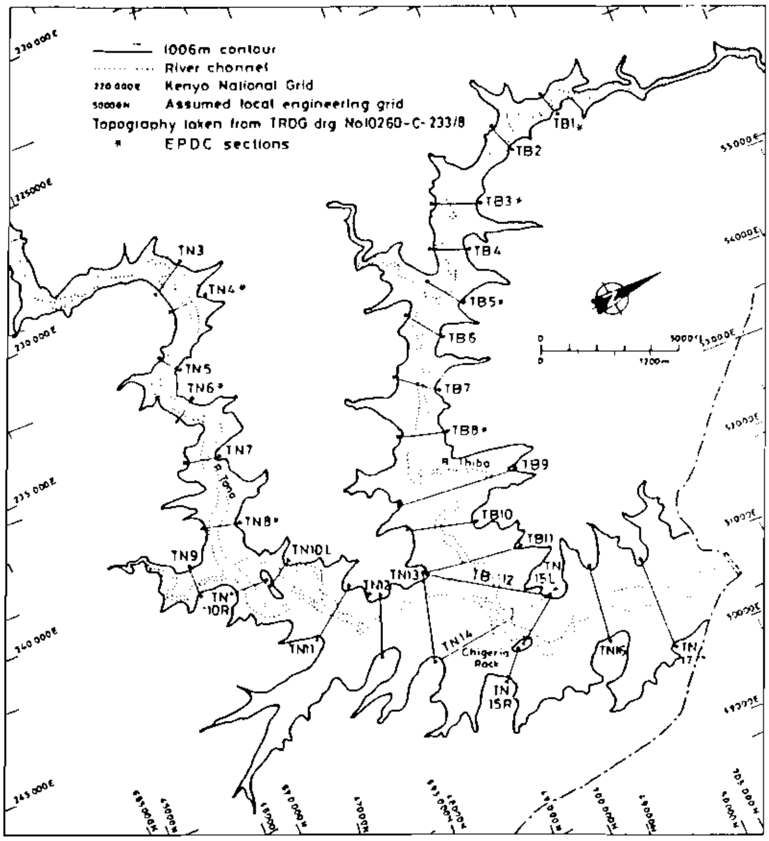
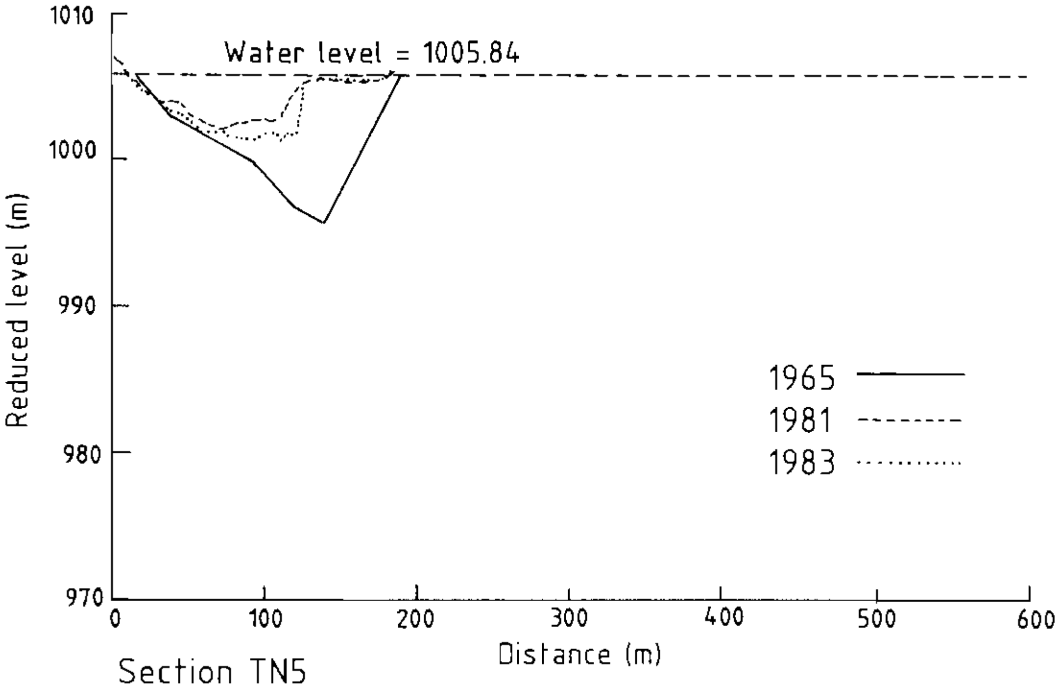

790
780
770
760
Reduced level (m)
Water level =781.20
1965
1981
1983
Section K3
790
780
770
760
Reduced level (m)
Water level =781.20
1965
1981
1983
Section K9
790
780
770
760
750
Reduced level (m)
Water level =781.20
1965
1981
0
100
200
300
400
500
600
Distance (m)
Section K10

Fig 3B

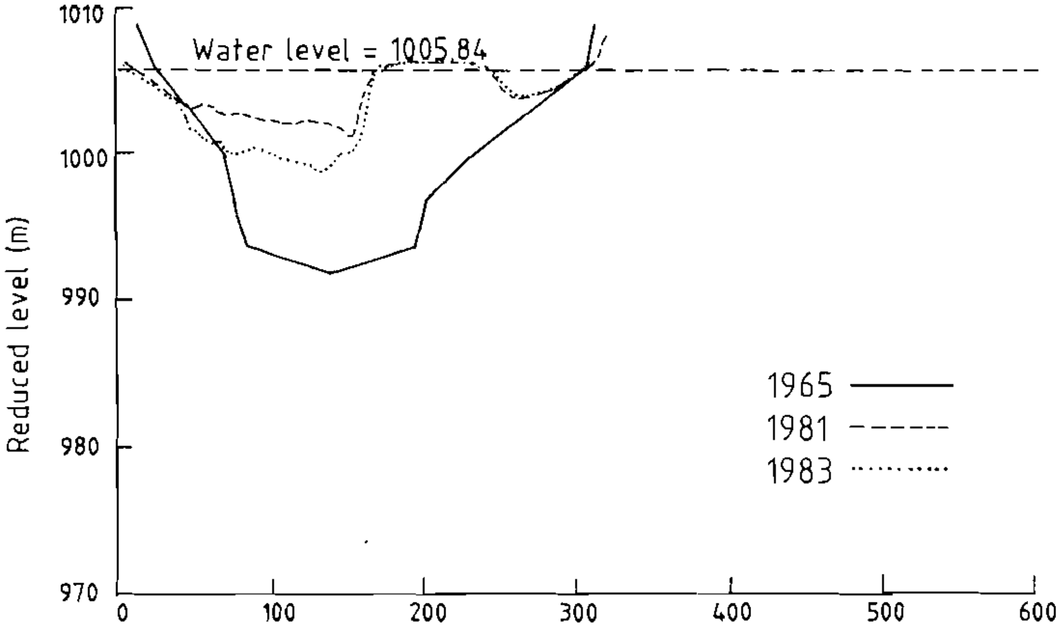


Kamburu Reservoir

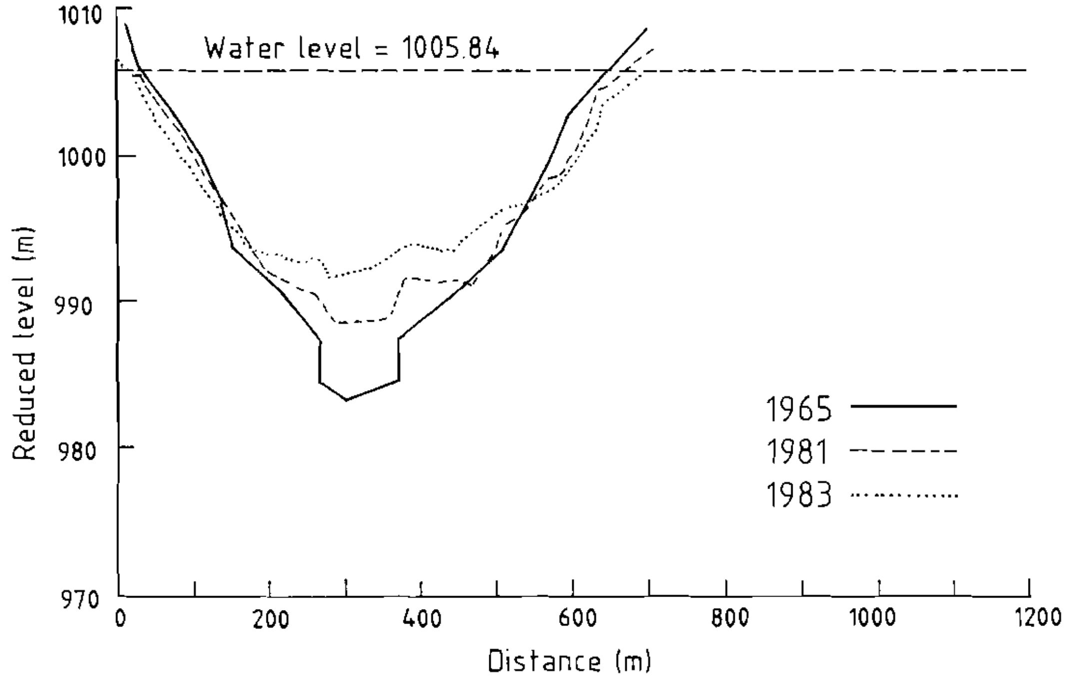


Section TN5

Fig 4 A   Kamburu Reservoir cross-sections

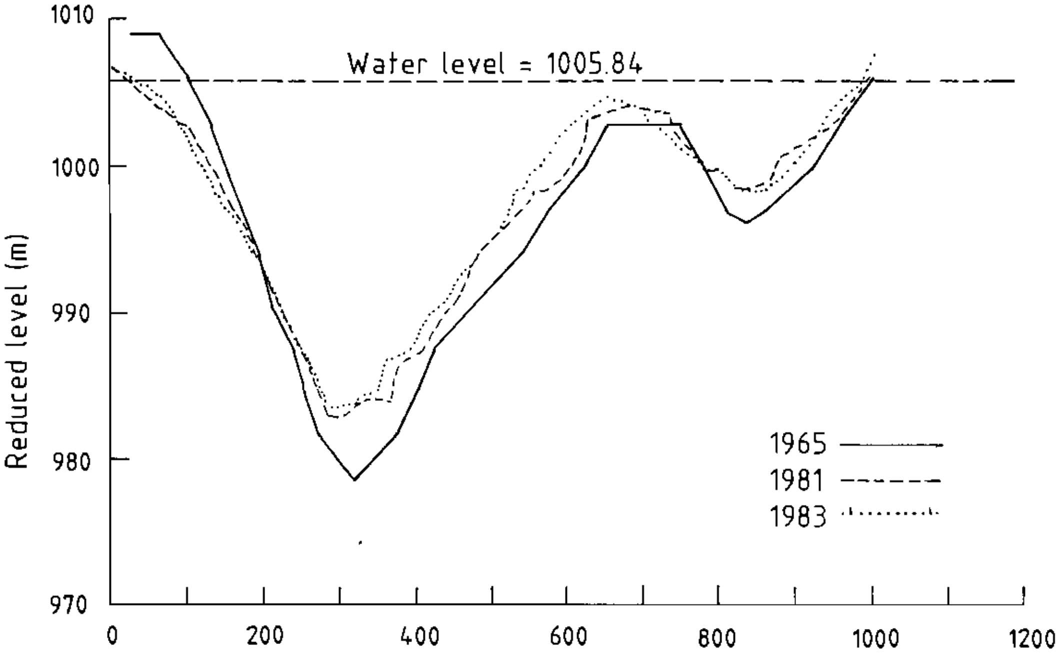


Section TN7

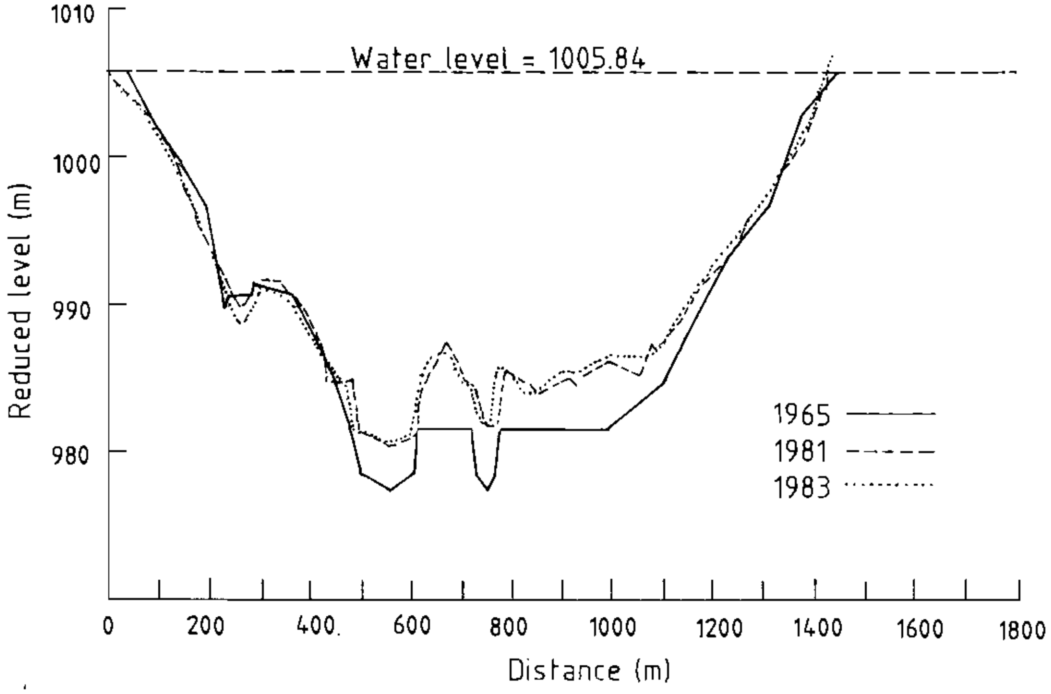


Section TN11

Fig 4B



Section TN13



Section TN14

Fig 4C

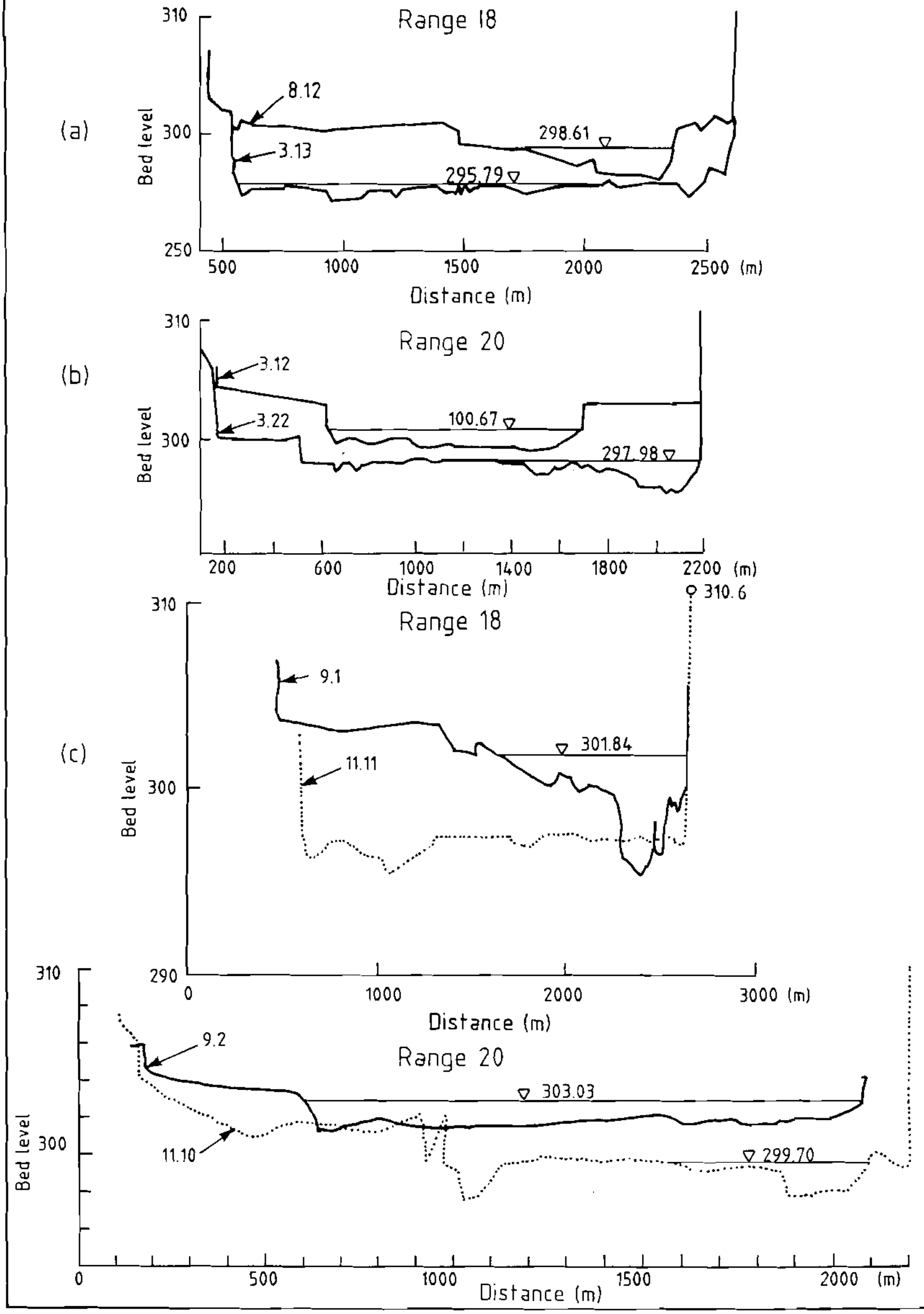


Fig 5A Sediment flushing at Guanting and Sanmenxia Reservoirs

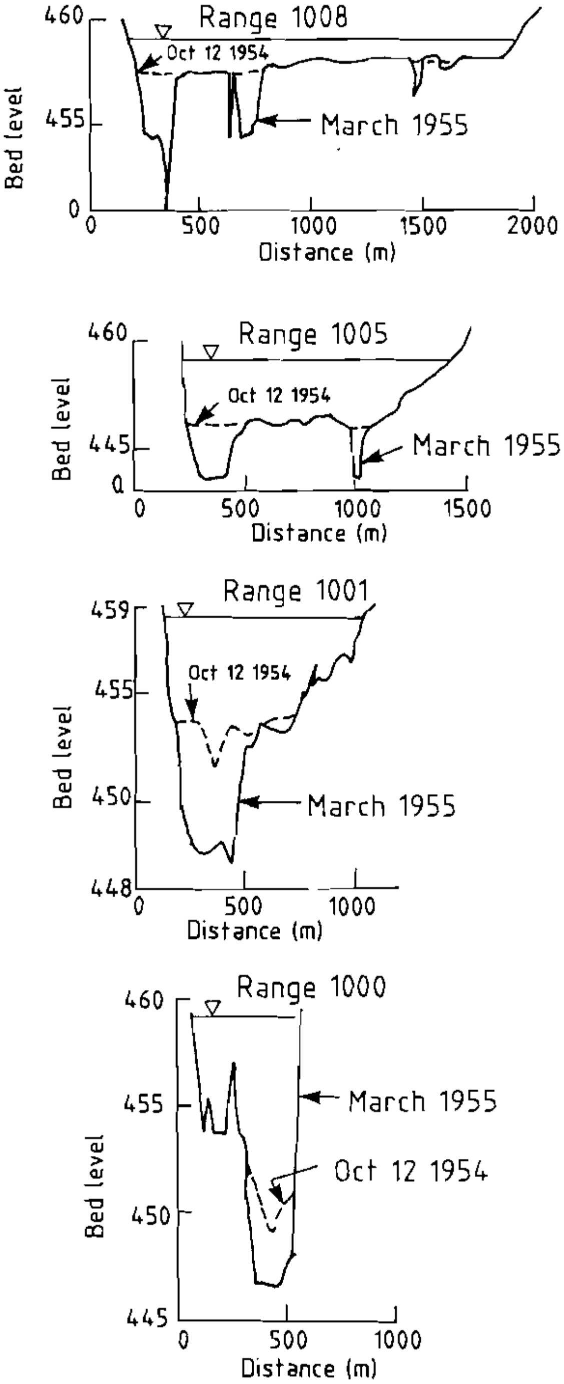

Range 1008
460
455
0
Bed level
Oct 12 1954
March 1955
0
500
1000
1500
2000
Distance (m)
Range 1005
460
445
0
Bed level
Oct 12 1954
March 1955
0
500
1000
1500
Distance (m)
Range 1001
459
455
450
448
Bed level
Oct 12 1954
March 1955
0
500
1000
Distance (m)
Range 1000
460
455
450
445
Bed level
March 1955
Oct 12 1954
0
500
1000
Distance (m)

Fig 5 B

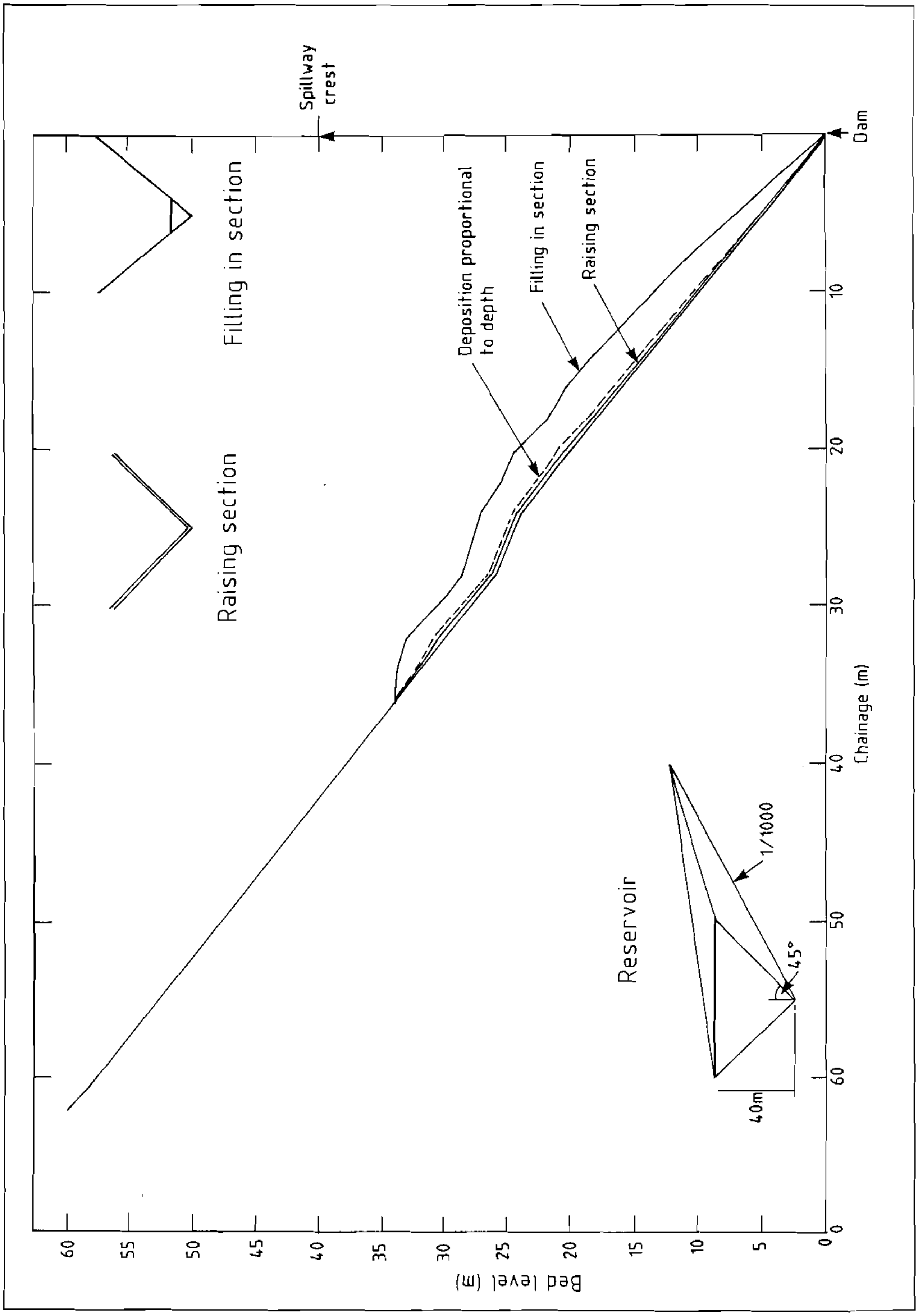


Fig 6 Longitudinal profiles for different algorithms

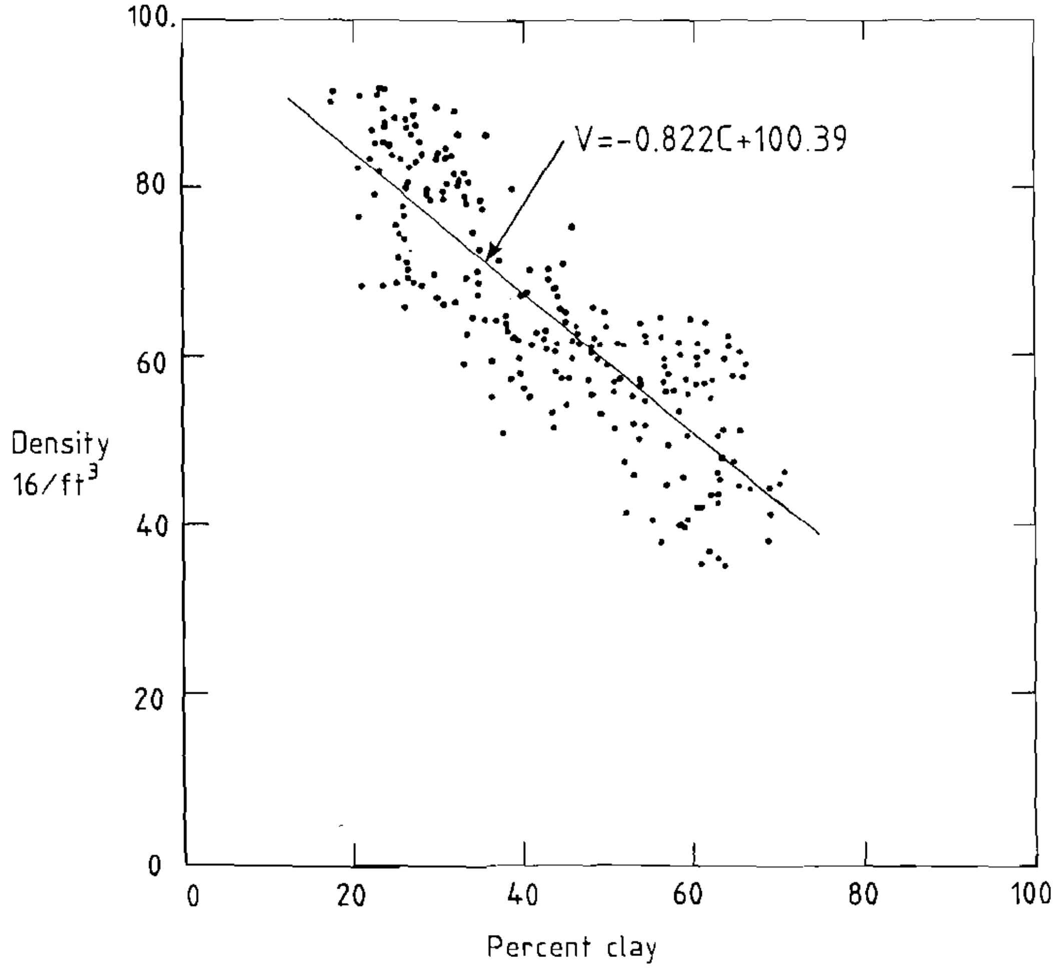


Fig 7 Percentage clay versus density

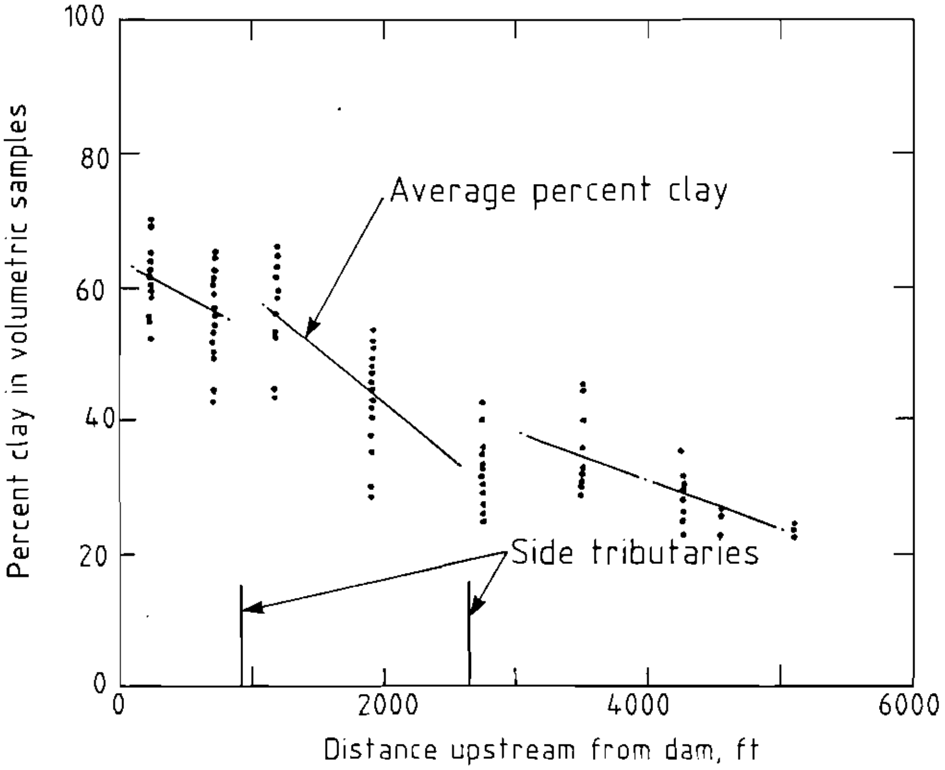


Fig 8 Percentage clay versus distance upstream from dam

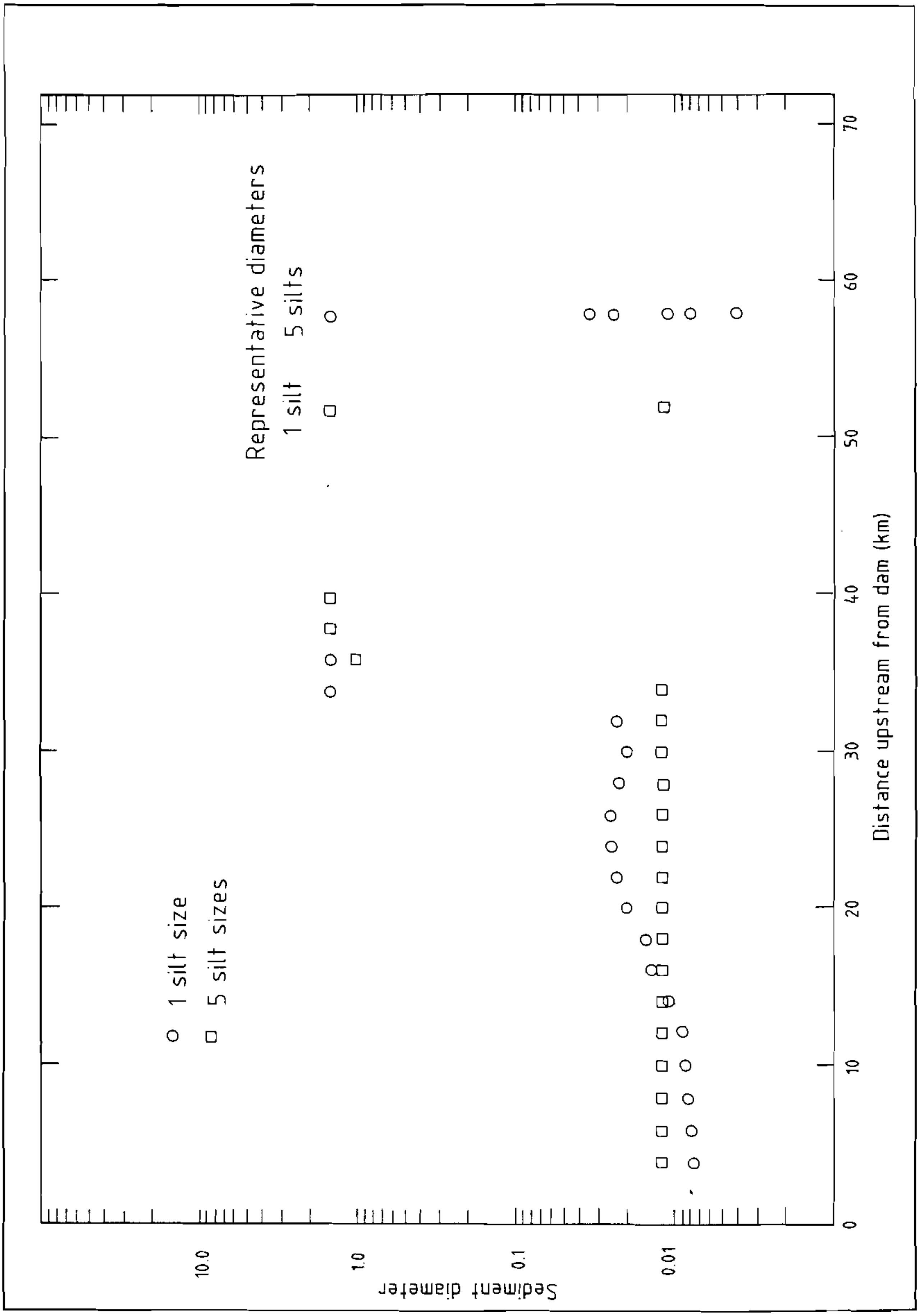


Fig 9 Sediment diameter against distance