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Hydraulics Research
Wallingford

TRAPPING EFFICIENCY OF RESERVOIRS

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Registered Office: Hydraulics Research Limited,
Wallingford, Oxfordshire OX10 8BA.
Telephone: 0491 35381. Telex: 848552

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HR nominated Project Officer: Dr W R White
Section Leader: Dr R Bettess

EXECUTIVE SUMMARY

This report describes a study undertaken by Hydraulics Research to investigate the factors which affect the trapping efficiency of reservoirs.

A numerical reservoir sedimentation model is used to investigate the effect of altering variables which represent the reservoir geometry, flow and sediment conditions.

The critical factors in determining reservoir trapping efficiency are the discharge, mean depth, width and shear velocity, and the sediment fall velocity.

The trapping efficiency of a reservoir is dependent on the mean depth to length ratio.

When assessing the trapping efficiency of a reservoir only the active length of the reservoir should be considered.

Two graphical procedures are developed for estimating reservoir trapping efficiency. In the first a backwater calculation is required to give the variation of shear velocity along the reservoir. In the second the active length of the reservoir is estimated from a plot of non-dimensional variables and then the mean shear velocity calculated. In both procedures the trapping efficiency is calculated from a plot giving trapping efficiency as a function of non-dimensional variables.

Both procedures give good agreement with the numerical model results except under extreme conditions such as very shallow reservoir or very high discharge.

When applied to a typical yearly cycle of reservoir inflows the procedures give good agreement with both the numerical model and Brune curves.

ABSTRACT

Because of the change in flow conditions that they create the construction of dams and the resulting reservoirs tend to trap a large proportion of the fluvial sediments that enter the reservoir. Knowledge of the trapping efficiency of reservoirs is important in assessing locations for new reservoirs as well as estimating the active life of existing reservoirs. A numerical reservoir sedimentation model is used to analyze the factors which affect reservoir trapping efficiency. The effect of altering variables which represent the reservoir geometry, flow and sediment conditions are investigated.

NOTATION

A	cross-sectional area of flow (m^2)
t	time (s)
Q	discharge (m^3/s)
x	distance along reservoir (m)
g	acceleration due to gravity (m/s^2)
d	depth of flow (m)
s_y	bed slope
s_f	friction slope
D	representative particle size (m)
s	specific gravity
v	flow velocity (m/s)
v_*	shear velocity at the bed (m/s)
ν	kinematic viscosity (m^2/s)
b	channel width (m)
z	bed height (m)
ω	fall velocity (m/s)
ω_o	single particle still water fall velocity (m/s)
ω_c	fall velocity in suspension of concentration C (m/s)
v_{*CRIT}	critical bed shear velocity (m/s)
L	reservoir length (m)
$\bar{b}$	mean reservoir width (m)
$\bar{d}$	mean reservoir depth (m)
Z1, Z2, Z3, Z5, Z6	non-dimensional variables
$\bar{v}_*$	representative (mean) shear velocity (m/s)
Qs_i	total volume of sediment transported by discharge i
Q_i	discharge in (m^3/s)
t_i	time for which discharge i occurs (s)
X_i	sediment concentration at discharge i
Qs_{TOT}	total sediment transported into the reservoir over a range of discharges (m^3)
$w_i = \frac{Qs_i}{Qs_{TOT}}$	weighting factor for trapping efficiency
TE_i	trapping efficiency at steady discharge Q_i (equation 5.4)
	trapping efficiency at fall velocity i (equation 6.9)
$\underline{TE}_{OVERALL}$	trapping efficiency over a range of discharges
EL	effective length (m)
$ELR = \frac{EL}{L}$	effective length ratio
$EMW = ELR \times \bar{b}$	effective mean width (m)
$EMD = ELR \times \bar{d}$	effective mean depth (m)
S	mean slope of reservoir
k_s	Colebrook-White roughness length (m)
PER_i	proportion sediment with fall velocity i is of the total sediment load
b_{MAX}	maximum reservoir width (m)
b_{MIN}	minimum reservoir width (m)
d_{MAX}	maximum reservoir depth (m)
d_{MIN}	minimum reservoir depth (m)

CONTENTS

CONTENTS (CONT'D)

CONTENTS (CONT'D)

TABLES (CONT'D)

FIGURES

APPENDICES

1 INTRODUCTION

It is the nature of reservoirs to cause a reduction in 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, the need to be able to assess sedimentation when a reservoir is being planned.

In considering the impact of sedimentation on a storage scheme it is important to know the loss of available storage after a given time period as this directly affects the yield of the reservoir. The distribution of the sediment deposits affects the stage/storage curve and so may have an impact on the operating rules of the reservoir. For the designer, therefore, there is a need to be able to predict both the amount and distribution of sedimentation.

1.1 Impact of reservoir sedimentation

The adverse effects caused by reservoir sedimentation may include :

(a) a reduction in the storage available and hence a reduction in the yield provided by the reservoir,

(b) degradation downstream of the dam. This may threaten structures associated with the dam and lead to problems at structures further downstream such as bridges and intakes,

(c) deposition at the head of the reservoir leading to an increase in flood levels in the contributing streams upstream,

(d) increased evaporation losses for a given storage volume.

Until recently reservoir sedimentation could only be assessed using simple, empirical methods. To estimate the volume of deposited material the notion of trapping efficiency was introduced. The trapping efficiency of a reservoir is defined as a ratio of the quantity of deposited sediment to the total sediment inflow.

Gottschalk (1948), Churchill (1948) and Brune (1953) provided simple graphical means to determine trapping efficiency and these have been used extensively. Since, however, the trapping efficiency must depend upon the sediment size, the flow through the reservoir, the distribution of flows into the reservoir and the way that the reservoir is operated, it follows that such estimates of trapping efficiency can only provide approximate values which may, on occasions, be seriously in error.

More recently, however, numerical models of sedimentation in reservoirs have been developed and these have provided a means of studying reservoir sedimentation in much greater detail. Unfortunately such models are complicated to use and expensive to apply.

1.2 Instantaneous trapping efficiency

Trapping efficiency may be measured by measuring any two of the following three quantities; the incoming sediment load, the sediment deposited in the reservoir and the outgoing sediment load (Brune, 1953). More frequently the volume of sediment deposited in the reservoir is determined by comparing surveys of the reservoir separated by a number of years. Thus the trapping efficiency quoted in work such as that by Brune represents the trapping efficiency determined over a number of years.

It is possible, however, to define an instantaneous trapping efficiency, that is, the value of the ratio of deposited to incoming sediment for a particular combination of inflow, outflow and reservoir level. When reservoir levels are low and the outflow is zero this may be large but when reservoir levels are high and the outflow is large the instantaneous trapping efficiency may be small. Thus the trapping efficiency can be regarded as varying throughout the year as the inflow and reservoir level varies. The trapping efficiency determined over a number of years is thus the instantaneous trapping efficiencies averaged in some appropriate way over a period of a number of years.

The notion of an instantaneous trapping efficiency is useful for the application of numerical models to the problem of reservoir sedimentation. While it is difficult to deal in some aggregate way with inflows and outflows over a number of years it is much easier to determine instantaneous conditions, perhaps on a daily basis, and then perform an averaging process on the results to determine the trapping efficiency over a year or number of years.

1.3 Scope of study

The objective of this study was to use a numerical reservoir sedimentation model to investigate the trapping efficiencies of a number of reservoir with a range of geometries and characteristics in order to improve the understanding of the factors determining trapping efficiency. This involved changing a number of variables such as reservoir length, width, depth, discharge and determining the corresponding trapping efficiencies. From this information, hopefully, a procedure can be developed to determine the instantaneous trapping efficiency of a reservoir. This procedure could then be used to consider the trapping efficiency of a reservoir at a number of different instants during a year so that the average yearly trapping efficiency could be determined.

By utilising this procedure the engineer will be able to quickly estimate the trapping efficiency, and thus active life, of existing reservoirs.

The procedure will also be of use when assessing sites for new reservoirs. Using the procedure the trapping efficiencies of reservoirs at different sites can be rapidly assessed.

Once a particular site and reservoir has been selected, a numerical reservoir sedimentation model can be used to identify the location of deposition together with subsequent changes in bed level and loss of storage.

2 MODEL FORMULATION

The numerical model is based upon the equations which describe the flow and sediment movement in open channels. The model is one-dimensional, that is, only variations along the length of the reservoir are considered and all the quantities calculated are averaged over the cross-sectional area. No account can be taken of variations across the width or through the depth.

2.1 Equations of water flow

The model is based upon the St Venant equations which describe the slowly varying unsteady flow of water in an open channel. The equations consist of a continuity equation which implies that the volume of water is conserved throughout the system,

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0 \qquad (2.1)$$

and a dynamic equation, in which the forces involved are related to the product of mass and acceleration,

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) + gA\frac{\partial d}{\partial x} = gA\,(s_y - s_f) \qquad (2.2)$$

These equations determine the water discharge and depth as a function of distance and time.

For the calculation of trapping efficiency the flow can be regarded as steady. The calculation of the water flow, therefore, reduces to a simple steady flow or backwater calculation. In order to carry out this calculation the discharge and water level at the dam are required.

The backwater calculation method used essentially follows that given by Chow (1959) with a Newton-Raphson iteration to determine the unknown upstream water level. The water level, velocity and water-surface slope is determined at points where the cross-section data is available.

2.2 Sediment transport equations

From the calculated velocities, depths and water-surface slopes, sediment concentrations at each cross-section may be calculated. The behaviour of sediments depends upon, among other things, sediment size. For sediments of sand size and larger (approximately D>0.06mm) the movement of the sediment depends only on the 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 silt fractions the sediment concentration depends not only upon the instantaneous local hydraulic conditions, but also the previous history of the flow. For the purposes of the calculation of the sediment transport, therefore, the sediment was divided into two size ranges. The finer size range, sediment diameters less than 0.06mm, consisted of material whose transport is usually independent of local hydraulic conditions and depends chiefly upon the supply. The coarser size range, with sediment diameters larger than 0.06mm, contain sand material whose transport is determined by the local hydraulic conditions.

2.2.1 Silt transport

The finer silt fractions are convected by the flow, but, if the conditions allow, some of the material settles out of suspension onto the bed. The rate of settling is dependent upon the fall velocity. The fall velocity is dependent upon the sediment diameter and varies with concentration and also with the flow conditions.

If the shear velocity is above a given threshold, v_{*CRIT}, then it is assumed that the turbulence generated is sufficient to maintain all the material in suspension. As the shear stress reduces the fall velocity tends to the still-water value. HR experience has shown that deposition does not take place for shear velocities in excess of 0.01m/s. This is the value used for v_{*CRIT} in the numerical model. The following equations for single particle fall velocity was used,

$$\omega = 0 \qquad v_* > v_{*CRIT} \qquad (2.3(i))$$

$$\omega = \omega_c \left(1 - \frac{v_*}{v_{*CRIT}}\right) \qquad v_* < v_{*CRIT} \qquad (2.3(ii))$$

Concentration also affects the fall velocity and it was assumed that ω_c is given by,

$$\omega_c = \frac{\omega_o}{1 + 1.56\, C^{0.33}} \qquad (2.4)$$

where ω_c is a fall velocity in a mixture of concentration C and ω_o is a single-particle, still-water fall velocity.

If the shear stress exceeds a certain critical value then material is picked up from the bed. The rate at which it is removed from the bed into suspension depends upon the amount by which the shear stress exceeds the critical value. Thus the re-erosion at high flows of silt previously deposited at low flows may be modelled.

The calculation of the silt concentrations requires cross- sections more closely spaced than for the flow calculations so extra cross-sections are interpolated between those used for the flow calculations. The calculated silt concentrations are then used to determine the transport rate of the silt fraction at each cross-section.

2.2.2 Sand transport

The transport of the sand sizes at each cross-section was calculated using the Ackers and White sediment transport theory (1973). In tests on an extensive set of field and flume data this theory produced the most satisfactory predictions of sediment transport (White, Milli and Crabbe, 1973).

The Ackers-White equations centre on several non-dimensional quantities; each have a distinct physical significance but incorporate coefficients determined from empirical data.

The sediment mobility F_{gr} is defined to be,

$$F_{gr} = \frac{v_*^n}{[gD(s-1)]^{\frac{1}{2}}} \left[\frac{V}{\sqrt{32}\,\log_{10}\left(\frac{10d}{D}\right)}\right]^{(1-n)} \qquad (2.5)$$

where n is the Ackers-White transition exponent.

The concentration is given by:

$$X = G_{gr} \frac{sD}{d} \left(\frac{V}{v_*}\right)^n PXX \qquad (2.6)$$

where $G_{gr} = C \left(\frac{F_{gr}}{A} - 1\right)^m$ (2.7)

C = Ackers-White parameter

A = Value of F_{gr} at initial motion

m = Ackers-White parameter

PXX = the proportion sand diameter D is of the total sand present on the bed

The parameters n, A, m and C are functions of the dimensionless particle size D_{gr} defined by:

$$D_{gr} = D \left[\frac{g\,(s-1)}{\nu^2}\right]^{1/3} \tag{2.8}$$

For coarse sediments ($D_{gr} > 60$)

$$n = 0.0$$
$$A = 0.17$$
$$m = 1.5 \tag{2.9}$$
$$C = 0.025$$

and for transitional sizes ($60 > D_{gr} > 1$)

$$n = 1.0 - 0.56 \log_{10} D_{gr}$$

$$A = \frac{0.23}{(D_{gr})^{1/2}} + 0.14 \tag{2.10}$$

$$m = 9.66/D_{gr} + 1.34$$

$$\log_{10} C = 2.86 \log_{10} D_{gr} - (\log_{10} D_{gr})^2 - 3.53$$

For all the numerical experiments described in this report all the sand size material transported into the reservoir was trapped viz all reservoirs tested were 100% efficient in trapping sand size material.

3 NUMERICAL SIMULATIONS/ PRESENTATION OF RESULTS

3.1 Numerical simulations

Initially a series of numerical experiments was carried out with different reservoir geometries, flow conditions and sediment fall velocities.

For these numerical simulations the simulated reservoirs had idealised geometries. In plan they consisted of an isosceles triangle with the river inflow at the vertex and the dam at the opposite side. In longitudinal profile the reservoir took the form of a right angled triangle with the right angle at the dam crest. The length, mean width and mean depth were used to characterise the geometry of these idealised reservoirs.

The fall velocities of sediments were used to represent variations in sediment size. The single particle still water fall velocity of different size sediments, at different temperatures, are given by Gibbs et al (1971). The fall velocity can be corrected for sediment concentration by using equation (2.4).

3.2 Presentation of results

The trapping efficiencies of the simulated reservoirs were calculated from the results of the numerical experiments. The trapping efficiency was taken to be the percentage of the sediment input at the upstream limit of the reservoir that was deposited in the reservoir. These trapping efficiencies are presented on non-dimensional diagrams. In this way the results are generally applicable and independent of the actual geometry, flow condition or sediment fall velocity.

3.2.1 Dimensional analysis

The trapping efficiency of a reservoir can only depend upon the geometry and flow characteristics of the reservoir itself, the input of water and sediment and the release of water and sediment. In the past when the characteristics of the river basin were introduced these could only be acting as approximations for the input of water and sediment. If we want to assess trapping efficiency we must, therefore, consider the characteristics of the reservoir and the inputs to it. The geometry will be crudely represented by the length, width and depth. The input of water will be mentioned explicitly in the form of the mean inflow and sediment inflow will be represented by the input of sediment and a measure of the sediment size.

Let us now consider which of these variables might be relevant to trapping efficiency. In the statements that follow about the effect of changes in specific variables it is implicitly assumed that as near as possible all other variables remain fixed.

(a) Length of reservoir, L

The longer the reservoir then the larger one would expect the trapping efficiency to be;

(b) Depth of reservoir, d

If the depth of a reservoir is reduced then the trapping efficiency should be correspondingly reduced. This can be clearly seen if one considers the limit as the depth reduces to that of the pre-reservoir river when one would expect the trapping efficiency to reduce to zero;

(c) Width of reservoir, b

The wider the reservoir then the larger one would expect the trapping efficiency to be;

(d) Velocity of flow, v

This variable is the discharge, Q, per unit area of cross-section. Any mean velocity through a reservoir will hinder settling. The trapping efficiency will decrease with increasing velocity until, if the velocity is everywhere sufficiently high, no settling of sediment will occur;

(e) Fall velocity, ω

One would expect the sediment size, represented by the fall velocity, to affect the trapping efficiency, the trapping efficiency increasing as the fall velocity increases.

(f) Input of sediment, X

This appears to have little affect on trapping efficiency. Doubling the inflow of sediment results in approximately twice as much material being deposited and twice as much passing through the dam, thus maintaining the same trapping efficiency.

(g) Shear velocity at the bed, v_*

The bed shear velocity will affect sediment deposition: the higher the bed shear velocity the less sediment will be deposited. Above a certain critical value of bed shear velocity there will be no sediment deposition. At the beginning of this study it was believed that the bed shear velocity would have little effect on reservoir trapping efficiency.

Based on the preceding discussion there are five dimensional variables which should be considered: ω, Q (or v), b, d and L. Representative values for b and d must be chosen to characterise a reservoir's geometry, and the mean values of b and d were chosen as the representative values. For the idealised reservoirs studied in the initial numerical simulations the mean values of b and d are the values of these variables at the point mid way along the length of the reservoir.

For the initial numerical simulations the five dimensional variables selected above were combined to give three non-dimensional variables :

$$Z1 = \bar{b}\bar{d}\omega/Q \qquad (3.1)$$

$$Z2 = \bar{b}/L \qquad (3.2)$$

$$Z3 = \bar{d}/L \qquad (3.3)$$

where $\bar{b}$ is the mean reservoir width (m)
$\bar{d}$ is the mean reservoir depth (m)
L is the reservoir length (m)
ω is the sediment fall velocity (m/s)
Q is the discharge (m^3/s)

These variables were used on the initial non-dimensional plots of trapping efficiency.

4 STEADY STATE RESERVOIR SIMULATIONS

In this chapter the results of the steady-state simulations of the idealised geometry reservoirs are presented. These results are divided into four sections according to whether the fall velocity, mean depth to length ratio, mean width to length ratio or discharge was varied. At the end of the chapter diagrams that can be used for estimating reservoir trapping efficiency are presented.

4.1 Sediment fall velocity

Figure 4.1 illustrates the effect of varying the sediment fall velocity on the trapping efficiency of reservoirs. In order to produce this figure all variables except the sediment fall velocity were held constant; this means that the variation in Z1 is due entirely to changes in sediment fall velocity.

Figure 4.1 illustrates the expected result: increases in sediment fall velocity, and thus increases in Z1, result in an increase in trapping efficiency. The change from zero to 100% trapping efficiency occurs over a two to three order of magnitude change in Z1 and thus a two to three order of magnitude change in sediment fall velocity. Figure 4.2 illustrates the relationship between sediment size and still-water single-particle fall velocity for sediment classified as silt in the numerical model viz sediment less than 0.06mm or 60 microns in diameter. This figure is produced from data presented by Gibbs et al (1971). It can be seen from Figure 4.2 that a one order of magnitude change in sediment size results in a two order of magnitude change in sediment fall velocity.

The curve shown in Figure 4.1 can be divided into three distinct portions. At trapping efficiencies below 20% the curve has a gentle slope. In this region large changes in sediment fall velocity result in only small changes in trapping efficiency. At trapping efficiencies from 20% to 90% the curve is steep. The increase in trapping efficiency from 20% to 90% occurs over a one order of magnitude change in fall velocity. Thus, by reference to Figure 4.2, for this region of the curve, a five times increase in sediment size can result in an increase in trapping efficiency from 20% to 90%. The final portion of the trapping efficiency curve occurs for trapping efficiencies in excess of 90%; in this region the curve becomes gentler again.

The dependence of trapping efficiency on sediment fall velocity and thus sediment size makes it imperative that great care be taken in the selection of a representative sediment size when estimates of the reservoir trapping efficiency are to be made.

4.2 Mean depth to length ratio - Z3

Figure 4.3 illustrates the effect of varying the mean depth to length ratio, Z3, on the trapping efficiency of reservoirs. The three different curves were obtained by holding the mean depth constant and altering the length of the reservoir. The form of each curve was calculated by varying the sediment fall velocity. A full discussion on the effect of varying the sediment fall velocity on trapping efficiency is given in section 4.1. Since the parameter Z1 is independent of the reservoir length this procedure means that for a given sediment fall velocity the value of Z1 is the same for each of the three Z3 values.

The results presented in Figure 4.3 show that for a given Z1 the reservoir trapping efficiency increases as the mean depth to length ratio decreases. Since the differences in Z3 values illustrated in Figure 4.3 are due to changes in reservoir length this implies that for a constant mean depth the trapping efficiency of a reservoir increases as the reservoir length increases.

Numerical experiments were carried out with reservoirs that had the same Z3 values as those shown on Figure 4.3 but different absolute mean depths and lengths.

The trapping efficiency curves for these reservoirs were identical to those, for the appropriate Z3 value, presented in Figure 4.3. This shows that the critical parameter in determining the position of the trapping efficiency curves on the Z3-trapping efficiency plot is the mean depth to length ratio, Z3, rather than the absolute length or mean depth.

4.3 Mean width to length ratio - Z2

Figure 4.4 illustrates the effect of varying the mean width to length ratio, Z2, on the trapping efficiency of reservoirs. The three curves were obtained by holding the mean width constant and altering the length of the reservoir. The form of each curve was calculated by varying the sediment fall velocity. A full discussion on the effect of the sediment fall velocity on trapping efficiency is given in section 4.1. Since the parameter Z1 is independent of the reservoir length this procedure means that for a given sediment fall velocity the value of Z1 is the same for each of the three Z2 values.

The results presented in Figure 4.4 show that for a given Z1 the trapping efficiency of a reservoir is independent of the mean width to length ratio.

Numerical experiments were carried out for reservoirs with a large number of different mean width to depth ratios. Provided the mean depth to length ratio was not altered all the trapping efficiency curves plotted at the same position on the Z1-trapping efficiency plot. This confirms the result outlined above that the trapping efficiency-Z1 relationship is independent of the mean width to length ratio.

4.4 Discharge

Figure 4.5 illustrates the effect of varying the discharge on the trapping efficiency of reservoirs.

The six curves presented relate to one reservoir geometry and were obtained by varying the discharge. The form of each curve was calculated by varying the sediment fall velocity. A full discussion on the effect of varying the sediment fall velocity on the trapping efficiency is given in section 4.1. This procedure means that for a given sediment fall velocity the differences in Z1 and trapping efficiency are due entirely to the changes in the discharge.

Figure 4.5 shows that at low discharges the trapping efficiency curves are effectively identical. At higher discharges the trapping efficiency curves plot at different points on the Z1-trapping efficiency diagram; the higher the discharge the further to the right the trapping efficiency curves plot.

The results presented in Figure 4.5 imply that the trapping efficiency of the simulated reservoir is dependent on the discharge. Since the method of presentation of the results was chosen in order to eliminate dimensional dependence this result is unreasonable; it implies that the non-dimensional variable Z1, which should have eliminated the dimensional dependence of discharge, has been incorrectly chosen.

4.4.1 Shear velocity, v_*, correction applied to Z1

The apparent dimensional dependence on discharge is in fact due to the value of sediment fall velocity that has been used to calculate Z1. In calculating the variable Z1 the single-particle still-water fall velocity is used. In the numerical model this fall velocity is modified as shown in equation (2.3). It is this modified fall velocity that is used to calculate the trapping efficiency. This inconsistency between the fall velocity used in the model and that used to calculate the variable Z1 is the reason for the apparent dependence of trapping efficiency on discharge. In order to overcome this problem the fall velocity used to calculate Z1 may be modified according to equation (2.3). The form of this modification depends on the value of a representative v_* relative to v_{*CRIT}, the critical shear velocity above which no deposition occurs. Provided v_* is less than v_{*CRIT} throughout the reservoir the whole of the reservoir is active viz. deposition can take place throughout the entire length of the reservoir. Under these circumstances a correction based on equation (2.3(ii)) should be used.

A representative value of v_* is required in order to apply this correction. To be consistent with the choice of representative values for the width and depth this representative value has been chosen to be the v_* that occurs at the mid-point of the reservoir; this representative value of v_* is referred to as the mean v_*.

When the correction based on equation (2.3(ii)) is applied the following modified form of equation (3.1) should be used to determine Z1,

$$Z1 = \frac{\bar{b}\,\bar{d}\,\omega}{Q}\left(1 - \frac{\bar{v}_*}{v_{*CRIT}}\right) \qquad (4.1)$$

where : $\bar{v}_*$ is the representative (mean) shear velocity and v_{*CRIT} is the critical shear velocity above which no deposition occurs.

At small discharges $\bar{v}_*$ is small relative to v_{*CRIT} and the correction given by $(1 - \bar{v}_*/v_{*CRIT})$ is negligible. Thus at low discharges there is no change to the Z1 calculated by equation (3.1); this is consistent with Figure 4.5 which shows that at low discharges there is no dimensional dependence on discharge.

At higher discharges $\bar{v}_*$ becomes larger relative to v_{*CRIT} and the correction $(1 - \bar{v}_* / v_{*CRIT})$ becomes significant. This means that at high discharges the modified value of Z1 given by equation (4.1) is smaller than the original value given by equation (3.1). Thus at higher discharges the result of the correction is that the trapping efficiency curves are moved to the left on the Z1-trapping efficiency plot.

When this correction is applied to the higher discharge curves in Figure 4.5 all the curves plot at the same location on the Z1-trapping efficiency plot; thus the apparent dimensional dependence on discharge is eliminated.

The procedure outlined above works very well providing v_* is less than v_{*CRIT} throughout the reservoir. As soon as this condition is violated the procedure breaks down. Under these circumstances the procedure outlined in the next section must be used.

4.4.2 Effective length correction

As discharge increases so does v_* and, in particular, v_* at the upstream end of the reservoir increases. Eventually a value of v_* in excess of v_{*CRIT} occurs. As discharge increases further the position where v_* exceeds v_{*CRIT} encroaches further down the reservoir. By equation (2.3(i)) no deposition occurs when v_* exceeds v_{*CRIT}. Hence if v_* exceeds v_{*CRIT} at any point in the reservoir then the active length of the reservoir over which deposition takes place is less than the actual length of the reservoir. Under these circumstances the active length of the reservoir rather than the geometric length needs to be used when assessing the trapping efficiency. In this report the active length of a reservoir is referred to as the reservoir effective length. When the effective length is less than the absolute reservoir length the v_* correction described in section 4.4.1 still needs to be applied.

The mean width, depth and v_* used to calculate Z1, Z2 and Z3 must relate to the active length of reservoir. Since when the active length is less than the total length the mean width and depth of the active reservoir will, in general, be greater than the mean width and depth of the total reservoir this means that the Z2 and Z3 will be greater for the active reservoir than for the total reservoir.

Thus in order to assess the trapping efficiency of a reservoir within which v_* exceeds v_{*CRIT} at some point towards the upstream limit we must in fact analyse a reservoir which has a greater mean depth to length ratio and mean width to length ratio.

Once the effective length and mean width, depth and v_* for this effective length have been calculated the procedure outlined in section 4.4.1 can be used to estimate Z1. Using this value for Z1 together with the value for Z3 which relates to the reservoir effective length figures similar to figure 4.3 can be used to calculate the trapping efficiency.

It must be noted at this stage that the results shown in Figures 4.1,4.3 and 4.4 are all for low discharges i.e conditions under which the corrections described in section 4.4 do not have to be applied.

4.5 Procedure for estimating reservoir trapping efficiency

In the preceding sections of this chapter the effect of changing variables which relate to reservoir geometry, flow conditions and sediment fall velocity on the trapping efficiency of the idealised geometry reservoirs simulated in the numerical model are discussed. Based on the results of this analysis a procedure has been developed which accurately determines reservoir trapping efficiency without using the numerical model. In order to apply this procedure a backwater calculation must be carried out to determine the variation of v_* throughout the length of the reservoir.

The procedure comprises two parts :

(1) Determine Z1 and Z3. This is done using the steps in Table 4.1

(2) Using the calculated values for Z1 and Z3 estimate the trapping efficiency using the curves shown in Figure 4.6. Linear interpolation can be used to find the trapping efficiency of reservoirs for which a Z3 is not shown.

4.6 Worked examples

In this section three worked examples are presented which use the procedure outlined in section 4.5 to estimate reservoir trapping efficiency. The results of these calculations are compared with the numerical model results. The three worked examples are for the same reservoir. The geometry of this reservoir is,

Length : 20km
Mean width : 2.5km
Mean depth : 12.5m

The worked examples are for three different cases,

(1) $\overline{v_*}$ negligible relative to v_{*CRIT} therefore correction to Z1 negligible.

(2) $\overline{v}_*$ significant relative to v_{*CRIT} therefore correction to Z1 important.

(3) effective (active) reservoir length less than the actual reservoir length.

For all three worked examples $v_{*CRIT} = 0.01$m/s as indicated in section 2.2.1.

For each of the worked examples a sediment fall velocity is chosen that gives a trapping efficiency of approximately 50%.

A backwater calculation was done for each worked example to calculate the variation of v_* along the reservoir.

4.6.1 <u>Discharge = 30m³/sec. Omega = 5.9188x10⁻⁷m/s</u>

v_* was less than 0.01 throughout the reservoir
$\bar{b}$ = 2500m
$\bar{d}$ = 12.5m
L = 20,000m
$\overline{v}_*$ = 0.000037m/s (from backwater calculation)

$$Z1 = \frac{\bar{b}\,\bar{d}\,\omega}{Q}\left(1 - \frac{\overline{v}_*}{v_{*CRIT}}\right) = \frac{2500 \times 12.5 \times 5.9188 \times 10^{-7}}{30}$$

$$\times \left(1 - \frac{0.000037}{0.01}\right) = 6.143 \times 10^{-4}$$

$$Z3 = \frac{\bar{d}}{L} = \frac{12.5}{20{,}000} = 6.25 \times 10^{-4}$$

From Figure 4.6 the trapping efficiency is given as 60%. The trapping efficiency calculated by the numerical model was also 60%.

4.6.2 Discharge = 1000m³/sec. Omega = 1.4794x10⁻⁵m/s

v_* was less than 0.01 throughout the reservoir.

$\bar{b}$ = 2500m

$\bar{d}$ = 12.5m

L = 20,000m

$\bar{v}_*$ = 0.00124m/s (from backwater calculation)

$$Z1 = \frac{\bar{b}\,\bar{d}\,\omega}{Q}\left(1 - \frac{\bar{v}_*}{v_{*CRIT}}\right) = \frac{2500 \times 12.5 \times 1.4794 \times 10^{-5}}{1000}$$

$$\times \left(1 - \frac{0.00124}{0.01}\right) = 4.05 \times 10^{-4}$$

$$Z3 = \frac{\bar{d}}{L} = \frac{12.5}{20,000} = 6.25 \times 10^{-4}$$

From Figure 4.6 the trapping efficiency is given as 45%. The trapping efficiency calculated by the numerical model was 42.6%.

4.6.3 Discharge = 5000m³/sec. Omega = 2.36x10⁻⁴m/s

v_* exceeds v_{*CRIT} at a distance 9000m from the dam. Thus the effective (active) length of the reservoir was 9000m.

L = 9,000m

$\bar{b}$ = 3860m

$\bar{d}$ = 16.6m

$\bar{v}_*$ = 0.0058m/s (from backwater calculation)

$$Z1 = \frac{\bar{b}\,\bar{d}\,\omega}{Q}\left(1 - \frac{\bar{v}_*}{v_{*CRIT}}\right) = \frac{3860 \times 16.6 \times 2.36 \times 10^{-4}}{5000} \times$$

$$\left(1 - \frac{0.0058}{0.01}\right) = 1.27 \times 10^{-3}$$

$$Z3 = \frac{\bar{d}}{L} = \frac{1606}{9,000} = 1.84 \times 10^{-3}$$

By using linear interpolation between the Z3 curves with values 1.125×10^{-3} and 2.25×10^{-3} the trapping efficiency is estimated from Figure 4.6 as 49%. The trapping efficiency calculated by the numerical model was 46.7%.

5 TRANSIENT RESERVOIR SIMULATIONS

At the end of the last chapter a procedure which accurately predicts the instantaneous trapping efficiencies calculated by the numerical model was outlined.

In reality the discharges into a reservoir are not steady but vary on both a short time scale during storm events and over a much longer time scale from season to season. A procedure is outlined in this chapter which allows the overall trapping efficiency of a reservoir, over a range of discharges, to be calculated from the instantaneous trapping efficiency curves presented in Chapter 4.

5.1 Weighting the instantaneous trapping efficiencies

Provided a backwater calculation can be carried out to calculate the variation of v_* along the length of reservoir the procedure outlined in Chapter 4 can be used to estimate the trapping efficiency at any given steady state discharge.

In order to estimate the overall trapping efficiency of a reservoir when the discharge is variable the discharge distribution must be represented by a series of steady discharges. The instantaneous trapping efficiency for each of these steady discharges is then calculated using the procedure given in section 4.5.

These instantaneous trapping efficiencies must be weighted in order to obtain an overall trapping efficiency. For a given discharge the weighting factor is the proportion of the total sediment input into the reservoir that is transported at that discharge.

For a given discharge, Q_i, the volume of sediment transported into the reservoir is given by,

$$Qs_i = Q_i \, t_i \, X_i \tag{5.1}$$

where Qs_i is the volume of sediment transported by discharge i

Q_i is the discharge

t_i is the amount of time for which the discharge occurs

X_i is the sediment concentration at that discharge

The total quantity of sediment transported into the reservoir over the range of discharges is,

$$Qs_{TOT} = \sum_{i=1}^{n} Qs_i = \sum_{i=1}^{n} Q_i \, t_i \, X_i \tag{5.2}$$

For any given discharge, Q_i, the weighting factor for the trapping efficiency, w_i, is :

$$w_i = \frac{Qs_i}{Qs_{TOT}} = \frac{Q_i \, t_i \, X_i}{\sum_{i=1}^{n} Q_i \, t_i \, X_i} \tag{5.3}$$

If the trapping efficiency at a steady discharge Q_i is TE_i then the overall trapping efficiency of the reservoir over the range of discharges is,

$$TE_{OVERALL} = \sum_{i=1}^{n} w_i \, TE_i \tag{5.4}$$

5.2 Application of procedure for estimating reservoir trapping efficiency with variable discharge

Figure 5.1 shows a representative annual flow sequence for a reservoir. This annual flow sequence was represented in the numerical model by a series of monthly mean discharges; each of these were assumed to be a steady discharge. The monthly mean discharges used are shown by the red line on Figure 5.1. The monthly mean discharges were chosen to ensure that the total volume of water entering the reservoir was the same as that for the representative annual flow sequence.

Using the monthly mean steady discharges shown on Figure 5.1 the numerical model was used to calculate the trapping efficiency, over a year, for a range of sediment sizes.

For each sediment size the procedure described in section 5.1 was used to estimate the overall trapping efficiency of the reservoir. At each steady discharge the instantaneous trapping efficiency was calculated using the procedure outlined in section 4.5. Table 5.1 shows the calculation of the overall trapping efficiency, using the procedure given in section 5.1, for a sediment size of 2 microns.

Table 5.2 is a comparison of the estimated overall trapping efficiency with those calculated by the numerical model. This table shows that the procedure given in section 5.1 gives very good agreement with the numerical model results.

By using the procedures given in sections 4.5 and 5.1 the overall trapping efficiency of a reservoir with variable discharge can be accurately calculated without using the numerical model.

6 PROCEDURE FOR ESTIMATING TRAPPING EFFICIENCY WITHOUT CARRYING OUT A BACKWATER CALCULATION

The procedure given in Chapter 4 for estimating the instantaneous trapping efficiency of a reservoir requires the distribution of shear velocity along the length of the reservoir to be known. This information is required in order to determine the effective length of the reservoir and also $\bar{v}_*$. It is suggested in Chapter 4 that this information be obtained by carrying out a backwater calculation. For all practical problems such a calculation requires software on a computer; this may not always be available. A modified procedure which involves hand calculation of the effective length and $\bar{v}_*$ is described in this chapter.

6.1 Estimating effective length

To be consistent with the approach taken in Chapter 4 the procedure for estimating effective length must be non- dimensional.

One obvious non-dimensional variable to use is the ratio of effective length to absolute length; this is referred to as the effective length ratio and is defined as,

$$ELR = EL/L \tag{6.1}$$

where : ELR is the effective length ratio
and EL is the effective length

The effective length of a reservoir will decrease as the discharge increases, hence discharge must be included in a second non-dimensional variable. The effective length is defined as the distance from the dam to the point where v_* equals v_{*CRIT}; clearly v_{*CRIT} must also be included in this second non-dimensional variable. In order to obtain a non-dimensional variable incorporating discharge and v_{*CRIT} parameters with dimensions L^2 are required: the square of the mean width was chosen. Hence the second non-dimensional variable was,

$$Z5 = Q/\bar{b}\bar{b}\ v_{*CRIT} \qquad (6.2)$$

In order to establish the variation of the effective length ratio with Z5 a certain effective length ratio was assumed, the discharge that gave this effective length ratio was estimated and the corresponding Z5 calculated.

The variation of the effective length ratio with Z5 was established for a number of reservoirs. This analysis revealed that the form of the relationship between these two non-dimensional variables was dependent on a further non-dimensional variable defined as:

$$Z6 = \bar{b}/\bar{d} \qquad (6.3)$$

Figure 6.1 shows the variation of the effective length ratio with Z5 at a single Z6 value. This Figure illustrates that at small Z5 values the change in ELR with Z5 is small. As Z5 increases the reduction in ELR becomes more rapid.

Figure 6.2 shows plots of ELR against Z5 for a number of Z6 values.

The procedure outlined in this section for determining the effective length ratio, ELR, as a function of the non-dimensional variables Z5 and Z6 is dependent on the choice of roughness length, K_s. Figure 6.2 shows the curves for a roughness length of 1m. The procedure was repeated with roughness lengths of 0.1m and 0.01m; the results of this analysis are shown in Figures 6.3 and 6.4 respectively.

The form of the curves in these three figures are similar but the exact position and shape of the curves is dependent on the value of the roughness length.

6.2 Estimating $\bar{v}_*$

Provided the mean width, mean depth, discharge, critical shear velocity and roughness length are known the procedure outlined in section 6.1 can be used to estimate the effective length ratio, ELR, of a reservoir. Since the absolute reservoir length will also be known the active or effective length of a reservoir can then be calculated using:

$$EL = ELR \times L \qquad (6.4)$$

In order to estimate $\bar{v}_*$ the Colebrook-White equation and the equation defining v_* are applied to a reservoir which has the same values for Z3 and Z6 as the real reservoir and an effective length calculated by equation (6.4). The mean width and mean depth of this reservoir, referred to here as the effective mean width and effective mean depth can be defined as,

$$EMW = ELR \times \bar{b} \qquad (6.5)$$

$$EMD = ELR \times \bar{d} \qquad (6.6)$$

where : EMW is the effective mean width
and EMD is the effective mean depth

The mean slope of this reservoir can be calculated using the Colebrook-White equation in the following form:

$$S = Q^2 / (EMWxEMD)^2 \; [32g \; EMD \; (\log_{10} \frac{K_s}{14.8 \; EMD})^2] \qquad (6.7)$$

$\bar{v}_*$ can then be calculated using

$$\bar{v}_* = \sqrt{g \times EMD \times S} \qquad (6.8)$$

6.3 Procedure for estimating reservoir trapping efficiency

The techniques outlined in sections 6.1 and 6.2 allow hand calculation of the effective length and v_* for a reservoir. Using these a procedure for estimating reservoir trapping efficiency without carrying out a backwater calculation, has been devised. This procedure comprises four parts:

(1) Determine the effective length of the reservoir

(2) Determine $\bar{v}_*$

(3) Determine Z1 and Z3

(4) Using the calculated values of Z1 and Z3 estimate the trapping efficiency using the curves shown in Figure 4.6. Linear interpolation can be used to find the trapping efficiency of reservoirs for which a Z3 value is not given.

The steps for carrying out parts (1) to (3) of this procedure are given in Table 6.1.

When the effective length ratio is less than one the above procedure involves analysing a reservoir which has a mean width and mean depth less than those of the total reservoir. This is different from the procedure developed in Chapter 4 which involved analysing a reservoir with a mean width and mean depth greater than those of the total reservoir when the effective length ratio was less than one. In reality the mean width and depth of a reservoir with an effective length ratio less than one will, in general, be greater than those of the total reservoir; the procedure developed in Chapter 4 is a conceptualisation of this reality. The procedure developed in this Chapter is a method for estimating reservoir trapping efficiency when a backwater calculation is not available; it is not a conceptualisation of reality.

6.4 Worked examples

In this section two examples applications of the desk procedure developed in this chapter are given. The first is an example when v_* is less than v_{*CRIT} throughout the reservoir and the second an example when v_* exceeds v_{*CRIT} at some location in the reservoir. In both examples the trapping efficiency of a reservoir with the following geometry was calculated,

$L = 10{,}000m$
$\bar{b} = 1{,}000m$
$\bar{d} = 100m$

In both examples the calculations are numbered according to the procedure given in Table 6.1

6.4.1 Discharge = 30m³/sec. Sediment fall velocity = 2.3675x10⁻⁶

1.1 $\bar{b} = 1{,}000$
$\bar{d} = 100$
$L = 10{,}000$
Assume $v_{*CRIT} = 0.01m/s$

1.2 $Z5 = \frac{Q}{\bar{b}\ \bar{b}\ v_{*CRIT}} = \frac{30}{(1000 \times 1000 \times 0.01)} = 0.003$

1.3 $Z6 = \frac{\bar{b}}{\bar{d}} = \frac{1,000}{100} = 10$

1.4 $K_s = 1m$

1.5 From Figure 6.2 ELR = 1

1.6 EL = ELR x L = 1 x 10,000 = 10,000

2.1 EMW = ELR x b = 1 x 1,000 = 1,000

2.2 EMD = ELR x d = 1 x 100 = 100

2.3 $S = Q^2 / (EMW \times EMD)^2\ [32g\ EMD\ (\log_{10} \frac{K_s}{14.8\ EMD})^2]$

$= 30^2 / (1000 \times 100)^2\ [32 \times 9.81 \times 100 \times (\log_{10} \frac{1}{14.8 \times 100})^2]$

$= 2.85 \times 10^{-13}$

2.4 $\bar{v}_* = \sqrt{g \times EMD \times S}$

$= \sqrt{9.81 \times 100 \times 2.85 \times 10^{-13}}$

$= 1.67 \times 10^{-5}$

3.1 $Z1 = \frac{EMW \times EMD \times \omega}{Q} (1 - \frac{\bar{v}_*}{v_{*CRIT}})$

$= \frac{1,000 \times 100 \times 2.3675 \times 10^{-6}}{30} (1 - \frac{1.67 \times 10^{-5}}{0.01})$

$= 7.88 \times 10^{-3}$

$Z3 = EMD/EL = 100/10{,}000 = 0.01$

From Figure 4.6 the trapping efficiency is given as 49%. The trapping efficiency calculated by the numerical model was 50%.

6.4.2 <u>Discharge = 5,000m^3/sec. Sediment fall velocity = 2.36×10^{-4}m/sec</u>

1.1 $\bar{b} = 1{,}000$

$\bar{d} = 100$

$L = 10{,}000$

Assume $v_{*CRIT} = 0.01$m/s

1.2 $$Z5 = \frac{Q}{\bar{b}\ \bar{b}\ v_{*CRIT}} = \frac{5{,}000}{(1{,}000 \times 1{,}000 \times 0.01)} = 0.5$$

1.3 $Z6 = \bar{b}/\bar{d} = 1000/100 = 10$

1.4 $K_s = 1$m

1.5 From Figure 6.2 ELR = 0.73

1.6 $EL = ELR \times L = 0.73 \times 10{,}000 = 7{,}300$

2.1 $EMW = ELR \times \bar{b} = 0.73 \times 1{,}000 = 730$

2.2 $EMD = ELR \times \bar{d} = 0.73 \times 100 = 73$

2.3 $$S = Q^2 / (EMW \times EMD)^2 \ [32g\ EMD\ (\log_{10} \frac{K_s}{14.8\ EMD})^2]$$

$$= 5{,}000^2 / (730 \times 73)^2 \ [32 \times 9.81 \times 73\ (\log_{10} \frac{1}{14.8 \times 73})^2]$$

$$= 4.17 \times 10^{-8}$$

2.4 $\bar{v}_* = \sqrt{g \times EMD \times S}$

$= \sqrt{9.81 \times 73 \times 4.17 \times 10^{-8}}$

$= 0.00546$

3.1 $Z1 = \frac{EMW \times EMD \times w}{Q} (1 - \frac{\bar{v}_*}{v_{*CRIT}})$

$= \frac{730 \times 73 \times 2.36 \times 10^{-4}}{5,000} (1 - \frac{0.00546}{0.01})$

$= 1.142 \times 10^{-3}$

$Z3 = \frac{EMD}{EL} = \frac{73}{7,300} = 0.01$

From Figure 4.6 the trapping efficiency is given as 10%. The trapping efficiency calculated by the numerical model was 19%.

6.5 Software for carrying out desk procedure

The procedures developed in this chapter allow the hand calculation of the instantaneous trapping efficiency of a reservoir of known geometry with any given flow condition and sediment fall velocity.

For practical problems which may involve several sediment sizes and/or many steady state discharges these calculations can be time consuming. Software to carry out the procedure described in section 6.3 has been developed, as part of a separate project, to overcome this problem; this software has been given the name TRAPEF. A brief description of TRAPEF together with an outline users guide is given in Appendix A. TRAPEF will be available through Wallingford Software in the near future.

TRAPEF operates in one of four modes depending on the number of steady state discharges and sediment fall velocities.

6.5.1 Mode 1. Single discharges, Single fall velocity

In this mode the procedure given in section 6.3 is executed computationally and the instantaneous trapping efficiency calculated.

6.5.2 Mode 2. Single discharge, Several fall velocities

In this mode the procedure given in section 6.3 is executed computationally for each sediment fall velocity and the corresponding instantaneous trapping efficiency calculated. The overall trapping efficiency is also calculated using the following equation :

$$\text{Overall trapping efficiency} = \sum_{i=1}^{n} TE_i \times PER_i \qquad (6.9)$$

where TE_i is the trapping efficiency for fall velocity i

PER_i is the proportion sediment with fall velocity i is of the total sediment load

n is the number of different fall velocities

6.5.3 Mode 3. Several discharges, Single fall velocity

In this mode the procedure given in section 6.3 is executed computationally for each discharge and the corresponding instantaneous trapping efficiency calculated. The overall trapping efficiency is calculated using the procedure outlined in section 5.1.

6.5.4 Mode 4. Several discharges, several fall velocities

The instantaneous trapping efficiency for each fall velocity and each discharge is calculated using the procedure given in section 6.3. The trapping efficiency for each discharge over all sediment fall velocities is calculated using equation (6.9). The trapping efficiency for each fall velocity over all discharges is calculated using the procedure given in section 5.1. The overall trapping efficiency over all discharges and all fall velocities is calculated by applying the procedure given in section 5.1 to the results obtained by applying equation (6.9) to the trapping efficiency for all the fall velocities at each discharge.

6.6 Comparison of TRAPEF with numerical model

In order to assess the accuracy of the TRAPEF a large number of tests were carried out using it; the results of these tests were compared with the results of numerical model simulations of similar reservoir conditions.

Since the accuracy of the software is dependent on the accuracy of the procedure given in section 6.3 most of the testing was carried out with a single discharge and single sediment fall velocity. Table 6.2 gives a sample comparison of TRAPEF and numerical model results for a number of different discharges and sediment sizes.

The tests revealed that good agreement between the software and numerical model breaks down under extreme conditions eg very high discharges or very shallow reservoirs. If these conditions occur the trapping efficiency estimated by TRAPEF should be treated with caution. However, since these situations rarely occur in practical problems the software, in general, gives good agreement with the numerical model.

The first row of Table 6.3 compares the software and numerical model for a mode 2 application viz. one discharge and several sediment fall velocities. Provided the discharge is not extreme, as discussed above, the agreement between the software and numerical model is extremely good.

The second row of Table 6.3 compares the software and numerical model for a mode 3 application viz. several discharges and one fall velocity. The agreement between the software and numerical model is always very good in this situation. This is because, in general, very few of the discharges will be extreme and thus any difference between the software and numerical model in these situations will have little influence on the final overall trapping efficiency.

The third row of Table 6.3 compares the software and numerical model for a mode 4 application viz. several discharges and several fall velocities. Once again, for the same reasons as discussed above for a mode 3 application, the agreement between the software and numerical model is always good.

7 APPLICATION OF TRAPEF TO REAL RESERVOIRS

The work described so far in this report has involved the use of a numerical model to investigate the dependence of reservoir trapping efficiency on variables which characterise the geometry, flow and sediment size. Based on the results of this work a graphical procedure has been derived which gives good agreement with the numerical model results. All of this work has been carried out on the idealised reservoir geometries described in Chapter 3.

In reality reservoirs do not have this idealised shape. In order to assess the accuracy of the derived procedure when applied to real reservoirs TRAPEF was applied to four real reservoirs. The estimated trapping efficiencies were compared with the results of the numerical model simulations of the same reservoirs with the same flow and sediment conditions. The four real reservoirs chosen for study were reservoirs in Zimbabwe which had previously been analysed at HR. These reservoirs had geometries that were increasingly divergent from the idealised geometry.

7.1 Calculation of mean width, $\bar{b}$, and mean depth, $\bar{d}$

The most difficult aspect of applying the graphical procedure to real reservoirs is the selection of mean widths and mean depths which characterise the reservoir geometry. Four different methods were used to estimate $\bar{b}$ and $\bar{d}$. Three of these methods require reservoir cross-sections at a number of locations along the reservoir. The fourth method requires the maximum and minimum depth and width of the reservoir to be known. The four methods used were:

(1) Mean method : the mean width was the average of the surface widths given by the cross-section data. The mean depth was the average of the depths, below retention level, given by the cross-section data.

(2) Median method : the mean width was the median of the surface widths given by the cross-section

data. The mean depth was the median of the depths, below retention level, given by the cross-section data.

(3) Area method : the objective of this method was to use the cross-section data to generate an idealised geometry reservoir which has the same volume as the real reservoir. The mean width was the mid-point width of an idealised reservoir which has the same surface area as the real reservoir. The mean depth is the mid-point depth of an idealised reservoir which has the same area, below retention level, on a longitudinal profile drawn along the centre-line of the real reservoir. This method is the most complex one to calculate $\bar{b}$ and $\bar{d}$.

(4) Maximum/Minimum method : this is the simplest method. It does not require cross-section data; only the maximum and minimum surface widths and depths below retention level are required. In this method b and d are defined as follows,

$$\bar{b} = (b_{MAX} - b_{MIN})/2 \tag{7.1}$$

$$\bar{d} = (d_{MAX} - d_{MIN})/2 \tag{7.2}$$

The four methods were applied to each of the four reservoirs using a single sediment fall velocity and over a range of discharges. The range of discharges were chosen to give a range of trapping efficiencies from 0 to 100% in the numerical model. The trapping efficiency estimated by TRAPEF was compared with the numerical model results. The root mean square error between the model and TRAPEF estimates of trapping efficiency was used as a measure of the goodness of fit. The root mean square error is defined as,

$$\text{RMS} = \frac{1}{n}\sqrt{(\text{model trapping efficiency - TRAPEF trapping efficiency})^2} \qquad (7.3)$$

where n is the number of discharges.

Table 7.1 gives the results of this analysis. It can be seen from this table that no one method gives the lowest root mean square error for each reservoir. The mean method gives the lowest root mean square error for Maynard; the area method the lowest root mean square error for Manjirenji and the maximum/minimum method the lowest root mean square error for both Gozho and Siya. The median method gives the highest root mean square error for Gozho, Siya and Manjirenji; the maximum/minimum method gives the highest root mean square error for Maynard. Over all reservoirs the mean method gives the lowest mean root mean square error and the median method the highest mean root mean square error.

Based on the results presented in Table 7.1 the mean method was chosen as the one for calculating $\bar{b}$ and $\bar{d}$. The above conclusion that the mean method is the best method for calculating $\bar{b}$ and $\bar{d}$ should be treated with caution. It is recommended that further work be carried out to investigate alternative methods for calculating $\bar{b}$ and $\bar{d}$. These methods should be applied to a wide range of reservoirs to test the robustness of any conclusion drawn.

In the next section detailed comparison of the instantaneous trapping efficiencies calculated by TRAPEF, with the mean method used to calculate $\bar{b}$ and $\bar{d}$, and the numerical model trapping efficiency is given. In section 7.3 the trapping efficiency, over a typical yearly cycle of inflows for each reservoir, calculated by TRAPEF, using the mean method to calculate $\bar{b}$ and $\bar{d}$, and the numerical model are compared. These two estimates of trapping efficiency are compared with the trapping efficiency estimated using Brune curves.

7.2 Comparison of TRAPEF and numerical model instantaneous trapping efficiencies

7.2.1 Gozho

The plan and longitudinal profile of Gozho are shown in Figure 7.1. With the exception of the widening approximately 300m from the dam the plan of this reservoir is quite close to that of an idealised reservoir. The longitudinal profile of Gozho shows a much steeper bed slope towards the upstream limit of the reservoir than occurs in the idealised reservoir shape.

When the mean method is applied to this reservoir a mean width of 196.2m and a mean depth of 9.2m are calculated. Table 7.2 compares the trapping efficiencies using TRAPEF with those obtained from the numerical model over a range of discharges at a single sediment size. At all discharges the software overestimates the trapping efficiency. The maximum difference between the software and the numerical model is approximately 27 percent.

7.2.2 Siya

The plan and longitudinal profile of Siya are shown in Figure 7.2. From the inlet to approximately 2000m from the dam this reservoir has a plan very similar to the idealised reservoir. Siya then narrows significantly to the dam making the overall divergence from the idealised plan shape significant. As with Gozho Siya shows a much steeper bed slope at the upstream limit than occurs in the idealised reservoir.

When the mean method is applied to Siya a mean width of 845m and a mean depth of 23.7m are calculated. Table 7.3 compares the trapping efficiencies calculated using TRAPEF with those obtained from the numerical model over a range of discharges at a constant sedimet size. As with Gozho, this shows that the software overestimates the trapping efficiency at all discharges. The maximum difference between the software and numerical model is approximately 30 percent. Overall the agreement, in terms of root mean square error, is worse than Gozho; this is to be expected since Siya deviates from the idealised shape more than Gozho.

7.2.3 Manjirenji

The plan and longitudinal profile of Manjirenji are shown in Figure 7.3. In plan this reservoir consists of three basins separated by narrow stretches of water. The bed of Manjirenji is concave from inlet to the dam.

When the mean method is applied to Manjirenji a mean width of 1723m and a mean depth of 28.96m are calculated. Table 7.4 compares the trapping efficiencies calculated using TRAPEF with those obtained from the numerical model over a range of discharges at a single sediment size. The maximum difference between the software and the numerical model is only 14 percent. Manjirenji gives a root mean square error much less than that of either Gozho or Siya.

7.2.4 Maynard

The plan and longitudinal profile of Maynard are shown in Figure 7.4. With the exception of the widening at 900m from the dam this reservoir has a relatively constant width of approximately 100m. Thus in planform Maynard is very different from the idealised reservoir geometry. The longitudinal profile of Maynard is very similar to that of an idealised reservoir.

When the mean method is applied to this reservoir a mean width of 134.2m and mean depth of 4.9m are calculated. Table 7.5 compares the trapping efficiencies calculating with the software with those obtained from the numerical model over a range of discharges at a single sediment size. Except for the very lowest discharges the software overestimates the trapping efficiency. The maximum difference between the software and the model is again only 12 percent. The root mean square error for Maynard is similar to that for Manjirenji.

Some general points can be noted from the above comparison of the trapping efficiency calculated using TRAPEF with those calculated by the numerical model for four real reservoirs. Firstly, the software tends to overestimate trapping efficiencies at all discharges. Secondly, and more important, the maximum difference in trapping efficiency between the software and the model is 30 percent or less. Such agreement is surprising especially for Manjirenji which has a plan shape which differs very greatly from that of the idealised reservoir.

7.3 Comparison of TRAPEF, numerical model and Brune curve estimates of trapping efficiency for typical yearly inflow cycles

The instantaneous trapping efficiency of a reservoir is rarely calculated. It is more common for estimates of the trapping efficiency over a year or longer to be required. In order to compare the TRAPEF and numerical model estimates of trapping efficiency under these conditions the overall trapping efficiency over a typical years inflows was calculated by the two methods. The inflow data was based on real flow data, held at HR, for the four reservoirs. For each reservoir a range of sediment sizes were used; these were based on grading curves.

The two estimates of trapping efficiency were also compared with the trapping efficiency estimated from Brune curves. Brune curves relate the reservoir trapping efficiency to the capacity inflow ratio; this is the ratio of storage volume to total inflow over a year.

Table 7.6 compares the trapping efficiency estimates by the three methods for each of the four reservoirs. The table shows that for each reservoir the TRAPEF and model estimates of trapping efficiency are close to each other and that both estimates are within the confidence limits associated with the Brune curves.

8 CONCLUSIONS

1. An increase in sediment fall velocity results in an increase in trapping efficiency. A three order of magnitude change in sediment fall velocity may result in a change in trapping efficiency from 0 to 100%. This equates to a 1.5 order of magnitude change in sediment size. Changes in trapping efficiency from 20 to 90% may occur over a one order of magnitude change in fall velocity; this is a 5 times increase in sediment size.

2. If all other parameters are constant trapping efficiency increases as the mean depth to length ratio decreases.

3. The relationship between trapping efficiency and Z1 is independent of the mean width to length ratio.

4. When estimating the trapping efficiency of a reservoir only the active length of the reservoir should be considered. When the active length of a reservoir is less than the total length, a reservoir with a greater mean depth to length ratio than the real reservoir needs to be analysed to estimate the trapping efficiency.

5. A correction needs to be applied which is dependent on the proportion the mean shear velocity is of the critical shear velocity.

6. A plot giving trapping efficiency as a function of non- dimensional variables which incorporate reservoir geometry, flow and sediment conditions can be produced; Figure 4.6 is an example.

7. A procedure for estimating instantaneous trapping efficiency, when a backwater calculation is carried out to estimate the variation of shear velocity with distance along the reservoir, is given in section 4.5 and Table 4.1. This procedure gives good agreement with the numerical model results.

8. The overall trapping efficiency of a reservoir over a discharge cycle can be obtained by approximating the discharge variation by a series of steady state discharges. The instantaneous trapping efficiency for each discharge can then be calculated. In order to calculate the overall trapping efficiency these instantaneous trapping efficiencies are weighted according to the proportion of the total sediment input which is

transported by each discharge. This method of weighting the instantaneous trapping efficiencies gives good agreement with the overall trapping efficiency calculated by the model over a series of discharges.

9. The effective length of a reservoir depends on the discharge, critical shear velocity, width to depth ratio and roughness length. Plots of effective length as a non-dimensional function of these variables can be produced; Figures 6.2 to 6.4 are examples.

10. The mean shear velocity of a reservoir of given effective length can be estimated by using the Colebrook-White equation and the equation which defines the shear velocity.

11. A procedure for estimating instantaneous trapping efficiency without carrying out a backwater calculation is given in section 6.3 and Table 6.1. This procedure gives good agreement with the model except under extreme conditions eg high discharges or very shallow reservoirs.

12. When the procedures developed in this report are applied to real reservoirs the major problem is assigning values for the mean width and mean depth. Four methods for doing this were investigated. The method based on the mean surface width and mean depth below retention level calculated from reservoir cross-section data gave the best overall fit for the four reservoirs analysed.

13. The developed graphical procedure tends to overestimate the instantaneous trapping efficiency of a reservoir when compared with the

numerical model. The greatest error between the two estimates, over a large range of reservoir geometries, is 30 percent.

14. When applied to a typical yearly cycle of inflows for the real reservoirs analysed, the graphical procedure agrees well with the numerical model results. Both these estimates of trapping efficiency are within the confidence limits associated with Brune curves.

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TABLES.

TABLE 4.1 : Procedure for calculating Z1 and Z3; Backwater calculation to give v_* variation through reservoir

1. Carry out backwater calculation to determine the variation of v_* throughout the length of the reservoir.

2. If v_* is less than v_{*CRIT} throughout the reservoir the active (effective) length of the reservoir is equal to the absolute length of the reservoir.

   If v_* is greater than v_{*CRIT} towards the upstream limit of the reservoir the active (effective) length is equal to the distance from the dam to the point at which v_* exceeds v_{*CRIT}. Let L equal the active or effective length.

3. Determine the mean width, $\bar{b}$, mean depth, $\bar{d}$, and the mean shear velocity, $\bar{v}_*$, for the active length of reservoir L. $\bar{b}$, $\bar{d}$ and $\bar{v}_*$ are respectively the width, depth and shear velocity at a point mid way between the dam and the upstream limit of the active reservoir.

4. Calculate : $$Z1 = \frac{\bar{b}\,\bar{d}\,\omega}{Q}\left(1 - \frac{\bar{v}_*}{v_{*CRIT}}\right)$$

   $$Z3 = \frac{\bar{d}}{L}$$

TABLE 5.1 : Estimating the overall trapping efficiency of a reservoir with variable discharge

Month	Mean monthly discharge (m^3/sec)	Volume transported (m^3)	Weighting factor	Trapping efficiency	Weighting Factor x Trapping efficiency
1	28	4565	0.029	86	2.494
2	63.5	10352	0.067	57	3.819
3	112	18258	0.117	40	4.68
4	367.65	59934	0.387	14	5.418
5	188	30648	0.197	26	5.122
6	83	13531	0.087	48	4.176
7	41.5	6765	0.044	73	3.212
8	25	4075	0.026	88	2.288
9	15	2445	0.016	96	1.536
10	10	1630	0.01	99	0.99
11	10	1630	0.01	99	0.99
12	10	1630	0.01	99	0.99
		155463	1.0		35.72%

TABLE 5.2 : Comparison of numerical model and graphical procedure predictions of overall trapping efficiency for a reservoir with variable discharge

Sediment size (microns)	Numerical model Trapping efficiency	Graphical Procedure Trapping efficiency
0.2	0.7%	0.5%
1	13.3%	14.2%
2	34.8%	35.7%
3	53.5%	53.6%
4	67.5%	69.3%

TABLE 6.1 : Procedure for estimating Z1 and Z3; no backwater calculation

1. Determining the effective length

1.1 Determine the mean width, $\bar{b}$, mean depth, $\bar{d}$, and length, L, of the reservoir. Select a critical shear velocity, v_{*CRIT}.

1.2 Calculate : $Z5 = Q / \bar{b}\bar{b}\, v_{*CRIT}$

1.3 Calculate : $Z6 = \bar{b}/\bar{d}$

1.4 Select a roughness length K_s.

1.5 Using the values for Z5, Z6 and K_s estimate the effective length ratio, ELR , from figures 6.2 to 6.4. On each figure linear interpolation may be used to find the ELR of a reservoir for which a Z6 value is not given. Linear interpolation may be used between the figures for K_s values not equal to 0.01,0.1 or 1m.

1.6 Calculate EL = ELR x L

2. Determine $\bar{v}_*$

2.1 Calculate : EMW = ELR x $\bar{b}$

2.2 Calculate : EMD = ELR x $\bar{d}$

2.3 Calculate : $S = Q^2 / (EMW \times EMD)^2 \left[32g\, EMD \left(\log_{10} \frac{K_s}{14.8\, EMD}\right)^2\right]$

2.4 Calculate : $\bar{v}_* = \sqrt{g \times EMD \times S}$

3. Determine Z1 and Z3

3.1 Calculate : $$Z1 = \frac{EMW \times EMD \times \omega}{Q} \left(1 - \frac{\bar{v}_*}{v_{*CRIT}}\right)$$

and $$Z3 = \frac{EMD}{EL}$$

TABLE 6.2 : Mode 1 : Comparison of TRAPEF and numerical model

Discharge	Fall velocity	TRAPEF trapping efficiency	Numerical model trapping efficiency
30	5.3269×10^{-8}	1.46%	1.5%
30	1.8×10^{-6}	38.34%	38.7%
300	3.788×10^{-7}	4.36%	5.3%
300	9.4689×10^{-6}	66.76%	75.1%
3000	3.7862×10^{-5}	4.69%	17.6%
5000	1.452×10^{-3}	44.71%	74.5%

TABLE 6.3 : Modes 2 to 4 : Comparison of TRAPEF and numerical model

Mode	Number of discharges	Number of fall velocities	TRAPEF trapping efficiency	Numerical model trapping efficiency
2	1	5	21.76%	23%
3	12	1	50.01%	50.4%
4	12	5	65.36%	65.6%

TABLE 7.1 : Comparison for different methods for estimating the mean width and mean depth of real reservoirs

	GOHZO			SIYA			MANJIRENJI			MAYNARD			
Method	$\bar{b}$	$\bar{d}$	root mean square error	$\bar{b}$	$\bar{d}$	root mean square error	$\bar{b}$	$\bar{d}$	root mean square error	$\bar{b}$	$\bar{d}$	root mean square error	MEAN ROOT MEAN SQUARE ERROR
Mean	196.2	9.2	5.85	845	23.7	6.81	1723	29	3.18	134.2	4.9	2.73	4.64
Median	198	10	6.7	892.2	27	9.81	476	35.1	19.71	115	4.7	3.16	9.85
Area	202	8.9	6.00	851	22.2	5.91	1947	28.5	2.84	133.5	5.6	5.21	4.99
Maximum/minimum	198.8	5.5	3.66	896.5	17.5	4.51	2722.5	22.9	3.74	87.5	5.1	8.21	5.03

TABLE 7.2 : Gozho : Comparison of TRAPEF and numerical model instantaneous trapping efficiency

Mean width and depth calculated by mean method

$\bar{b}$ = 196.23m

$\bar{d}$ = 9.18m

L = 1593m

Discharge	TRAPEF trapping efficiency	Numerical model trapping efficiency	Trapping efficiency error (numerical model - TRAPEF)
10	99.05	91.55	-7.5
20	88.7	64.4	-24.3
30	71.67	44.77	-26.9
40	55.63	30.78	-24.85
50	41.21	21.25	-19.96
60	29.75	14.38	-15.37
70	20.19	10	-10.39
80	12.43	6.43	-6
90	6.1	3.72	-2.38

$$\frac{1}{n}\sqrt{(\text{trapping efficiency error})^2} = 5.85$$

TABLE 7.3 : Siya : Comparison of TRAPEF and numerical model instantaneous trapping efficiency

Mean width and depth calculated by mean method

$\bar{b}$ = 845m

$\bar{d}$ = 23.74m

L = 9716m

Discharge	TRAPEF trapping efficiency	Numerical model trapping efficiency	Trapping efficiency error (numerical model - TRAPEF)
30	100	100	0
80	100	100	0
300	97.3	85.16	-12.14
500	81.32	51.5	-29.82
800	45.72	23.7	-22.02
1000	23.88	11.8	-12.08

$$\frac{1}{n}\sqrt{(\text{trapping efficiency error})^2} = 6.81$$

TABLE 7.4 : Manjirenji : Comparison of TRAPEF and numerical model instantaneous trapping efficiency

Mean width and depth calculated by mean method

$\bar{b}$ = 1723m

$\bar{d}$ = 28.96m

L = 4689m

Discharge	TRAPEF trapping efficiency	Numerical model trapping efficiency	Trapping efficiency error (numerical model - TRAPEF)
300	98.36	100	1.64
500	90.68	96.2	5.52
800	73.03	78.3	5.27
1000	61.04	61.3	0.26
2000	18.86	27.8	8.94
3000	0	14.9	14.9

$\frac{1}{n}\sqrt{(\text{trapping efficiency error})^2} = 3.18$

TABLE 7.5 : Maynard : Comparison of TRAPEF and numerical model instantaneous trapping efficiency

Mean width and depth calculated by mean method

$\bar{b}$ = 134.16m

$\bar{d}$ = 4.85m

L = 1978m

Discharge	TRAPEF trapping efficiency	Numerical model trapping efficiency	Trapping efficiency error (numerical model - TRAPEF)
5	99.88	100	0.12
10	95.89	97.25	1.36
12.5	89.79	87.73	-2.06
15	80.96	75.42	-5.54
17.5	70.34	62.53	-7.81
20	58.38	46.1	-12.28
22.5	46.45	36.29	-10.16
25	34.52	23.41	-11.11

$\frac{1}{n}\sqrt{(\text{trapp ing efficiency error})^2} = 2.73$

TABLE 7.6 : Comparison of Brune curves, numerical model and TRAPEF trapping efficiencies for real reservoirs with variable discharge

Reservoir	Brune curve trapping efficiency	Numerical model trapping efficiency	TRAPEF trapping efficiency
Gozho	95%±4%	94%	99%
Siya	98%±2%	97%	100%
Manjirenji	98%±2%	97%	96%
Maynard	60%±12%	69%	66%

FIGURES.

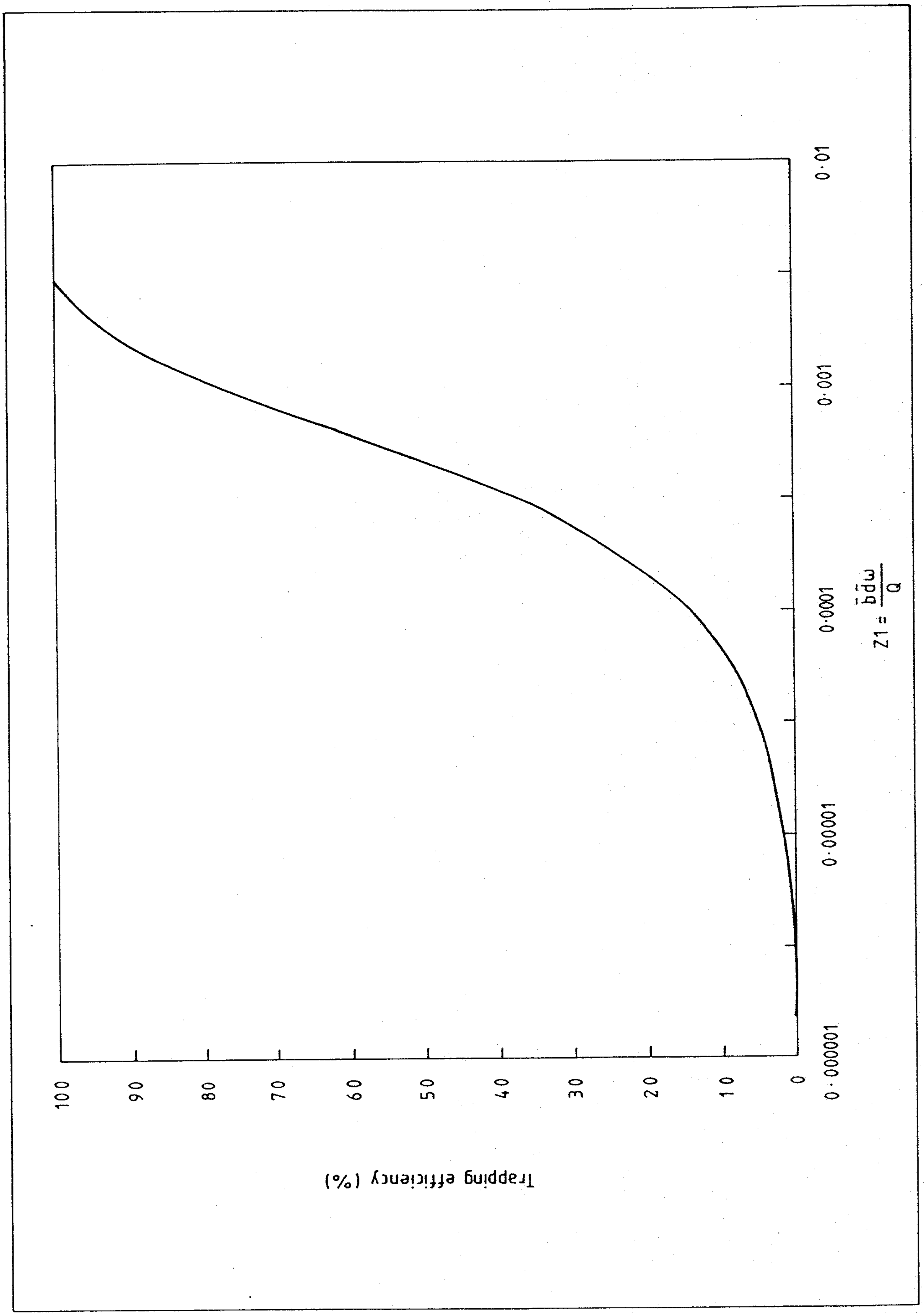

Fig 4·1 Variation of trapping efficiency with sediment fall velocity

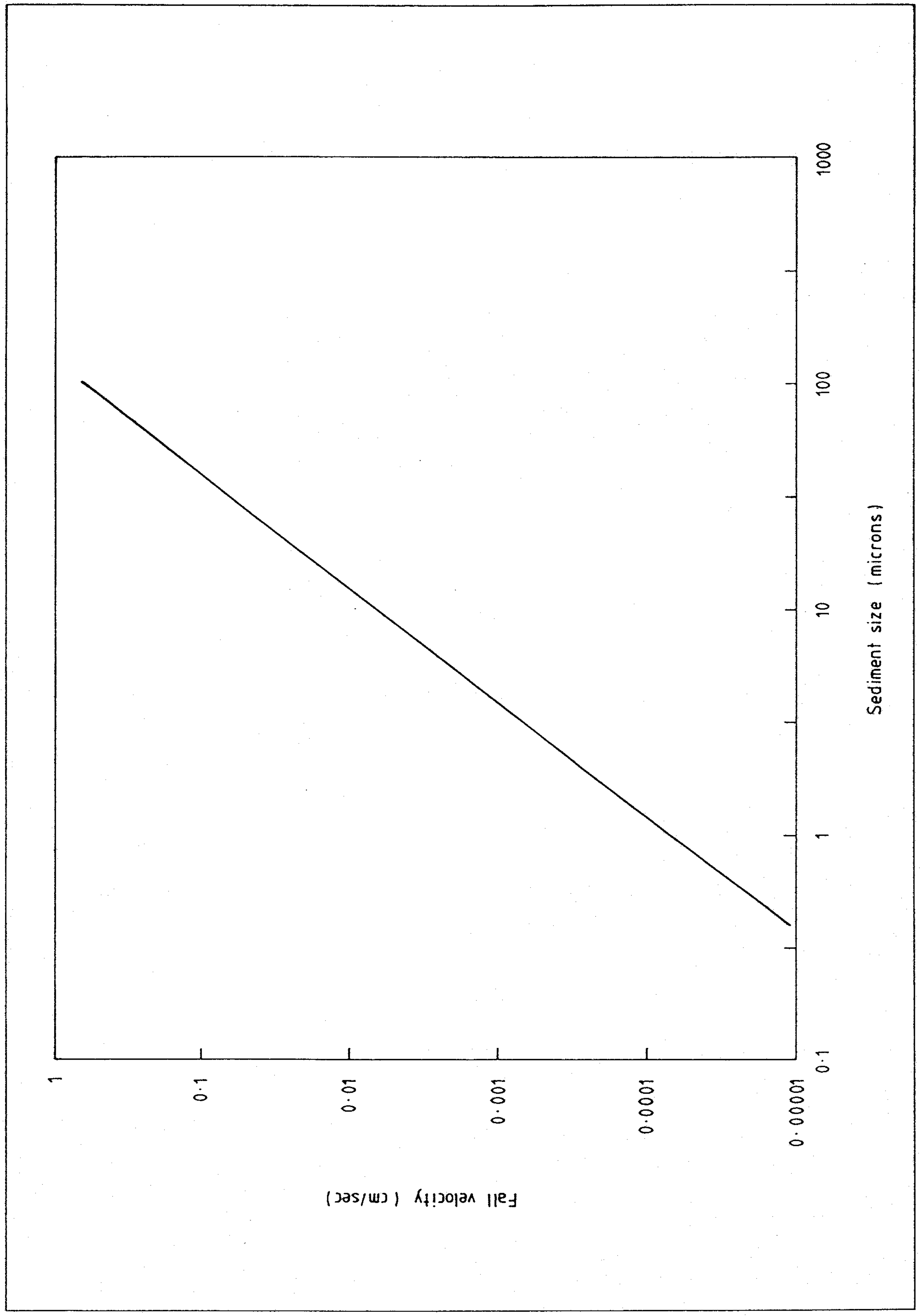

Fig 4·2   Variation of sediment fall velocity with sediment size

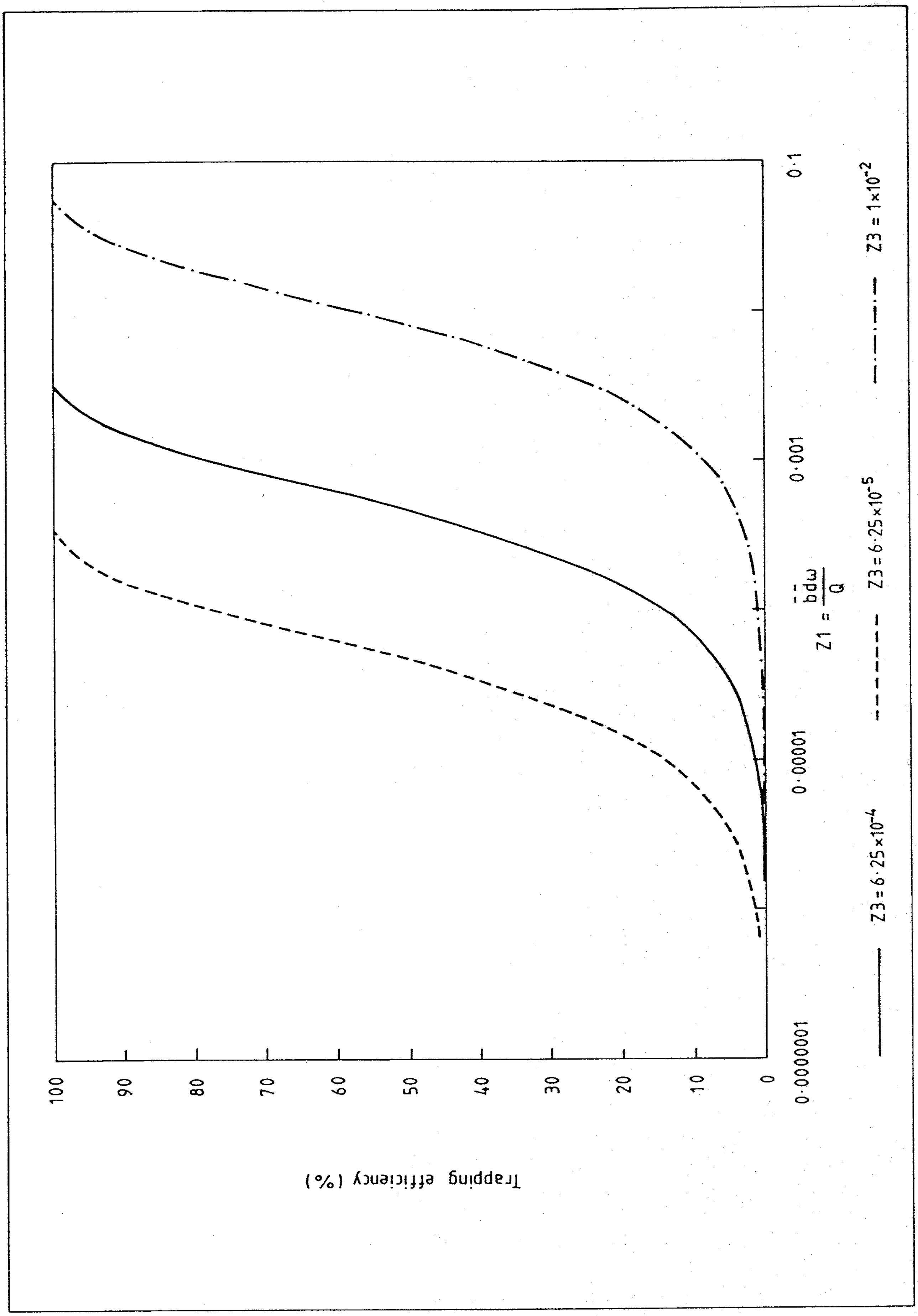

Fig 4·3 Variation of trapping efficiency with Z3

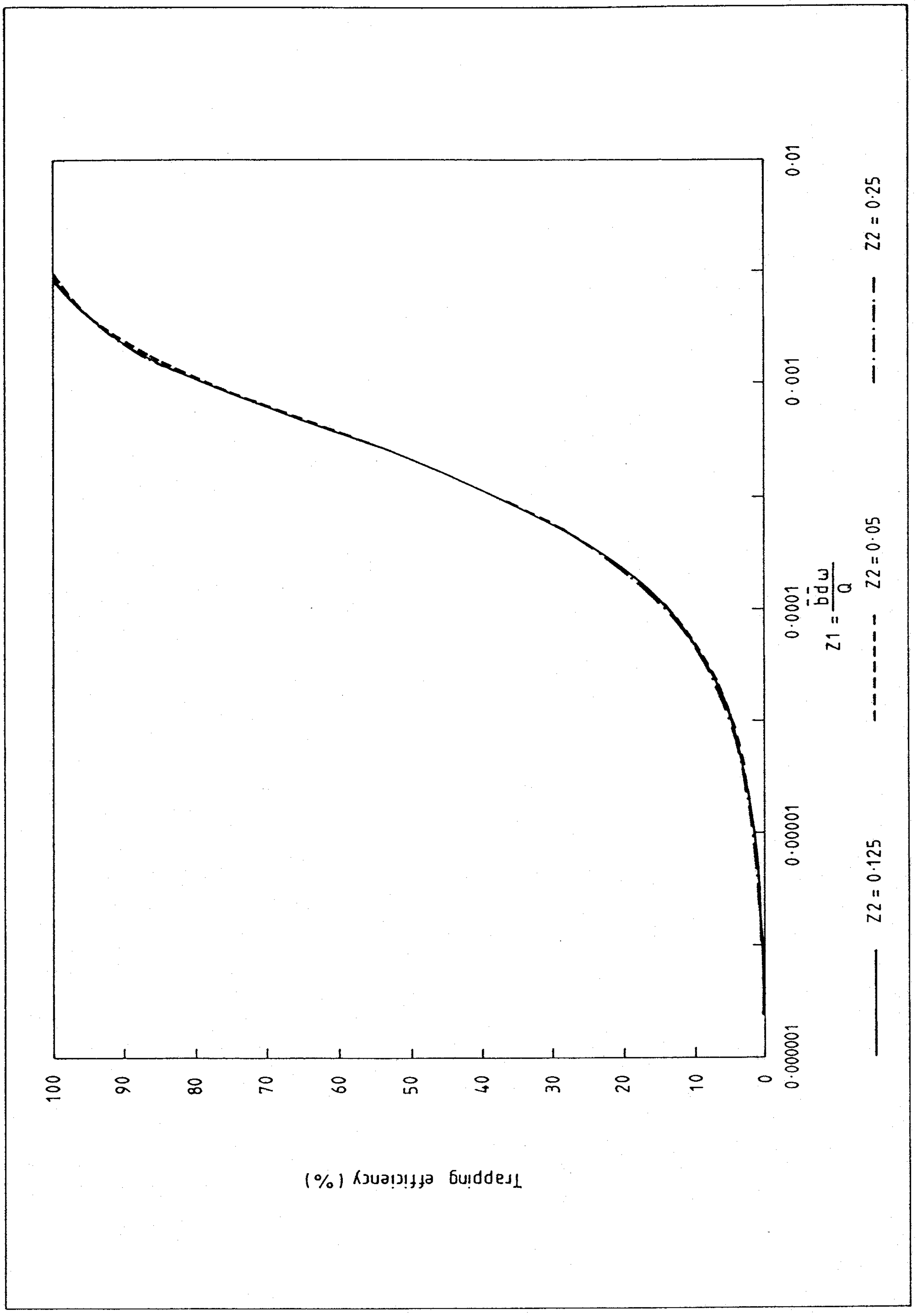

Fig 4·4 Variation of trapping efficiency with Z2

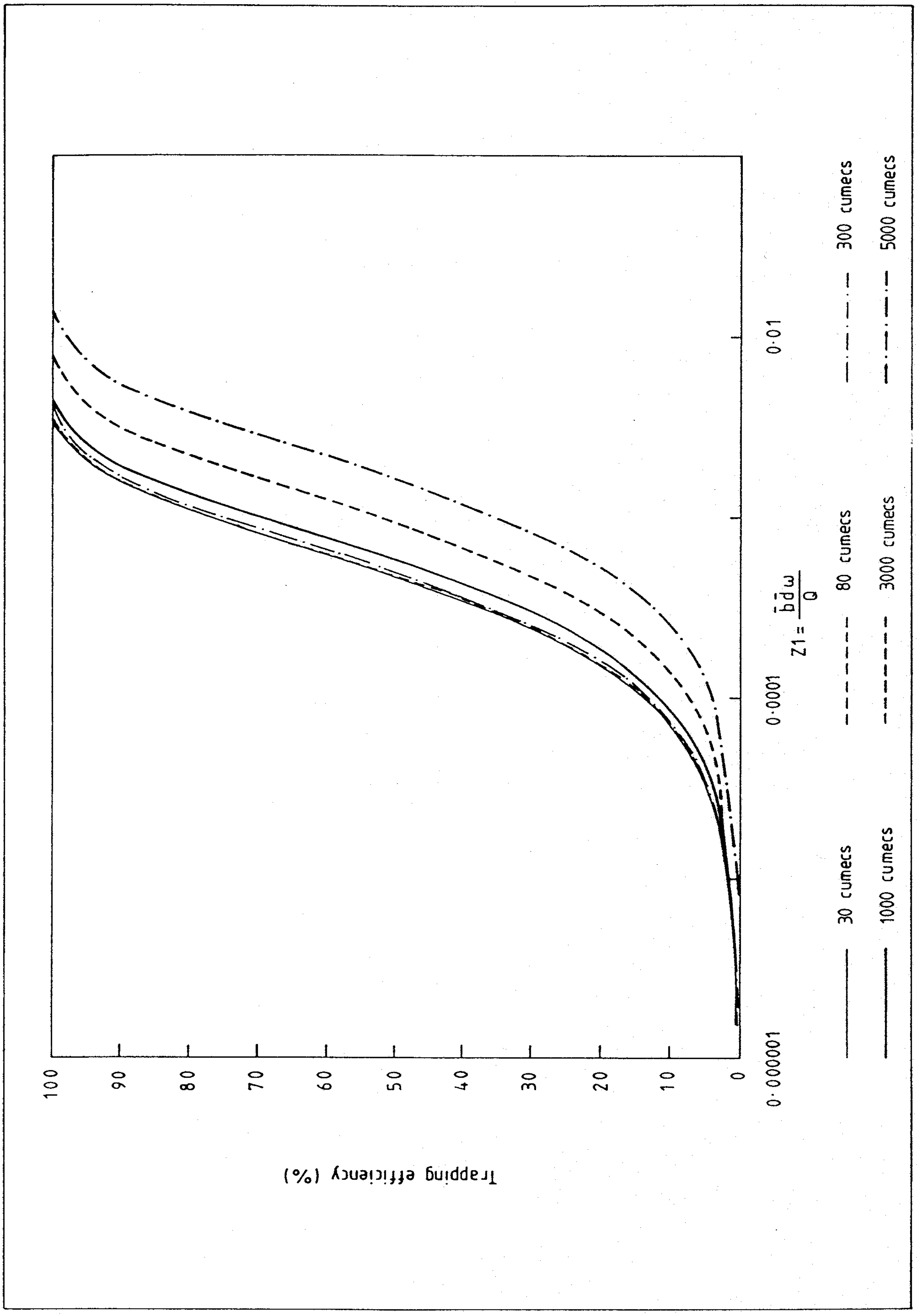

Fig 4·5 Variation of trapping efficiency with discharge

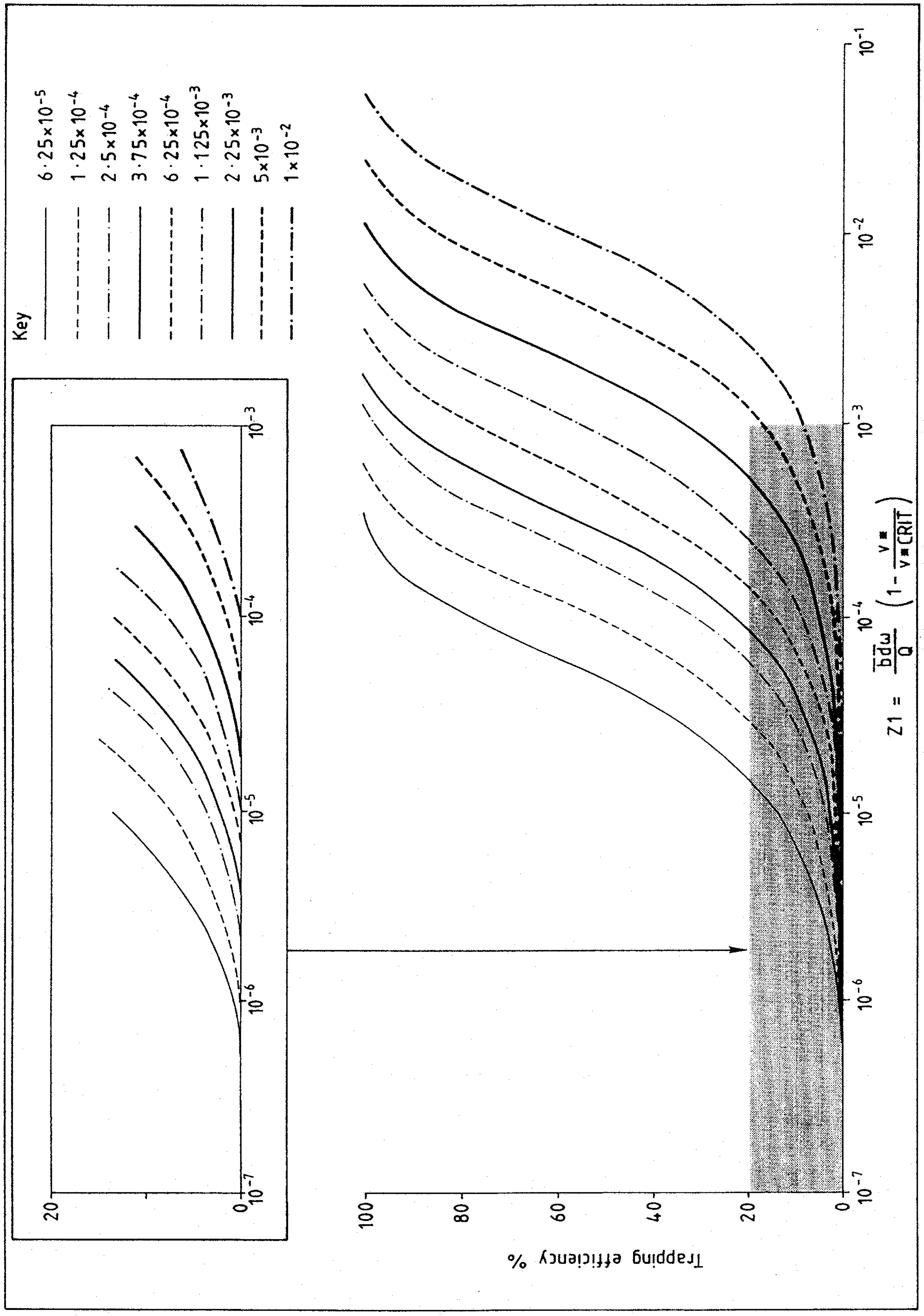

Fig 4·6 Trapping efficiency v Z1

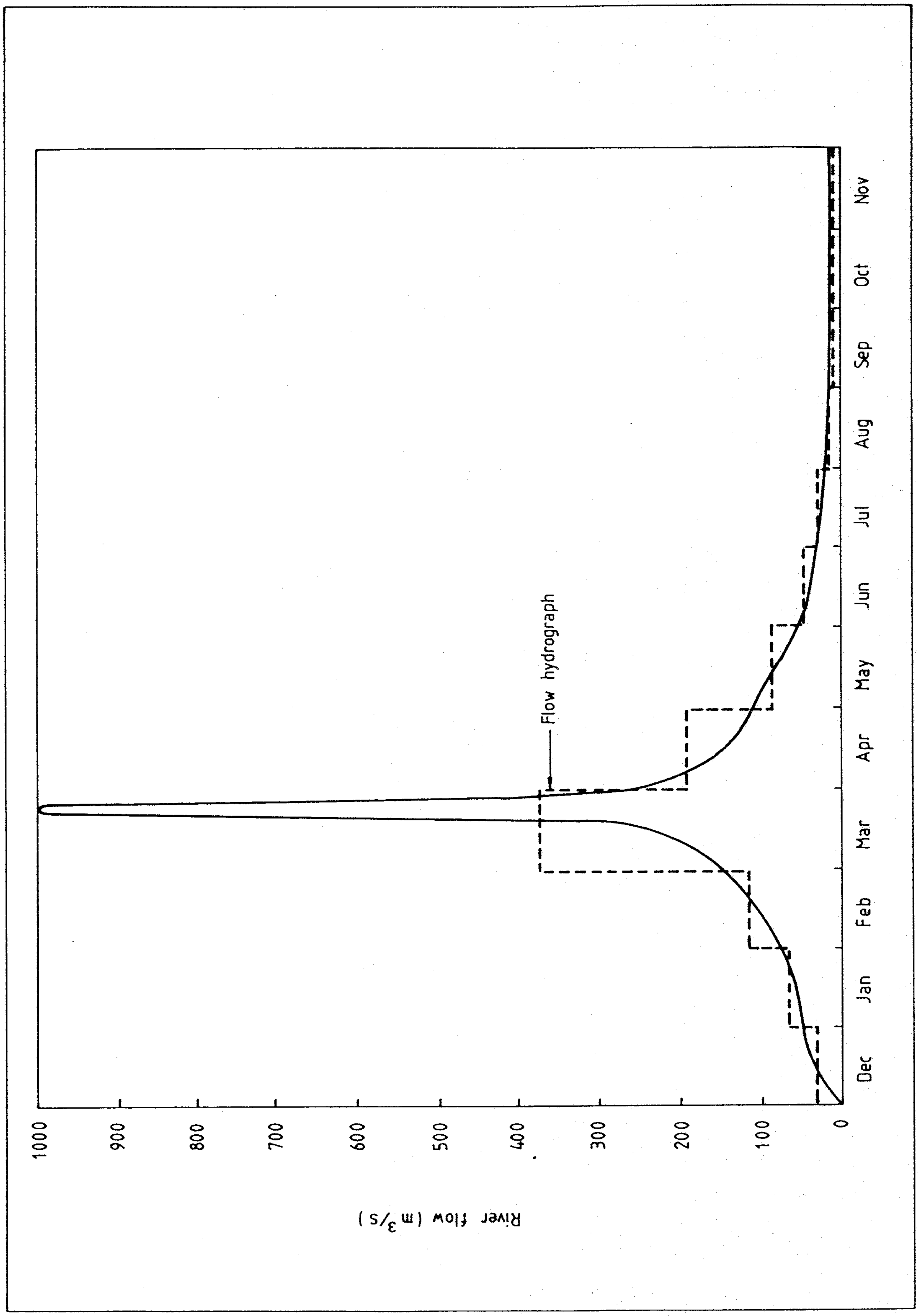

Fig 5·1 Representative annual flow sequence

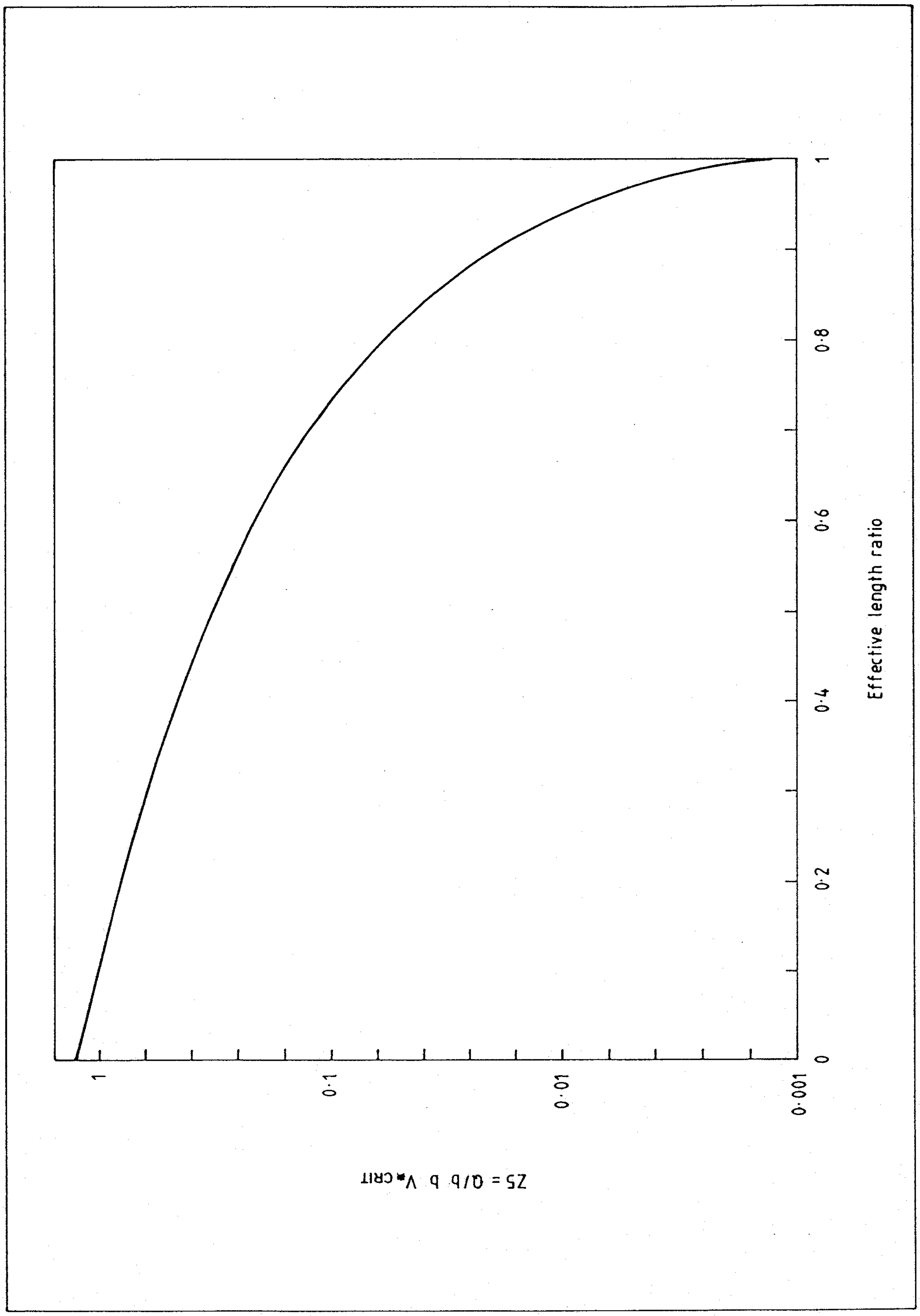

Fig 6·1 Effective length ratio against Z5 Ks = 1m $\bar{b}/\bar{d}$ = 44·4

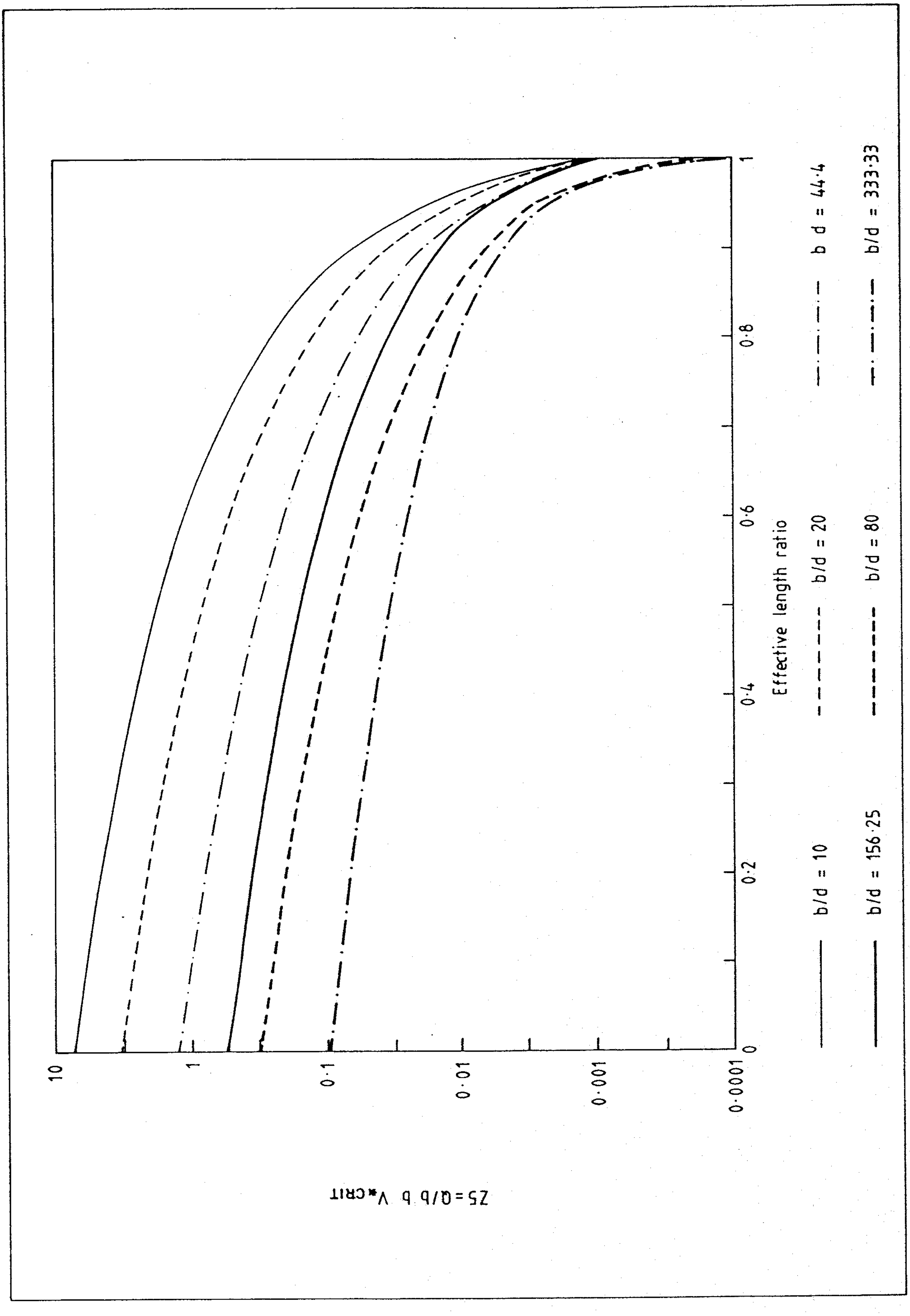

Fig 6·2 Effective length ratio against Z5 Ks = 1m

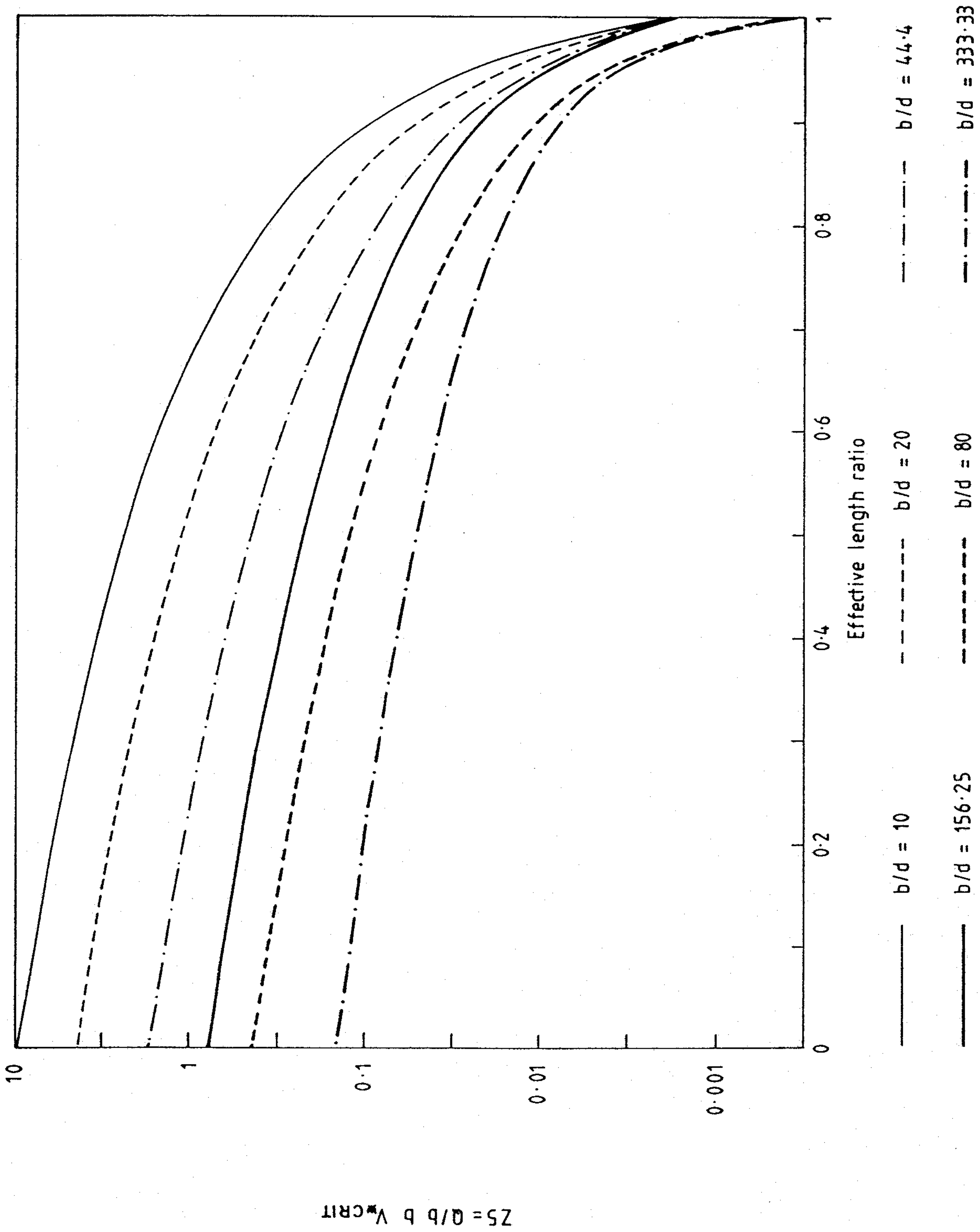

Fig 6·3 Effective length ratio against Z5 Ks = 0·1m

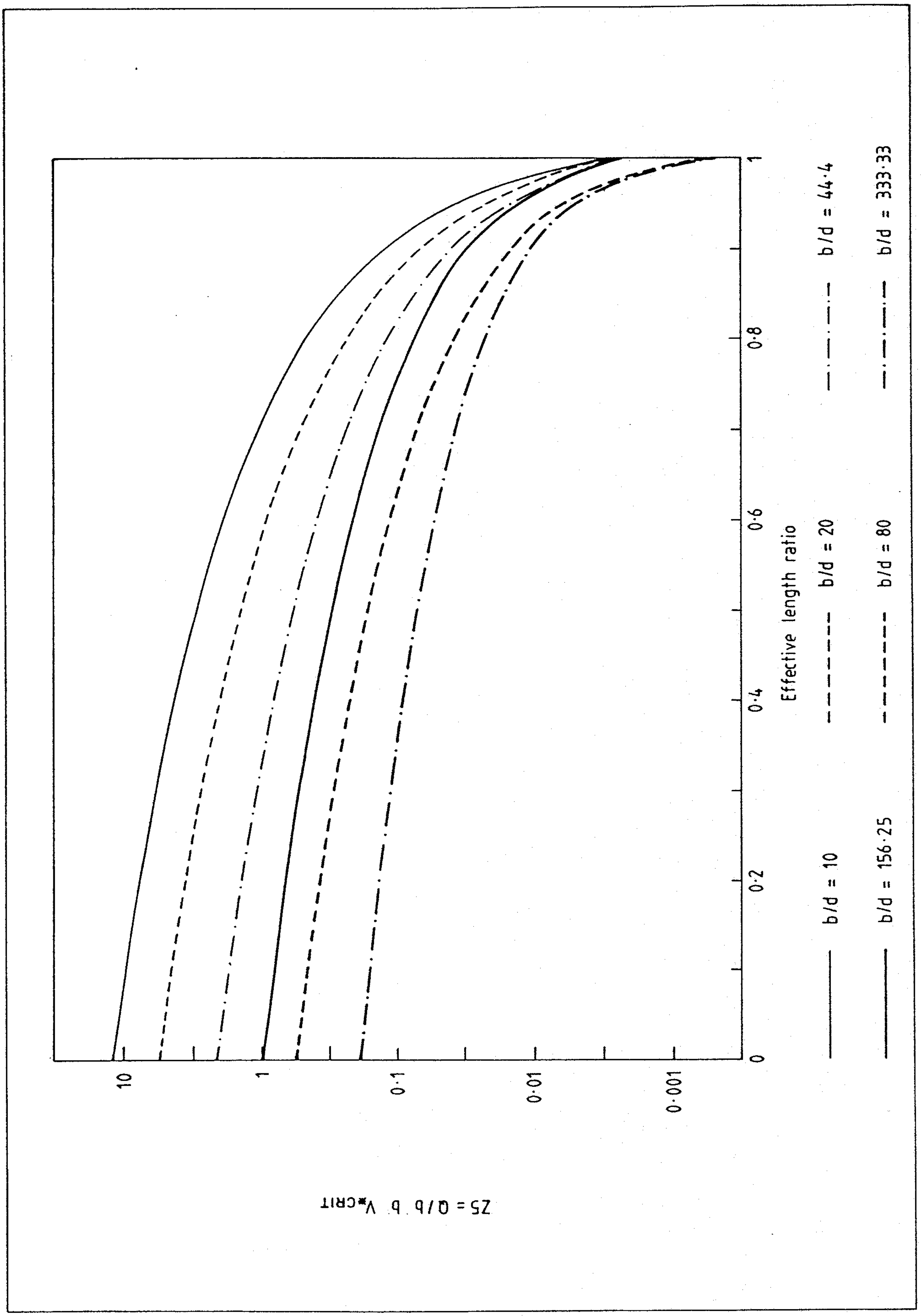

Fig 6·4 Effective length ratio against Z5 Ks = 0·01m

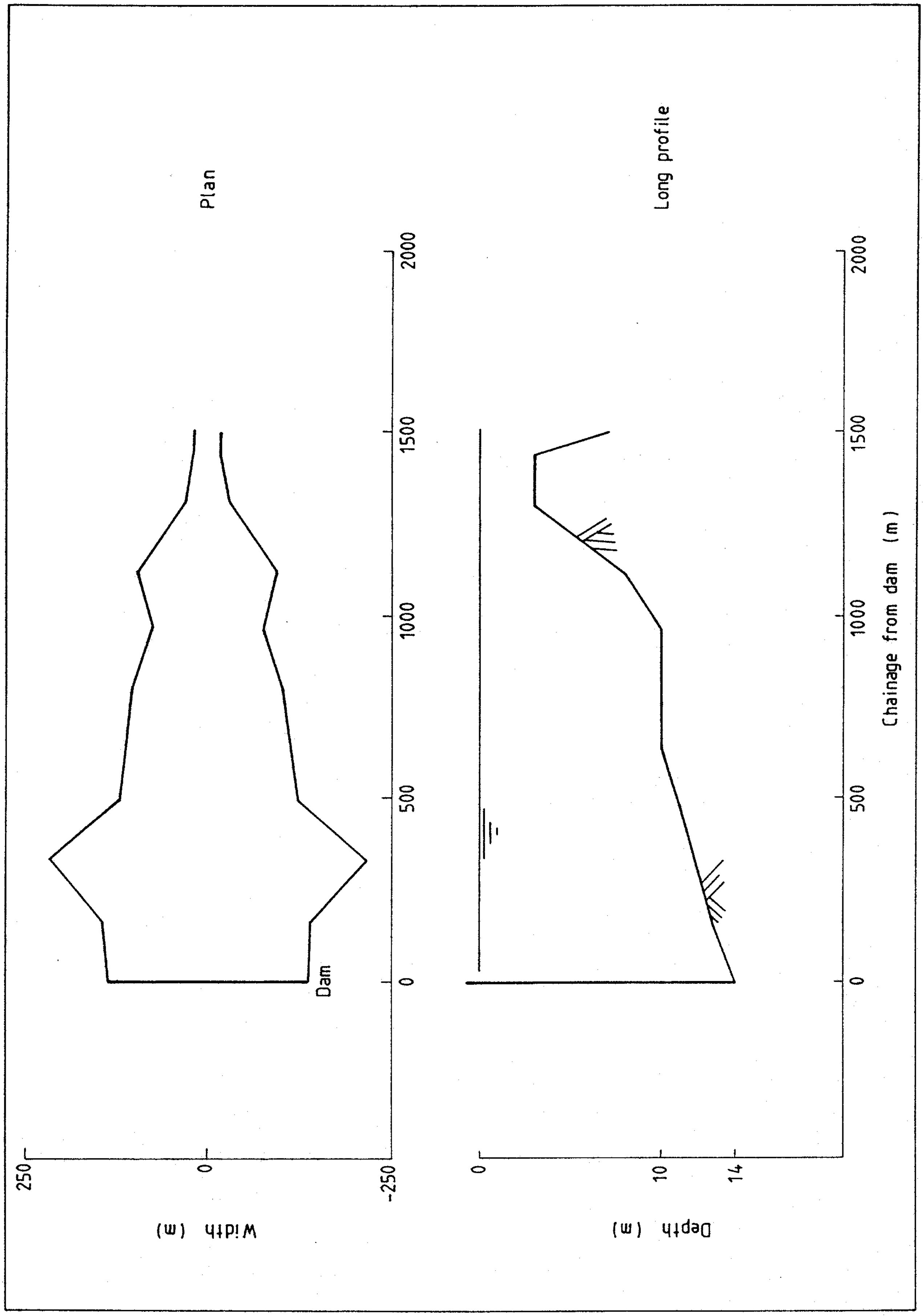

Fig 7·1 Gozho reservoir - plan and longitudinal profile

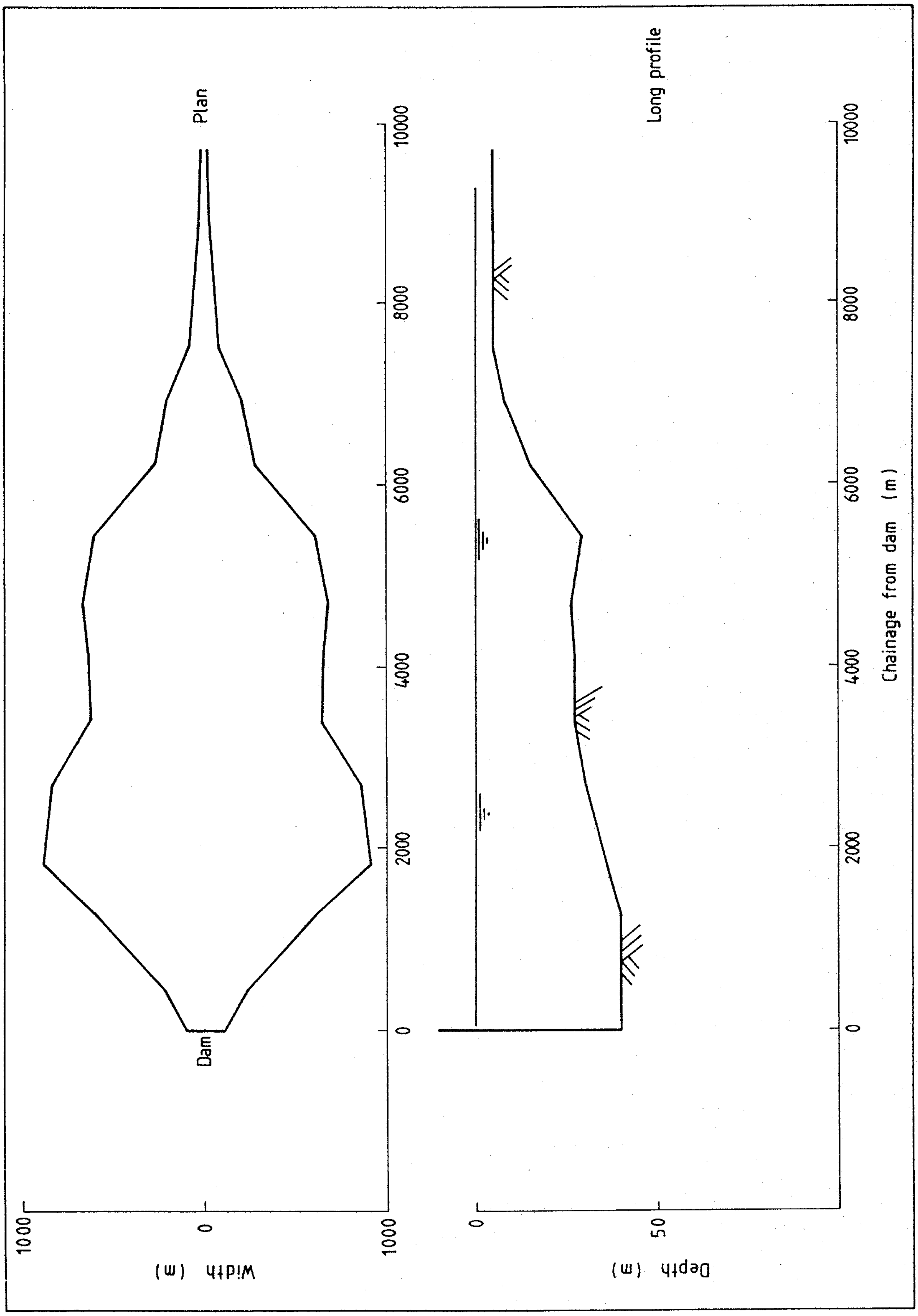

Fig 7·2 Siya reservoir - plan and longitudinal profile

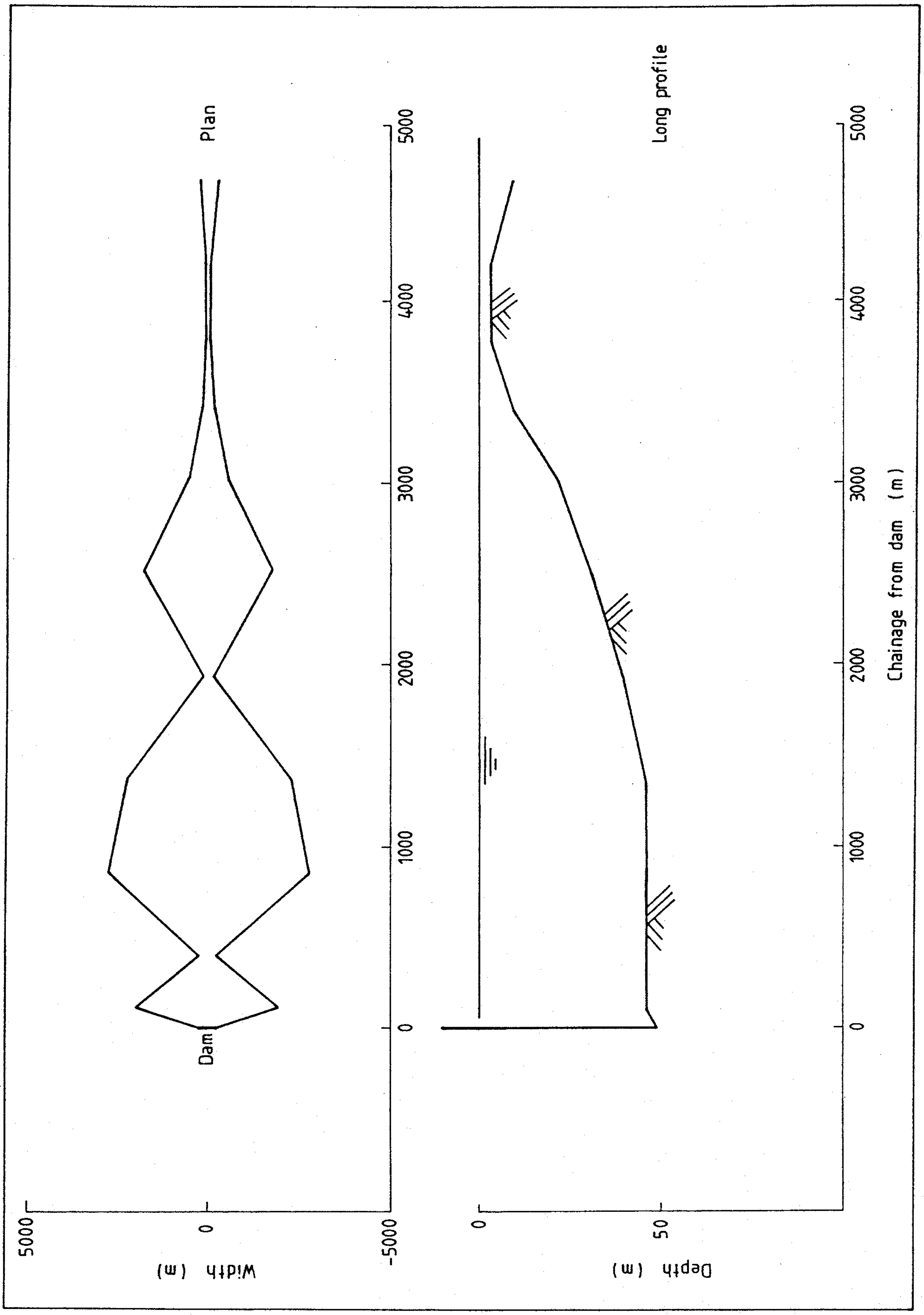

Fig 7·3 Manjirenji reservoir - plan and longitudinal profile

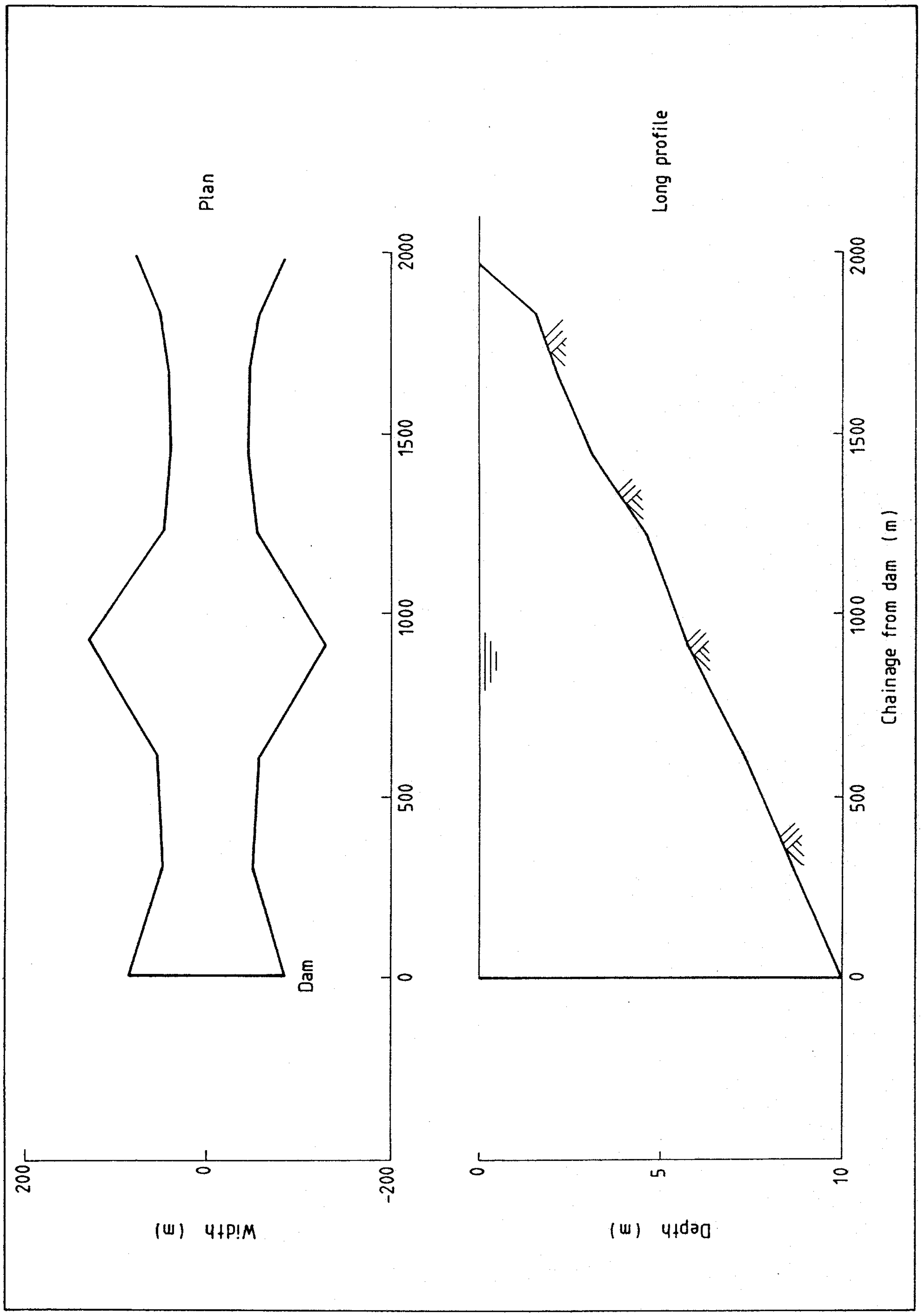

Fig 7·4 Maynard reservoir - plan and longitudinal profile

APPENDIX.

APPENDIX A

TRAPEF - Software for estimating reservoir trapping efficiency

A.1 Introduction

Given data for any reservoir the program TRAPEF calculates dimensionless parameters and uses them to interpolate within the non-dimensional effective length and trapping efficiency curves to obtain first the effective length ratio, and then the trapping efficiency. This appendix describes the general computational procedure adopted by TRAPEF and the format of the input data file.

A.2 Computational procedure

The program TRAPEF starts by reading in data which describe the reservoir geometry, the roughness length and shear velocity. Default values can be used for these last two items; under these circumstances no values are read in. The program then reads discharges and associated durations, and fall velocities and associated load proportions. The discharges can be specified for any suitable time duration, such as hours, days or months. The same duration type must be used within each run. Therefore the trapping efficiency during a flood hydrograph could be determined separately from the trapping efficiencies calculated on a monthly basis. If more than one fall velocity is specified, the sum of the proportions for each velocity should equal 1.0 this is because the proportions are used to weight the corresponding trapping efficiencies, so that the overall trapping efficiency for a particular discharge can be determined. Similarly, the discharge durations are used to weight the efficiencies to give a overall trapping efficiency summed over all discharges and fall velocities.

Depending on the number of discharges and fall velocities read in, the program determines which of four cases will be used for both calculating and printing out the results. The four cases are summarised below,

Number of discharges

		1	>1
Number of fall velocities	1	1	3
	>1	2	4

For case 2 the program calculates the trapping efficiency for each sediment fall velocity and will weight according to the proportion that sediment is of the total sediment load to give an overall value for trapping efficiency.

For case 3 the program will calculate the trapping efficiency for each discharge and will weight according to the duration to give an overall trapping efficiency.

For case 4 the program determines the efficiency for each discharge by weighting according to the sediment proportions. In time these efficiencies are weighted according to the duration to give the overall value.

The computational procedure starts by the program calculating the effective length ratio for the first, or only, discharge value. The effective length data curves are roughness length dependent; therefore three sets have been generated for K_s values of 1.0, 0.1 and

0.01m. The program checks that the specified roughness length lies within this range; if not a warning is printed and the set of curves closest to the specified value is used. The effective length ratio is then determined using Z5 and Z6 parameters, weighting according to the K_s value.

Linear interpolation is used throughout the program. If the interpolated value lies above or below the range of a particular curve a warning is printed and the end value is used. In the case of the effective length ratio this would be 0 or 1. These warning messages can be switched off. It is recommended that they are used for the first run of a set of data to check that the reservoir is behaving as expected. If the Z6 parameter indicates that the interpolated point lies completely outside the data set TRAPEF will perform an extrapolation based on the first or last two curves and will print a warning message which cannot be switched off.

Having obtained the effective length ratio, the reservoir effective length, mean width and depth are adjusted. The mean shear velocity and Z3 parameter are then calculated. The program then loops for each sediment fall velocity, calculating the Z1 parameter and hence the corresponding trapping efficiency. These values are weighted as described above to give the overall trapping efficiencies summed over discharge and/or fall velocity. If the program detects that the calculated mean shear velocity is greater than the critical shear velocity no interpolation is undertaken and the trapping efficienciy is set to zero.

The next section describes the format of the input data file required by TRAPEF. Examples of Input and output files are given in Tables A1 to A8.

A.3 Specification of input data file

The program TRAPEF reads data from a single input file via unit 1. The program assumes that all input files have the extension .DAT. Similarly, the program results are contained in a single file (via unit 2) with the extension .PRN. After typing TRAPEF, to start execution, the program will ask for the names of the input and output files which should be given without the extension.

The following section describes the structure of the input file giving the order of the various parameters. Free format has been used throughout so there are no restrictions on the layout of the various parameters. The input data file should be set up, prior to running TRAPEF, by any convenient means.

Input data file - order of records

Item	Description	Sub-item	Description	Record type
1	Title			1
2	Reservoir dimensions			2
3	Warning indicator			3
4	Critical shear velocity	4.1	Logical control parameter	4
		4.2	Critical shear	5
5	Roughness length	5.1	Logical control parameter	6
		5.2	Colebrook-White K_s	7

6	Discharge data	6.1	Title	1
		6.2	Logical control parameter	8
		6.3	Steady state discharge	9
		6.4	Number of discharges	10
		6.5	Discharges and duration	11
7	Fall velocity data	7.1	Title	1
		7.2	Number of fall velocities	12
		7.3	Single fall velocity	13
		7.4	Fall velocities and proportions	14

<u>Record type 1 - Title</u>

Item	Description	Format
1	Main title for model run	Character

In addition to the main title, titles are also placed before the discharge and fall velocity data to make the data file easier to understand. These additional titles are not used by the program.

Record type 2 - Reservoir dimensions

Item	Description	Format
1	Length	Real
2	Mean width	Real
3	Mean depth	Real

Record type 3 - Warning indicator

Item	Description	Format
1	Control parameter to turn warning messages on or off	Logical

In the interpolating procedure, warnings will be generated if the value lies above or below the range of each curve. These warnings will not be printed if the user sets the above parameter to FALSE. If the parameter is set to TRUE all warnings will be printed. If the program has to extrapolate a value, because it lies completely outside the dimensionless curves, this warning will always be printed even if the parameter is set to FALSE.

Record type 4 - Logical control parameter for shear velocity

Item	Description	Format
1	Logical parameter used to set critical shear velocity	Logical

If this parameter is set to TRUE the program will read the critical shear velocity on the next line. If it is set to FALSE the default velocity of 0.01 m/s will be used and record type 5 (below) should be omitted.

Record type 5 - Critical shear velocity

Item	Description	Format
1	Critical shear velocity	Real

If the logical parameter above has been set to TRUE then the user must supply a critical shear velocity.

Record type 6 - Logical control parameter for roughness length

Item	Description	Format
1	Logical parameter used to set roughness length	Logical

If this parameter is set to TRUE the program will read the Colebrook-White Ks value on the next line. If it is set to FALSE the default value of 0.1m will be used for K_s, and record type 7 (below) should be omitted.

Record type 7 - Roughness length

Item	Description	Format
1	Colebrook-White K_s value	Real

If the logical control parameter has been set to TRUE the user must supply a K_s value in meters.

Record type 8 - Logical control parameter for discharge data

Item	Description	Format
1	Control parameter for steady state or transient discharges	Logical

If this parameter is set to TRUE a single steady state discharge will be read in as record type 9. If the parameter is set to FALSE the program will read in several discharges and durations as defined by record types 10 and 11.

<u>Record type 9 - Steady state discharge</u>

Item	Description	Format
1	Steady state discharge	Real

A single discharge value in cumecs is given if the control parameter was set to TRUE.

<u>Record type 10 - Number of discharge values</u>

Item	Description	Format
1	Number of discharges	Integer
2	Duration type	Integer

Item 2 defines the units for the durations given on record type 11 i.e. whether they are hours, days, weeks etc. Only one duration type must be used in any simulation run. The duration type should be one of the following,

1 = seconds
2 = minutes
3 = hours
4 = days
5 = weeks
6 = months

The duration type is not used in the calculations but is simply used when printing out the discharges and associated durations.

Record type 11 - Transient discharge data

Item	Description	Format
1	Discharge in cumecs	Real
2	Duration	Real

This record is repeated for each discharge value as specified by record type 10. The duration of each discharge should also be given. Durations may be given in any of the units specified on record type 10.

Record type 12 - Number of fall velocities

Item	Description	Format
1	Number of fall velocities	Integer

Record type 13 - Single fall velocity

Item	Description	Format
1	Fall velocity in m/s	Real

A single velocity is given if record type 12 was set to 1.

Record type 14 - Fall velocities and proportions

Item	Description	Format
1	Fall velocity in m/s	Real
2	Proportion of load for this fall velocity	Real

This record is repeated for each fall velocity as specified by record type 12. The proportion should be given as a decimal e.g. 0.2, 0.45 etc. and the sum of all the proportions should equal 1.0

TABLE A1 : Case 1 : Example input file

```
Case 1 example
10000  1000  100
false
true
1.0
Discharge data
true
5000
Fall velocity data
1
0.00023675
```

TABLE A2 : Case 1 : Example output file

Reservoir sedimentation analysis

Run title - Case 1 example

Reservoir dimensions

Length = 10000.0 (m)
Mean width = 1000.0 (m)
Mean depth = 100.0 (m)

Critical shear velocity = .010 (m/s)

Roughness (K_s) = 1.00 (m)

Steady-state flow calculation - discharge = 5000.00 (cumecs)

Discharge = 5000.00 (cumecs)

Effective length ratio = .732

Fall velocity = .0002367

Trapping efficiency = 9.19%

WARNINGS WERE GENERATED IN SUBROUTINE FIND BUT WERE NOT PRINTED OUT

TABLE A3 : Case 2 : Example input file

```
Case 2 example
10000  1000  100
false
false
true
1.0
Discharge data
true
5000
Fall velocity data
4
0.0001         0.25
0.00023675     0.25
0.0009         0.25
0.004          0.25
```

TABLE A4 : Case 2 : Example output file

Reservoir sedimentation analysis

Run title - Case 2 example

Reservoir dimensions

Length = 10000.0 (m)
Mean width = 1000.0 (m)
Mean depth = 100.0 (m)

Critical shear velocity = .010 (m/s)

Roughness (K_s) = 1.00 (m)

Steady-state flow calculation - discharge = 5000.00 (cumecs)

Discharge = 5000.00 (cumecs)

Effective length ratio = .732

Fall velocity	Trapping efficiency	Proportion of load
.0001000	4.01	.25
.0002367	9.19	.25
.0009000	30.67	.25
.0040000	80.86	.25

Overall trapping efficiency = 31.18%

WARNINGS WERE GENERATED IN SUBROUTINE FIND BUT WERE NOT PRINTED OUT

TABLE A5 : Case 3 : Example input file

```
Case 3 example
10000  1000  100
false
false
true
1.0
Discharge data
false
4    5
3000      1
4000      1
5000      1
6000      1
Fall velocity data
1
0.00023675
```

TABLE A6 : Case 3 : Example output file

```
Reservoir sedimentation analysis

Run title - Case 3 example

Reservoir dimensions

     Length      = 10000.0 (m)
     Mean width =  1000.0 (m)
     Mean depth =   100.0 (m)

Critical sheart velocity = .010 (m/s)
```

Roughness (K_s) = 1.00 (m)

```
Transient flow calculation

     Discharge          Duration (weeks)

     3000.00                 1.00
     4000.00                 1.00
     5000.00                 1.00
     6000.00                 1.00
```

Fall velocity = .0002367

Discharge	Effective length ratio	Trapping efficiency
3000.00	.791	25.86
4000.00	.759	15.67
5000.00	.732	9.19
6000.00	.706	4.76

Overall trapping efficiency = 11.93%

WARNINGS WERE GENERATED IN SUBROUTINE FIND BUT WERE NOT PRINTED OUT

TABLE A7 : Case 4 : Example input file

```
Case 4 example
10000  1000  100
false
false
true
1.0
Discharge data
false
4    5
3000        1
4000        1
5000        1
6000        1
Fall velocity data
4
0.0001              0.25
0.00023675          0.25
0.0009              0.25
0.004               0.25
```

TABLE A8 : Case 4 : Example output file

Reservoir sedimentation analysis

Run title - Case 4 example

Reservoir dimensions

Length = 10000.0 (m)
Mean width = 1000.0 (m)
Mean depth = 100.0 (m)

Critical shear velocity = .010 (m/s)

Roughness (K_s) = 1.00 (m)

Transient flow calculation

Discharge	Duration (weeks)
3000.00	1.00
4000.00	1.00
5000.00	1.00
6000.00	1.00

Discharge = 3000.00 (cumecs)

Effective length ratio = .791

Fall velocity	Trapping efficiency	Proportion of load
.0001000	11.82	.25
.0002367	25.86	.25
.0009000	68.30	.25
.0040000	100.00	.25

Overall trapping efficiency = 51.50%

Discharge = 4000.00 (cumecs)

Effective length ratio = .759

Fall velocity	Trapping efficiency	Proportion of load
.0001000	6.95	.25
.0002367	15.67	.25
.0009000	47.87	.25
.0040000	94.60	.25

Overall trapping efficiency = 41.27%

Discharge = 5000.00 (cumecs)

Effective length ratio = .732

Fall velocity	Trapping efficiency	Proportion of load
.0001000	4.01	.25
.0002367	9.19	.25
.0009000	30.67	.25
.0040000	80.86	.25

Overall trapping efficiency = 31.18%

Discharge = 6000.00 (cumecs)

Effective length ratio = .706

Fall velocity	Trapping efficiency	Proportion of load
.0001000	2.05	.25
.0002367	4.76	.25
.0009000	16.83	.25
.0040000	55.77	.25

Overall trapping efficiency = 19.85%

Summary of trapping efficiencies

Trapping efficiences summed over all fall velocities

	Discharges			
	3000.00	4000.00	5000.00	6000.00
Efficiences	51.50	41.27	31.18	19.85

Trapping efficiencies summed over all discharges

	Fall velocities			
	.0001000	.0002367	.0009000	.0040000
Efficiencies	5.31	11.93	36.15	78.74

Overall trapping efficiency for all discharges and fall velocities = 33.03%

WARNINGS WERE GENERATED IN SUBROUTINE FIND BUT WERE NOT PRINTED OUT