The Feasibility of Flushing Sediment from Reservoirs

E Atkinson

(TDR Project R5839)

Report OD 137
November 1996

HR Wallingford

ODA

The Feasibility of Flushing Sediment from Reservoirs

E Atkinson

(TDR Project R5839)

Report OD 137
November 1996

HR Wallingford

Address and Registered Office: **HR Wallingford Ltd.** Howbery Park, Wallingford, Oxon OX10 8BA
Tel: + 44 (0)1491 835381 Fax: + 44 (0)1491 832233

Registered in England No. 2562099. HR Wallingford is a wholly owned subsidiary of HR Wallingford Group Ltd.

Contract

This report describes work carries out by the Overseas Development Unit (ODU) of HR Wallingford.

The work was carried out for the Overseas Development Administration (ODA) of the British Government. The ODA Technology Development and Research theme and project details are as follows:

Theme	To Improve Integrated Water Resources Development and Management, including Droughts and Floods
Theme No.	W1
Project	Reservoir Sedimentation
Project No.	R5839

Prepared by E. Atkinson (name) Senior Scientist (job title)

Approved by K. Rammurgauth Head/ODU

Date November 1996

Summary

The Feasibility of Flushing Sediment from Reservoirs

E Atkinson

(TDR Project R5839)

Report OD 137

November 1996

Flushing offers the only means of recovering lost reservoir storage without employing costly mechanical measures such as dredging.

Flushing is not widely practised however due to certain limitations: (a) large volumes of water are required, (b) reservoirs have to be drawn down for substantial periods while flushing is carried out, and © low level outlet gates with a large discharge capacity must be included in the dam at construction.

There are many reservoirs where storage loss due to sedimentation is severe, and where these limitations can be overcome. In these circumstances flushing may offer a viable means of recovering and maintaining storage capacity especially when the costs are compared with those of other options.

The purpose of the work described here is to assess the feasibility of flushing sediment from reservoirs using simple criteria which require readily available data. By applying these criteria, reservoirs at which flushing might be viable can be identified, and a preliminary estimate of the sustainable storage capacity can be made. More detailed studies can then be undertaken for those reservoirs.

The report discusses the processes involved in reservoir flushing and derives methods to quantify two key requirements for effective flushing: firstly, the quantity of sediment removed during flushing should at least match the quantity of sediment that deposits in the reservoir during the periods between flushing operations, and secondly the useful storage capacity that can be maintained should be a substantial proportion (above about 50%) of the original capacity.

The criteria derived have been verified against observations of attempts to flush reservoirs, both successful and unsuccessful, in order to establish the accuracy of the methods. They have been applied to fourteen reservoirs in total. At six of these, flushing was observed to maintain a long term capacity well in excess of half the original capacity, while at the other eight reservoirs observations indicated that flushing would maintain less than a third of the original capacity. The criteria successfully differentiated between the reservoirs which could be flushed effectively and those which could not.

Recommendations for further work include incorporation of the methods derived into a numerical model of reservoir sedimentation processes, and further research into the prediction of side slope steepness in a flushed reservoir.

List of Symbols

A_f	cross sectional area of valley scoured out by flushing (m^2)
A_r	cross sectional area of reservoir in reach immediately upstream from the dam (for simplified reservoir geometry) (m^2)
C_o	the original storage capacity of the reservoir (m^3)
DDR	drawdown ratio, which describes the extent of drawdown, defined in Equation 8
El_f	water surface elevation at the dam during flushing (m)
El_{max}	elevation of top water level (m)
El_{min}	the minimum bed elevation which is usually the river bed elevation immediately upstream from the dam (m)
FWR	flushing width ratio, defined in Equation 9
g	gravitational acceleration (g = 9.81m/s^2)
h_f	a height defined in Figure A4.2 (m)
h_l	a height defined in Figure A4.2 (m)
h_m	a height defined in Figure A4.2 (m)
k_s	representative roughness height for the channel bed (m)
L	reservoir length (m)
LTCR	long term capacity ratio, defined in Equation 7
M_{dep}	the mass of sediment which deposits annually in the reservoir (t)
M_f	the mass of sediment flushed annually from the reservoir (t)
M_{in}	mean annual sediment inflow (t)
N	number of years between flushing operations
Q_f	representative discharge passing through reservoir during flushing (or sluicing if appropriate) (m^3/s)
Q_s	sediment load during flushing (t/s)
R	hydraulic radius of flow (m)
S	longitudinal slope during flushing
SBR	sediment balance ratio, defined in Equation 4
SBR_d	sediment balance ratio calculated for full drawdown
SS_{res}	a representative side slope for the reservoir
SS_s	representative side slope for the deposits exposed by flushing
TE	trapping efficiency of reservoir (%)
T_f	duration of flushing (days)
TWR	top width ratio, defined in Equation 10
u	mean velocity of flow (m/s)
u_*	shear velocity, defined as $(\tau/\rho_w)^{0.5}$ (m/s)
V_{in}	mean annual inflow volume (m^3)
W	the representative width of flow for flushing conditions (m)
W_{bf}	bottom width of the scoured valley at full drawdown (m)
W_{bot}	a representative bottom width for the reservoir (m)
W_f	width of flow at the bed of the flushing channel (m)
W_{res}	representative reservoir width in the reach upstream from the dam at the flushing water surface elevation (m)
W_t	reservoir width at the top water level (m)
W_{td}	width at top water level of the scoured valley, when drawdown is complete (m)
W_{tf}	top width of the scoured valley, ie at the top water level (m)
x	deposit depth (m)
α	angle of a slope of reservoir deposits which is just stable (°)
ϕ	angle of friction for deposit material (°)

List of Symbols *continued*

ψ	multiplier in the Tsinghua University method for sediment load prediction
ρ	density of deposits (kg/m^3)
ρ_{bulk}	bulk density of deposits (kg/m^3)
ρ_d	dry density of deposits (t/m^3)
ρ_w	water density (kg/m^3)
σ'	effective stress within deposit material (N/m^2)
τ	bed shear stress (N/m^2)
τ_{cr}	the critical bed shear stress for initiation of erosion (N/m^2)

Contents

Figures

Appendices

1 Introduction

Approximately 1% of the storage volume of the world's reservoirs is lost annually due to sediment deposition (Yoon, 1992). In some developing countries, where population pressures on fragile upland ecosystems has led to accelerated rates of soil erosion, reservoir storage is being lost at much larger rates. While there are some options for reducing the rates at which sediment deposits in reservoirs, flushing offers the only means of recovering lost storage without incurring the expenditure of dredging or other mechanical means of removing sediment. Most of the best sites for reservoirs have already been utilised. There is now a background of environmental and political pressures surrounding proposals for construction of new large dams, which is likely to result in fewer dams being constructed in the coming decades. Interest is therefore increasing in means of reducing the rate at which storage capacities are being lost. Where it is feasible, flushing can offer an attractive means of recovering and maintaining a useful storage capacity when compared with the cost of alternative methods.

In this report simple quantitative criteria for assessing the feasibility of flushing sediments from reservoirs are developed. They are designed to determine whether, at a particular site, there is the potential to restore lost capacity and to maintain a usable storage volume in the long term. Development of the criteria, and their calculation procedures, are described in Chapters 2 and 3. Chapters 4 and 5 describe applying the criteria to fourteen reservoirs that have been flushed and observations of its effect are available, in order to establish how closely the predicted behaviour matches observed behaviour. A detailed example of an application of the criteria is presented in Appendix 5.

Flushing is not the only means of desilting a reservoir, an overview of reservoir desilting methods and other means of preserving reservoir capacity is presented in an earlier HR Wallingford report (Brabben, 1988).

1.1 Sediment flushing

Flushing is the scouring out of deposited sediment from reservoirs through the use of low level outlets in a dam to lower water levels, and so increase the flow velocities in the reservoir. The technique is not widely practised because:

- it is usually only effective in narrow reservoirs,
- it involves large volumes of water being passed through the dam, and
- it requires the reservoir to be emptied.

However flushing has proved to be highly effective at some sites. For example at the Mangahao reservoir in New Zealand 59% of the original operating storage had been lost by 1958, 34 years after the reservoir was first impounded. The reservoir was flushed in 1969, when 75% of the accumulated sediment was removed in a month (Jowett, 1984).

'Drawdown' is the lowering the water levels in a reservoir. Drawing down a reservoir for a few weeks or months during the flood season is also a form of flushing, although the principal purpose of drawdown is to pass the high sediment loads carried by flood flows through the reservoir. In the literature this practice is commonly termed "sluicing". Sluicing is usually considered as distinct from flushing, but in this report it is considered to be a particular kind of flushing.

A number of attempts at sediment flushing have been reported in the literature, but only some have proved successful. Table 1 lists some reservoirs where maintenance of storage volumes in excess of about 50% of their original capacity was found to be possible through flushing.

Table 1 Reservoirs that have been successfully flushed

Reservoir	Country	Reference
Baira	India	Jaggi and Kashyap (1984)
Gebidem	Switzerland	Dawans et al (1982)
Gmund	Austria	Rienossl and Schnelle (1982)
Hengshan	China	IRTCES (1985)
Honglingjin	China	IRTCES (1985)
Mangahao	New Zealand	Jowett (1984)
Naodehai	China	IRTCES (1985)
Palagneda	Switzerland	Swiss Nat. Committee on Large Dams (1982)
Santo Domingo	Venezuela	Krumdiek and Chamot (1979)

1.2 Existing flushing criteria

Criteria for determining whether flushing at a particular reservoir will be successful are required. The literature survey on reservoir sedimentation by Sloff (Sloff, 1991) discusses such criteria, but they are qualitative and cannot be used to assess the feasibility of flushing.

Some quantitative criteria for successful flushing are presented in the literature. A tentative criterion that the ratio of reservoir capacity to mean annual runoff must be less than 1/50 is reported by Annandale (1987). The criterion is satisfied for some of the reservoirs in Table 1, Baira, Santo Domingo and Gmund; but is not satisfied for Gebidem, Hengshan, Honglingjin and Naodehai. (The ratio could not be derived for the Palagneda and Mangahao reservoirs). Ackers and Thompson (1987) state that this ratio should be as large as a half or more for reservoirs with a half life shorter than 100 years. (Half life is the time taken before a reservoir looses half of its useful storage).

Criteria are also given by Paul and Dhillon (1988). They provide plots to determine the area of low level sluice required for flushing from the initial capacity and the annual sediment inflow. Estimates of the sluice areas made for the reservoirs shown in Table 1 indicate that their criteria is not met for at least four of the reservoirs where flushing has been successful.

Pitt and Thompson (1984) report that "effective flushing has generally only been observed where the drawdown level is below about half the height of the dam, and where the sluice capacity exceeds the mean annual flow by at least a factor of 2". If the sluice capacity is defined as the flushing discharge when the low level outlets are fully open, and the water level behind the dam is at its maximum, then both these criteria are met comfortably at all the reservoirs listed in Table 1. However the criteria are also met at reservoirs where the results of flushing indicate that a sustainable capacity will be much less than half the original capacity, for example the Heisonglin reservoir (Xia and Ren, 1980), the Sanmenxia reservoir (Zhang and Long, 1980) and the Zemo-Afchar reservoir (IRTCES, 1985).

Mahmood (1987) presents a number of criteria for quantifying the efficiency and effectiveness of flushing, but these can only be applied after a reservoir has been flushed, and thus cannot be used to predict flushing performance.

It is concluded that existing criteria to determine the potential effectiveness of flushing at a particular reservoir are either qualitative, or provide conflicting results when tested against observed results of flushing.

1.3 New flushing criteria

Improved criteria for assessing the feasibility of reservoir flushing are required. Reservoir flushing will be feasible when the following conditions prevail:

(a) the sediment quantities transported through the low level outlets during flushing are sufficient to enable a long term balance between the sediment inflow and the sediment flushed,

(b) the volume of deposits remaining in the reservoir after a sediment balance has been achieved is sufficiently small to enable a specified storage requirement to be met, and

(c) the cost of flushing does not exceed the benefits; costs are principally the value of the water used, but may include the cost of providing new flushing gates or the damage caused by the injection of high sediment concentrations to the downstream river system, while benefits are principally the value of the additional water which can be stored.

This report is largely concerned with quantifying the first and second criteria above. The economic value of water and off site impacts of flushing are beyond the scope of the report; they would usually be investigated in more detailed studies once the potential for flushing has been established. However, the quantity of water required for flushing is estimated in this report (it is a component in the first criterion.)

2 Sediment balance

2.1 Description of processes

'Complete drawdown' is defined as the lowering of the water level in a reservoir until the reservoir is empty, and the river flow passes through the reservoir at depths similar to river depths before impoundment. In general, flushing without complete drawdown of water levels will be ineffective. This conclusion has been made by many authors, for example Paul and Dhillon (1988), IWHR (1983), Mahmood (1987), Fan and Morris (1992) and White and Bettess (1984).

When low level outlets in a dam are first opened high flow velocities are produced in the immediate vicinity of the outlet. Sediment deposits are thus scoured from a region close to the outlets. Flow velocities further away from the outlets are small and hence no scour occurs.

White and Bettess (1984) investigated flushing before complete drawdown by applying a simple inviscid flow model. The reservoir geometry considered was a flat horizontal bed, with an outlet specified as a sink, and the criterion for effective flushing was that the velocity of the flow near the bed should exceed 0.1m/s. Their results have been reproduced as Figure 1. The figure indicates that the region from which sediment will be flushed extends only a few metres from the outlet gates when the reservoir is not fully drawn down.

Numerical model simulations to confirm White and Bettess's simple inviscid flow results are reported in Appendix 1. A three dimensional model was used, which included the effects of turbulence, bed roughness and the shear threshold for scour. The model indicated that Figure 1 provides overestimates for the extent of scour.

When low level outlets in a dam are first opened, the scour is too localised to produce significant sediment removal from the reservoir. It is only when the reservoir is nearly empty that significant sediment quantities are passed through the outlets. For example Figure 2 shows data reported by Jaggi and Kashyap (1984) which were collected during drawdown and flushing of the Baira reservoir in India. The figure shows how the sediment concentrations being flushed from the reservoir were relatively low until they suddenly rose a hundredfold, when water levels dropped to their final drawn down level.

When flushing is first attempted at a dam where the low level outlets have insufficient capacity to achieve full drawdown, then little sediment is removed from the reservoir. The flushing will produce full drawdown in the upper reaches of the reservoir, where bed elevations are higher, and sediment will be scoured from this region. The sediment will be deposited again upstream from the dam where drawdown is incomplete. After several flushing operations of this kind, sediment levels in the reach immediately upstream from the dam will have risen to a little below the drawn down water level. Drawdown during flushing will then be complete because it will lower water levels to the new higher bed elevations. Thus flushing will eventually remove significant sediment quantities from the reservoir and further rises in bed elevations will be prevented.

Flushing at the Ouchi-Kurgan Reservoir, USSR, is an example of this process (IRTCES, 1985), Figure 3. Low level outlets through the dam were provided, but they had a relatively low capacity, and the drawdown was only about 5m during the period of flushing (late May through to early September). Despite high discharges during flushing, 2000 to 5000m^3/s, bed levels upstream from the dam were rising to within about 5m of the drawdown water level. Equivalent results, found at the Ichari reservoir, are shown on Figure 4 (copied from Mohan et al, 1982). At this reservoir there are no low level outlets and so drawdown during flushing is limited by the spillway crest elevation.

Whether full drawdown is established immediately, or after a period of bed level rise upstream from the dam, eventually the quantities of sediment deposited in the reservoir between flushing operations will balance the quantities removed by flushing. This sediment balance can be expressed:

$$Q_s \, T_f = N \, M_{in} \, TE \qquad (1)$$

where

Q_s is the sediment transporting capacity of the flow in the drawn down reservoir (which is a function of the discharge, the channel width and slope, and the deposited sediment properties),

T_f is the duration of flushing,

N is the interval between flushings in years,

M_{in} is the sediment inflow rate, and

TE is the trapping efficiency, the proportion of the sediment inflow which deposits in the reservoir.

2.2 Transporting capacity of flushing flows

The transporting capacity of flushing flows can be estimated using an empirical method reported in IRTCES (1985). The method is based on observations of flushing at reservoirs in China, where the predominant practice is annual flushing and so relatively little consolidation occurs between flushing operations. The method is based on the equation:

$$Q_s = \psi \frac{Q_f^{1.6} \; S^{1.2}}{W^{0.6}} \qquad (2)$$

where

Q_s is sediment transporting capacity (t/s)

Q_f is flushing discharge (m^3/s)

S is bed slope

W is channel width (m), and

ψ is a constant set from the sediment type:
- 1600 for loess sediments
- 650 for other sediments with median size finer than 0.1mm
- 300 for sediments with median size larger than 0.1mm
- 180 for flushing with a low discharge.

Equation 2 was attributed to Tsinghua University by IRTCES (1985) and is referred to here as the 'Tsinghua University method'. Figure 5 presents the method and the data on which it is based. The discrepancy between an individual observation shown on Figure 5 and its prediction is within half to twice for 87% of the observations. Such discrepancy is common for predictions of sediment transport processes.

The data used to develop the method were collected from reservoirs in China, where flushing practice and predominant sediment characteristics may not be representative of other regions. Verification of the formulae using data from other regions was therefore undertaken. Although a complete data set for testing Equation 2 was not found in the literature, sufficient information is available in four papers to enable an independent evaluation of the method to be made.

Appendix 2 presents details of how data sets from four reservoirs were derived for testing Equation 2. Data from the reservoirs are shown in Table 2 below.

Table 2 Testing Equation 2 using data from the literature

Reservoir	Sediment Type	Condition	Predicted Q_s (t/s)	Observed Q_s (t/s)	Ratio: Observed / Predicted
Baira	low Q_f assumed		60	15	0.25
Guernsey	D_{50} < 0.1mm	1960 flushing	6.8	0.66	0.10
		1961	5.1	0.35	0.07
		1962	5.3	0.26	0.05
Ichari	D_{50} > 0.1mm	Q_f= 400m^3/s	108	36	0.33
		1000m^3/s	450	91	0.20
Zemo-Afchar	D_{50} > 0.1mm	1950 flushing	14	20	1.43
	assumed	1961	8.4	3.8	0.45

Overall the observed sediment loads are significantly less than the predicted ones. For the Guernsey and Ichari reservoirs there are identifiable reasons for an overprediction of sediment loads during flushing. At Guernsey, flushing was first attempted 33 years after impoundment and so consolidation would have increased the resistance to erosion of the deposits being flushed. Equation 2 was derived using data from reservoirs where relatively little consolidation occurred because flushing was performed annually. At the Ichari reservoir, the reason for overprediction appears to be the relatively coarse material in the reservoir deposits (Appendix 2): Equation 2 has only one category for all sediments above 0.1mm and so where sediment sizes are significantly larger than 0.1mm overprediction by the method can be expected.

No other prediction method for the transporting power of reservoir flushing flows has been identified, so Equation 2 is used in this report. However it appears that the equation will produce an overestimate of transporting power (by a factor of perhaps three or even more) when applied in conditions dissimilar to those in China where the original data were collected. However this can be allowed for by the use of a correction factor.

2.3 Channel widths during flushing

As channel width is an input to the sediment transport prediction method discussed in Section 2.2 it must be predicted before the method can be applied. Width prediction is also vital when estimating the sustainable capacity which can be achieved in a flushed reservoir, as discussed further in the next Chapter.

The channel which cuts into sediment deposits during flushing is self formed, and so its width can be expected to be controlled principally by the discharge, slope and sediment properties. However, channel width during flushing has been found to correlate well with the flushing discharge alone, with no apparent sensitivity to slope or sediment properties. Figure 6, which was derived from data presented by IRTCES (1985), Jaggi and Kashyap (1984) and Jarecki and Murphy (1963), shows the correlation.

A line has been fitted to the points shown on Figure 6, it has the following equation:

$$W_f = 12.8\ Q_f^{0.5} \qquad (3)$$

where
Q_f is the flushing discharge (m^3/s), and
W_f is the flushing width (m).

Equation 3 has the same power as the well established Lacey regime relationship for irrigation canals (Lacey, 1930) but a larger multiplier, (4.8 for the Lacey relationship in SI units.)

2.4 A criterion for successful flushing based on the sediment balance concept

An equation expressing the sediment balance (Equation 1) and methods which can be used to calculate the sediment loads during flushing have been presented in the preceding sections. Here the application of these methods to set a criterion for successful flushing is described.

A sediment balance ratio, SBR, is defined:

$$SBR = \frac{\text{sediment mass flushed annually}}{\text{sediment mass depositing annually}} \qquad (4)$$

Using the variables defined for Equation 1, Equation 4 can be expressed:

$$SBR = \frac{Q_s\ T_f}{N\ M_{in}\ TE} \qquad (5)$$

If SBR > 1.0 then it is expected that a sediment balance can be achieved and so this criterion is satisfied.

The calculation procedure for SBR would be:

(i) Decide the likely frequency and duration of flushing. This could be an extended period of partial drawdown to pass high sediment loads in the flood season without deposition (sluicing), or complete drawdown for flushing for periods of days or weeks each year, or occasional flushing carried out every few years. The choice would depend on factors such as the purpose of the impoundment, the reservoir capacity relative to inflow, and the incoming sediment loads.

(ii) Estimate the sediment quantity to be removed from the reservoir by each flushing operation. In most cases this will be the product, $N\ M_{in}\ TE$, of the number of years between flushings, the annual sediment inflow and the reservoir trapping efficiency. Trapping efficiency can be estimated using Brune's or Churchill's methods presented in the ASCE Sedimentation Manual (Vanoni, 1975), Brune's curves are reproduced in Appendix 4 in this report (Figure A4.1). For sluicing operation a trapping efficiency of 100% is appropriate for the drawdown period, as all the incoming sediment must be passed through the reservoir.

(iii) Select an initial value for the design flushing discharge. After the reservoir is drawn down the discharge during flushing will be the river discharge, and thus it will depend upon the time of year when flushing operations are planned. Discharge can be estimated from hydrological records for the rivers entering the reservoir. The flushing discharge must be passed through the dam with water levels close to their full drawdown levels and so the size of the low level outlets may limit the flushing discharge. There may be times of year when the reservoir should not be flushed. The penalty of providing small outlets that may limit flushing discharges should be compared with the greater costs of larger more effective outlets.

If the reservoir is to be flushed over a long period then the expected discharge hydrograph should be estimated. When the discharge in the this hydrograph exceeds the design flushing discharge, sediments will deposit in the backwater region upstream from the dam. Therefore, periods with high river discharges should not be included in the computations of sediment removal by flushing.

(iv) Estimate the width of channel produced by flushing using Equation 3. For cases with a discharge hydrograph, rather than a single value, a means of combining the discharges to predict a "dominant discharge" is required. A method which provides some weighting towards the higher discharges in the range would be suitable. Other uncertainties in the method do not warrant more precise calculations. The width predicted from Equation 3 should be compared with the original bed width in narrow reservoirs, as the width before impoundment at the bottom of the reservoir may limit the channel width that can be achieved.

(v) The purpose of flushing is usually to maintain the lowest bed elevation across each section at the original river bed elevation before impoundment. Therefore the slope of the channel at the end of flushing can be taken as the original river bed slope.

(vi) The three inputs to the calculation of sediment transporting capacity, Q_s, are now determined: discharge, width and slope. Transporting capacity can be calculated using Equation 2, noting that the sediment sizes are those depositing in the reservoir, not the river bed material size. If conditions are different from those for which the prediction method was developed, a factor of 3 should be applied to reduce the predicted Q_s value. An even greater factor should be applied where median sediment size is much larger than 0.1mm or where flushing is to be attempted after a long period of deposition and consolidation. The factor will allow for the expected overestimate in Q_s (see Section 2.2).

(vii) Estimate the duration of flushing, T_f, the flushing discharge and inflow hydrographs during the season when flushing will be undertaken will affect this estimate, together with considerations of the costs in interrupting normal reservoir operation.

(viii) Values for all the variables input to Equation 4 have been derived above. The equation can be used to derive the sediment balance ratio, SBR. If SBR > 1.0 then the criterion is satisfied.

(ix) If SBR is too low, then flushing may only be feasible at higher discharges, which may be possible by changing the period when the reservoir is to be flushed, or by providing larger flushing outlets in the dam.

A step by step description of how the sediment balance ratio, SBR, can be calculated is presented in Appendix 4.

3 Sustainable reservoir capacity

3.1 Description of processes

Sustainable reservoir capacity is defined as the storage capacity of a reservoir which can be sustained by flushing in the long term.

If the lowest bed levels at each section of a reservoir that has been flushed have been returned to the original river bed (as described in the previous chapter), and the reservoir is narrower than the width of a self formed channel produced by the flushing flow, then very little sediment will have remained in the reservoir. Small pockets of sediment may remain where the shape of the reservoir protects sediment from the flushing flow, but the sustainable reservoir capacity will be approximately equal to the original capacity.

However, the channel scoured out by flushing will usually be narrower than the reservoir width, and substantial sediment deposits will remain after flushing. Data from the 8.6Mm^3 Heisonglin reservoir, which is regularly flushed, illustrate the process well. Figure 7, reproduced from Xia and Ren (1980), shows bed elevations taken from a cross section near the dam. Figure 7(a) shows how the thalweg (the lowest elevation at the section) is maintained close to the original river bed elevation. However, flushing has only produced a narrow channel, and has not prevented severe accretion over most of the section. Figure 7(b) shows how bed elevations in the region outside of the influence of the scoured channel have risen steadily while the thalweg has remained at its original elevation.

Similar observations at the 9 640Mm^3 Sanmenxia reservoir are reported in IRTCES (1985). The reservoir suffered from severe accretion and loss of capacity in the years immediately after impoundment, but from 1965 a change in operation and a gradual increase in the flushing capacity of the bottom outlets has enabled some lost capacity to be restored. Figure 8(a) shows the variation of capacity with time: storage over the main channel of the river before impoundment steadily increased after 1965, while storage over the flood plain remained at its reduced value. Changes in bed elevation at a cross section are shown on Figure 8(b), which demonstrates both how a scoured channel has developed and how much of the deposited material has remained unaffected by flushing. Overall behaviour is the same as at Heisonglin despite conditions being very different in scale and in sedimentation history.

The shape of cross sections that will eventually develop in flushed reservoirs can be determined on the basis of these observations. Firstly, flat deposits will form at the reservoir operating level, secondly flushing will produce a scoured channel with an approximately trapezoidal section. The depth of the scoured channel will equal the reservoir operating level minus the original river bed elevation, the bottom width will equal the flushing width and the flushed channel will have uniform side slopes.

A total reservoir volume can be calculated from these assumed final cross sections. This volume will be the reservoir capacity which can be assumed to be sustainable in the long term: the 'sustainable capacity'. In order to carry out the calculation of sustainable capacity a method for predicting the side slopes of the flushed channel is needed.

3.2 Side slope prediction

Side slopes of channels which cut down through reservoir deposits can vary enormously. At one extreme vertical sides can form where the sediment is fully consolidated, at the other extreme slopes as low as 2.5% have been observed for poorly consolidated material. A variation within a reservoir is commonly observed, for example at the Hengshan reservoir vertical sides were observed near the upstream end while side slopes of about 5% were measured near the dam.

The side slope which will develop during flushing depends on the sediment properties, the degree of consolidation, the depth of deposits and perhaps also the extent of water level fluctuation during flushing. The last effect applies particularly to sand deposits. A sand deposit exposed by flushing will initially form near vertical sides due to the development of negative pore pressures, however the banks will later collapse after re-submergence because the pore pressures will then equalise.

Appendix 3 presents the theoretical development of two methods which predict the side slope. The methods are based on theoretical concepts, laboratory observations of estuarine muds and a prediction equation for submerged deposits. The simpler of the two methods is the equation:

$$\tan \alpha = \frac{31.5}{5} \rho_d^{4.7} \qquad (6)$$

where

α is the angle of slope which is just stable, and

ρ_d is dry density in t/m^3.

Observations of side slope were derived from the literature for nine reservoirs: Baira, Hengshan, Santo Domingo, Guanting, Guernsey, Heisonglin, Sanmenxia, Sefid-Rud and Shuicaozi. The references from which data has been derived are discussed in Chapter 4 below. Ten sets of observations were derived, each for locations in a reservoir where silts and clays appear to predominate in the deposits. The data used to predict side slope were not known with certainty, especially the values for deposit dry density which were only estimated. They have been predicted using Miller's (1953) development of the Lane and Koelzer (1953) method, but only in the case of the Guernsey and Sefid-Rud reservoirs has the input to that method, the relative proportions of sand silt and clay, been known directly.

Figure 9 shows a comparison between predicted and observed side slope. There are large discrepancies between prediction and observation, which can only partially be explained by the errors produced by uncertainty in the input data. The Figure A3.3 method appears to underpredict side slope by about 10 times, while Equation 6 appears give overpredictions of the same order.

There is a need for further research on this question before a reliable prediction technique can be developed. Meanwhile, in the absence of alternatives, predictions using the simpler method (Equation 6) can be made, and the slope adjusted to allow for the expected error. However the results should be treated with caution.

3.3 A criterion for successful flushing based on the sustainable capacity concept

Section 3.1 above described the assumed shape of the cross sections that will eventually develop in flushed reservoirs, as derived from observations of reservoirs which have been flushed:

flat deposits at the reservoir operating level, with

a trapezoidal shaped scoured channel with its bottom at the original river bed elevation, and

the bottom width equal to the flushing width.

The total reservoir volume which can be calculated from these assumed final cross sections has been termed the 'sustainable capacity'. A long term capacity ratio, LTCR, can be defined:

$$\text{LTCR} = \frac{\text{sustainable capacity}}{\text{original capacity}} \qquad (7)$$

The reservoir capacities in Equation 7 are based on a simplified geometry. Figure 10 shows the simplified geometry, and how it can be fitted to actual reservoir geometries.

Values of LTCR greater than about 0.5 would indicate that the capacity criterion is partially satisfied, values approaching unity indicate that the criterion is fully satisfied. An acceptable value for LTCR will depend on the costs associated with flushing. In this report a value of 0.5 is arbitrarily taken as the minimum for the criterion to be satisfied.

A more detailed definition, and a step by step description of how the ratio is calculated, is presented in Appendix 4.

4 Evaluation of criteria using data from flushed reservoirs

4.1 Data from flushed reservoirs

In this chapter the simple criteria for assessing the feasibility of flushing, which have been described earlier, are evaluated using data from fourteen reservoirs where flushing has been attempted, and where sufficient information is available to allow the methods to be applied.

The fourteen reservoirs have been split into two categories: six reservoirs where observations of flushing indicated that it was successful, and eight reservoirs where flushing was not successful, or was only a partial success. The success of flushing was assessed in terms of the reservoir storage capacity which appeared to be sustainable in the long term.

Data on the reservoirs, and the references from which they were derived, are given in Appendix 6 for the reservoirs where flushing appeared to be successful, and in Appendix 7 for the reservoirs where flushing was not. Some of the information needed is not given directly in the references, so the appendices include descriptions of how these data were derived.

4.2 Evaluation of criteria

Table 3 presents estimated sediment balance ratios and capacity ratios for the six reservoirs, as listed in Appendix 6, where flushing has proved successful.

Table 3 Application of sediment balance and capacity ratios for the successfully flushed reservoirs

Reservoir Name	Country	Initial Capacity (Mm^3)	SBR Value	LTCR Value	Estimated Long Term Capacity (% of original)
Baira	India	9.6	7	0.85	about 85%
Gebidem	Switzer-land	9	7	0.99	near 100%
Gmund	Austria	0.93	21	0.98	about 86%
Hengshan	China	13.3	about 3	0.77	about 75%
Palagnedra	Switzer-land	5.5	33	1.0	100% *
Santo Domingo	Venezuela	3	11	1.0	97% *

* Note: there was some sediment clearance by bulldozer for the flushings reported at these reservoirs. See comments on Tables A6.5 and A6.6 in Appendix 6 for more explanation.

Table 3 shows that the sediment balance criterion is comfortably achieved for each reservoir. The capacity criterion is also satisfied for all the six reservoirs: the minimum LTCR value is 0.77.

The remaining eight of the fourteen reservoirs have estimated long term capacities well below half the original capacity. Table 4 below presents the SBR and LTCR values calculated from the data in Appendix 7.

Table 4 Application of sediment balance and capacity ratios for the reservoirs not flushed successfully

Reservoir Name	Country	Initial Capacity (Mm^3)	SBR Value	LTCR Value	Estimated Long Term Capacity (% of original)
Guanting	China	2,270	**0.2**	**0.20**	low
Guernsey	USA	91	1.0	**0.26**	low
Heisonglin	China	8.6	**about 0.7**	**0.30**	23% to 35%
Ichari	India	11.6	7	**0.36**	about 35%
Ouchi-Kurgan	Former USSR	56	7	**about 0.1**	low
Sanmenxia	China	9,640	3.4	**0.39**	about 31%
Sefid - Rud	Iran	1,760	4	**0.13**	less than 26%
Shuicaozi	China	9.6	4.6	**0.39**	low

Values are printed in bold in Table 4 where they are below the value required for the relevant criterion to be satisfied. These results show that the sediment balance criterion is not met at two of the reservoirs, but the capacity criterion is not satisfied at all eight reservoirs. This is an encouraging result because it shows that the criteria can correctly identify reservoirs where flushing was ineffective.

5 Use of further criteria to assess constraints to successful flushing

5.1 Description of new criteria

It is possible to investigate in more detail the flushing experience at the eight reservoirs where flushing did not prove successful, and in particular the factors which prevented effective flushing can be identified. Four separate constraints to effective flushing can be considered, and a quantitative criterion can be applied for each one. The four constraints are:

(i) <u>Incomplete drawdown of the reservoir.</u> The extent of drawdown can be expressed as a ratio, DDR:

$$DDR = 1 - \frac{\text{flow depth for the flushing water level}}{\text{flow depth for the normal impounding level}} \qquad (8)$$

The depths in Equation 8 are depths above the dam base. Drawdown could be insufficient if DDR is less than about 0.7.

(ii) Insufficient flushing flows for a sediment balance. Because incomplete drawdown can also compromise the sediment balance, a new definition of sediment balance ratio is required. The SBR ratio can be made independent of drawdown by calculating it for conditions when thalwegs are at the original river bed elevations, that is for conditions of full drawdown. This new ratio is termed SBR_d.

(iii) Insufficient channel width formed by flushing. The scoured valley formed by flushing will have a bottom width approximately equal to the flushing width calculated from Equation 3, unless this calculated width exceeds the width of the reservoir at that elevation. Flushing channel width should also be assessed independently of the extent of drawdown, so a flushing width ratio, FWR, can be defined:

$$FWR = \frac{\text{predicted flushing width from Equation 3}}{\text{representative bottom width of reservoir}} \qquad (9)$$

If FWR is significantly less than unity then flushing width can be considered an important constraint. An exception will arise, however, for reservoirs where the side slope of the exposed deposits is shallow, this is discussed in (iv) below.

(iv) Side slope too steep. A steep side slope in the scoured valley formed by flushing will be a constraint when either constraint (iii) above applies, or when reservoir bottom widths are small when compared to the top widths (that is width at full storage level). Side slope can be quantified as a constraint by means of a reservoir top width ratio, TWR:

$$TWR = \frac{\text{top width of scoured valley}}{\text{actual top width}} \qquad (10)$$

The scoured section should be assumed to be constrained only by the reservoir bottom width for the calculation of this ratio. Any lack of drawdown should not be considered in the calculation of top widths. If constraint (iii) is important then TWR should comfortably exceed 1 (say TWR > 2) to overcome that constraint. If (iii) is not a constraint, then TWR values approaching 1 are sufficient.

Appendix 4 presents the steps required to calculate each of the four ratios just described.

5.2 Application of new criteria to assess constraints

Table 5 gives values for the four ratios defined above at the fourteen reservoirs studied.

Table 5 Application of the detailed flushing criteria

Reservoir Name	(i) DDR Value	(ii) SBR_d Value	(iii) FWR Value	(iv) TWR Value
Reservoirs flushed successfully				
Baira	0.68	24	3.4	1.6
Gebidem	0.93	20	6.7	1.5
Gmund	0.89	58	5.2	1.3
Hengshan	0.77	about 4	0.10	7.1
Palagnedra	1.00	33	1.4	1.0
Santo Domingo	1.00	11	1.4	1.8
Reservoirs flushed unsuccessfully				
Guanting	0.81	**0.3**	**0.04**	**0.5**
Guernsey	**0.44**	3.2	1.4	**0.26**
Heisonglin	0.77	about 1	**0.06**	**0.8**
Ichari	**0.31**	33	9.9	1.4
Ouchi - Kurgan	**0.14**	110	about 2	**about 0.3**
Sanmenxia	0.75	4.8	**0.26**	**0.9**
Sefid - Rud	0.96	4.3	**0.3**	**0.1**
Shuicaozi	**0.37**	15	1.0	2.1

Values in Table 5 have been printed in bold where a criterion has clearly not been satisfied; where constraint (iii) applies, the FWR value is only given in bold if constraint (iv) also applies (as explained in iv above).

Table 5 shows that all four criteria are met for the six successfully flushed reservoirs, whereas at least one is not met at the other eight reservoirs. An exception is the Baira reservoir, where the arbitrary limit of 0.7 for DDR is just not satisfied (DDR=0.68).

Insufficient drawdown is in most cases a constraint which can be rectified by reservoir designers, by increasing the size of dam outlet structures. It may also be possible to change the timing of flushing, with the existing outlets, so that flushing discharges are reduced and so greater drawdown achieved. The other three constraints to improved flushing performance are largely functions of reservoir geometry, available flushing flows, and soil side slopes: all these factors are related to the reservoir site, and are thus beyond the scope of design or operational changes.

If it is assumed that any constraints to full drawdown can be addressed at the reservoirs where flushing was not effective, then the criteria indicate that two of the eight reservoirs can be flushed successfully. They are the Ichari and the Shuicaozi reservoirs.

Thus the geometry, hydrology, sediment properties and operational requirements at a further two of the original fourteen reservoirs enable flushing to be successful, or potentially so. These same factors cause flushing to be unsuitable at the remaining reservoirs: at these sites flushing has not been successful, and will never be. It is of interest that the six reservoirs where flushing has been successful, and the two where it could be successful, all have original capacities below $14Mm^3$. Only one reservoir where flushing cannot be successful, Heisonglin, has an original capacity below $14Mm^3$, the other five reservoirs have original capacities in the range $50Mm^3$ to $10,000Mm^3$. The limited width of the flushed channel is the important constraint at larger reservoirs.

The side slope criterion, (iv) above, suffers from inaccuracy in the method for side slope prediction (see Section 3.2) and so it can only be applied with complete confidence at a reservoir where flushing has been attempted. The other three criteria can be applied with reasonable confidence at reservoirs where flushing has not yet been attempted. Application of only these three criteria still proved sufficient to indicate serious problems at all eight reservoirs where flushing did not prove satisfactory. Therefore, inaccuracies in the side slope prediction may not be a serious limitation in an overall assessment of the feasibility of flushing.

6 Conclusions and further work

The report has explained the development of criteria for assessing whether flushing at a reservoir will be successful, where success is defined as the usable storage capacity which can be maintained in the long term. Two overall criteria have been developed:

(a) a sediment balance criterion which assesses whether the sediment mass flushed exceeds the mass depositing in the reservoir between flushing operations, and

(b) a capacity criterion which assesses the reservoir storage capacity that can be maintained in the long term.

The criteria are presented in Sections 2.4 and 3.3, and in Appendix 4 in more detail. In addition to these broad criteria four specific criteria are presented which assess the four possible constraints to successful flushing: insufficient drawdown, the lack of a sediment balance (independent of drawdown), insufficient bottom width of the scoured valley formed in the sediment deposits, and finally an excessively steep side slope in that valley. When these criteria were used to assess flushing performance at fourteen reservoirs, which are located throughout the world, the following conclusions were drawn:

i) The criteria correctly identified the six reservoirs where flushing proved successful, and the eight reservoirs where flushing was not successful. This confirms the effectiveness of the method for assessing whether flushing at a certain reservoir will be successful.

ii) Inappropriate design of outlet structures at the dam, causing insufficient drawdown of water levels during flushing, was a significant constraint for half of the reservoirs where flushing was not successful. Insufficient width of the scoured valley formed by flushing was a constraint for six of the eight reservoirs. There were only two reservoirs where changes to the design of the outlet structures could have produced effective flushing.

iii) Eight of the fourteen reservoirs were constructed at sites where the criteria indicated that flushing would be effective, or could potentially be effective by increasing the capacity of the low level outlets. These reservoirs were all relatively small (less than $14Mm^3$), while most of the reservoirs where flushing could not be effective were much larger. Width constraints become more important at large reservoirs.

Certain aspects of the work require further development:

iv) The methods for predicting the side slopes of the valley formed by flushing require further work before they can be used with confidence. In particular, more data on the properties of sediment deposits and on side slopes are required, so that theoretical work can proceed.

v) The work reported here allows flushing at a certain reservoir to be assessed in general terms. If the assessment shows that flushing is likely to be beneficial then a more detailed numerical model study would be appropriate. Such a study would be able to account for reservoir geometry, hydrology and operation in more detail than the simple criteria allow, so the predictions would be correspondingly more accurate and would enable selection of a suitable period between flushing operations. A numerical model for simulating sediment movement and scoured channel formation in flushed reservoirs has now been developed. It is reported separately (Atkinson, 1996).

vi) The analysis reported here has used long term reservoir capacity as the measure of the success of reservoir flushing. However, in many circumstances flushing can greatly reduce the rate of net deposition as well as enable a long term capacity to be maintained. This is especially the case when reservoirs are 'sluiced', that is when drawdown is extended over most of the season for which river sediment loads are high. An assessment of the effect of sluicing on annual sedimentation rate can be made by estimating the proportion of the annual sediment load which enters the reservoir during the period of drawdown. The model discussed in (v) above would enable a more comprehensive assessment to be made.

vii) If, between flushing operations, density currents keep sediments within the valley scoured out by flushing, then the effectiveness of flushing is further enhanced. Deposition only occurs within the previously scoured channel and so all deposited sediments can be subsequently flushed. There is evidence of this process at the Sefid-Rud reservoir (Tolouie et al, 1991). The link between density currents and flushing performance requires further research before its effect on reservoir life can be predicted.

viii) The report does not address the potential problems of sediment disposal which have to be considered before flushing is accepted as a viable option for a particular reservoir.

While it is clear that sediment flushing cannot be a universal solution to sedimentation problems in reservoirs, the technique will prove effective in many circumstances. Use of the assessment criteria given in this report will help engineers to identify reservoirs where flushing has potential. When sites suitable for flushing are identified at the design stage, then construction of low level outlets with sufficient capacity for flushing is recommended. Flexibility for flushing would then be built into the project design, as recommended by Ackers and Thompson (1987) and by Jowett (1984).

7 Acknowledgements

This work has been carried out in the Overseas Development Unit at HR Wallingford, which is headed by Dr K Sanmuganathan. Funding has been provided by the British Overseas Development Administration.

8 References

ACKERS P and THOMPSON G, 1987. Reservoir sedimentation and influence of flushing. In: Thorne C R, Bathurst J C and Hey R D eds, Sediment Transport in Gravel-Bed Rivers, Wiley, Chichester, UK.

AHMED T E S and HAMAD O E T, 1986. Sediment transport in relation to reservoirs. Int. Conf. on Water Resources Needs and Planning in Drought Prone Areas. Khartoum, December 1986, Sudan.

ANNANDALE G W, 1987. Reservoir sedimentation. Developments in Water Science, Title 29. Elsevier Science Publishers, Amsterdam, The Netherlands.

ATKINSON E, 1995. A numerical model for predicting sediment exclusion at intakes. Report OD 130, HR Wallingford, UK.

ATKINSON E, 1996. Flushing sediment from reservoirs: RESFLUSH user manual. Report OD/ITM 54, HR Wallingford, UK.

BEEN K and SILLS G C, 1981. Self-weight consolidation of soft soils: an experimental and theoretical study. Geotechnique, Vol. 31.

BHARGAVA D N, NARAIM L, TIAGI S S and GUPTA P P, 1987. Sedimentation problems at low dams in the Himalayas. Water Power and Dam Construction, January 1987.

BOLTON M, 1979. A guide to soil mechanics. MacMillan Press Ltd, London.

BRABBEN T E, 1988. Reservoir desilting methods. Report OD/TN 32. HR Wallingford, UK.

BRUNE G M, 1983. Trap efficiency of reservoirs. Trans. of the Am. Geophysical Union, Vol. 34, No. 3, Washington DC.

CHANDRA S, 1986. Sedimentation in reservoirs. Report RN-26, National Institute of Hydrology, Jal Vigyan Bhawan, Roorkee, India.

DAWANS P H, CHARPIE J, GIEZENDANNER W and RUFWENACHT H P, 1982. Le degravement de la retenue de Gebidem. 14th Congress on Large Dams, ICOLD, Rio de Janeiro 1982. Q54, R25.

FAN J and MORRIS G L, 1992. Reservoir sedimentation II: reservoir desiltation and long-term storage capacity. Am. Soc. Civil Eng., Journ. Hydr. Eng. Vol. 118, No. 3, March 1992.

GINGER C M, 1987. Simulation and experimental determination of a consolidating mud deposit. Report SR 95, HR Wallingford, UK.

HR Wallingford, 1990. Poole middle channel mud properties. HR Wallingford report EX 2118, UK. (Restricted circulation).

HR Wallingford, 1992. Estuarine muds manual. Report SR 309, HR Wallingford, UK.

IRTCES, 1985. Lecture notes of the training course on reservoir sedimentation. International Research and Training Centre on Erosion and Sedimentation, Tsinghua University, Beijing, China.

IWHR, 1983. The rational operation of drawdown flushing in Shuicaozi Reservoir on the Xili River. English abstract of paper SR 8301 in:
Abstract of papers 1983, Institute of Water Conservancy and Hydroelectric Power Research, P.O. Box 366, Beijing,, China.

JAGGI A L and KASHYAP B R, 1984. Desilting of Baira reservoir of Baira Siul project. Irrigation and Power, October 1984.

JARECKI E A and MURPHY T D, 1963. Sediment withdrawal investigation - Guernsey Reservoir. Paper No. 91, Proc. Inter-Agency sedimentation conference, Misc Publication No. 970, US Dept. of Agriculture.

JOWETT I, 1984. Sedimentation in New Zealand hydroelectric schemes. Water International, 9, 1984.

KRUMDIECK A and CHAMOT P, 1979. Sediment flushing at the Santo Domingo reservoir. Water Power and Dam Construction, December 1979.

LACEY G, 1930. Stable channels in alluvium. Minutes of Proc. ICE, 229, UK.

LANE E W and KOELZER V A, 1953. Density of sediments deposited in reservoirs. Report No. 9 of A Study of Methods Used in Measurement and Analysis of Sediment Loads in Streams, St Paul United States Engineering District, St Paul, Minn, US.

LIECHTI W and HAEBERLI W, 1970. Les sedimentations dans le bassin de compensation de Palagnedra et les dispositions prises pour le deblaiement des alluvions. International Commission on Large Dams, 10th Congress, Montreal.

MAHMOOD K, 1987. Reservoir sedimentation: impact, extent and mitigation. Technical paper No. 71, World Bank, Washington DC.

MIGNIOT C, 1981. Erosion and sedimentation in sea and river, La Pratique des sols et des fondations, editions Le Moniteur 1981.

MILLER C R, 1953. Determination of unit weight of sediment for use in sediment volume computations. Memorandum, Bureau of Reclamation, US Department of the Interior, Denver, Colo, US.

MOHAN J, TIAGI S S and RAJVANSHI U S, 1982. Effects of sedimentation at Ichari reservoir. 14th Congress on Large Dams, ICOLD, Rio de Janeiro, 1982.

NEVE R S and GUSBI M M, 1991. Mathematical modelling of reservoir flows. In: Computer Methods in Water Resources II, Vol. 2 Computational Hydraulics and Hydrology. Computational Mechanics Publications, Southampton, UK.

PAUL T C and DHILLON G S, 1988. Sluice dimensioning for desilting reservoirs. Water Power and Dam Construction, May 1988.

PITT J D and THOMPSON G, 1984. The impact of sediment on reservoir life. Proc. Conf. on Challenges in African Hydrology and Water Resources. Int. Association of Hydrology Scs. Publication No. 144.

RIENOSSAL K and SCHNELLE P, 1982. Sedimentation of small reservoirs in the high alps. 14th Congress on Large Dams, ICOLD, Rio de Janeiro, 1982.

RODI W, 1984. Examples of turbulence-model applications. In: Turbulence Models and Their Applications, Vol. 2 by B E Launder, W C Reynolds, W Rodi, J Matthew and D Jeandel. Editions Eyrolles, Paris, France.

SCHEUERLEIN H, 1987. Sedimentation of reservoirs - methods of preventing and techniques of rehabilitation. First Iranian Symposium on Dam Engineering Tehran, Iran.

SLOFF C J, 1991. Reservoir sedimentation: a literature survey. Communications on Hydraulic and Geotechnical Engineering, Report No. 91-2. Faculty of Civil Engineering, Delft University of Technology, The Netherlands.

SVENSSON U, 1985. PHOENICS in Environmental Flows. A Review of Applications at SMHI Presented at the 1st International PHOENICS User Conference, Dartford, Kent 1985. Proceedings published Lecture Notes in Engineering 18, Springer-Verlag.

Swiss National Committee on Large Dams, 1982. General paper. 14th Congress on Large Dams, ICOLD, Rio de Janeiro, 1982.

TEISSON C, 1991. Cohesive suspended sediment transport: feasibility and limitations of numerical modelling. Journ. of Hydr. Res. Vol. 29, No. 6.

TOLOUIE E, WEST J R and BILLAM J, 1991. Sedimentation and desiltation in the Sefid-Rud reservoir. Paper presented at the British Geomorphological Research Group meeting on Geomorphology and Sedimentology of Lakes and Reservoirs, St Andrews, UK.

VANONI, V A (editor), 1975. Sedimentation engineering. Manuals and Reports on Engineering Practice - No. 54, American Society of Civil Engineers, New York.

WHITE W R and BETTESS R, 1984. The feasibility of flushing sediments through reservoirs. Proc. of the Harare Symposium "Challenges in African Hydrology and Water Resources", July 1984. IAHS Publ. No. 144.

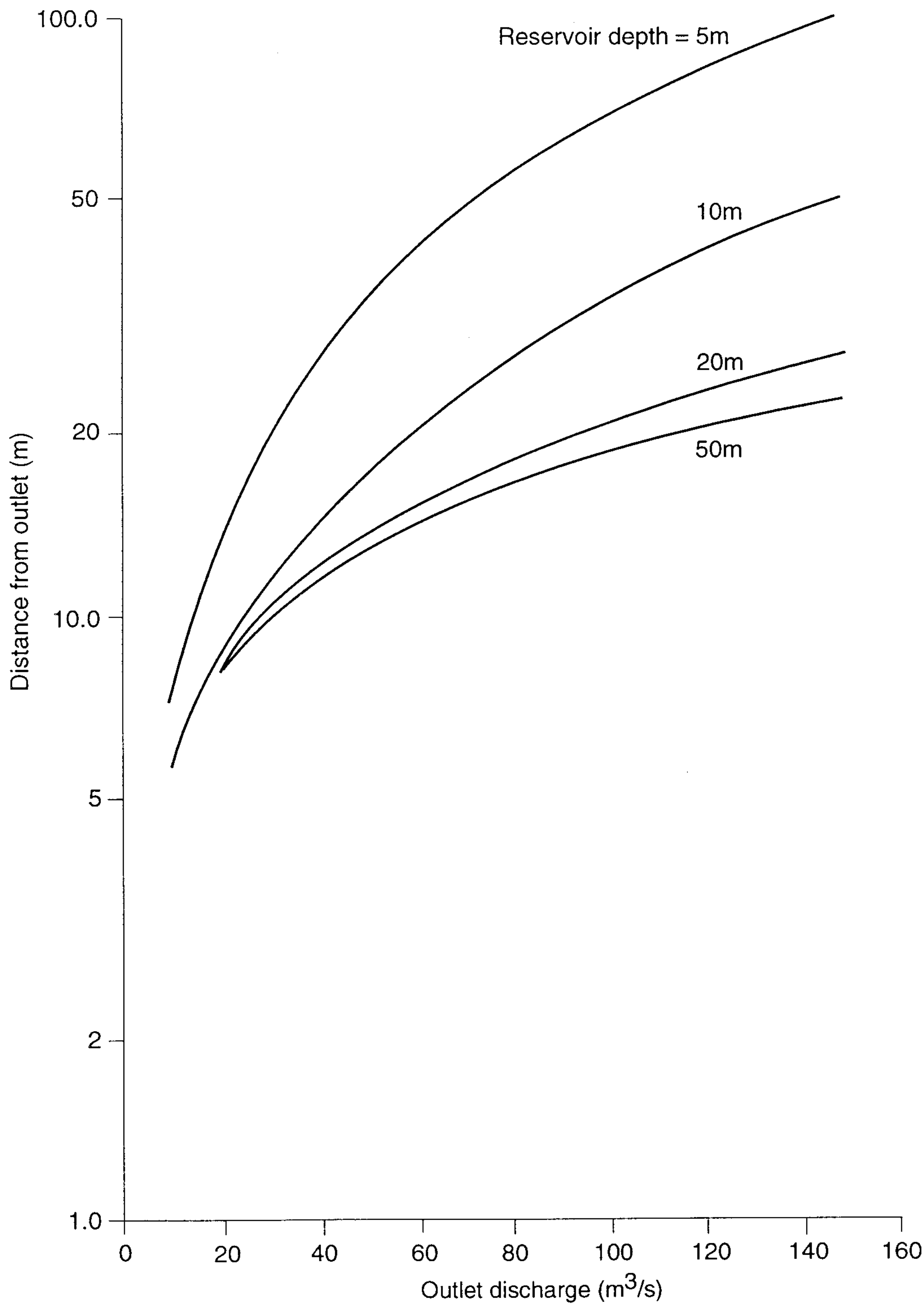
WOOLDRIDGE R, 1984. Sedimentation in reservoirs Tana River Basin Kenya, III. Analysis of hydrographic surveys of three reservoirs in June/July 1983. Report OD 61, HR Wallingford, UK.

XIA MAIDING and REN ZENGHAI, 1980. Methods of sluicing sediment from Heisonglin reservoir and its utilization downstream. Preprints of the International Symposium on River Sedimentation, March 1980, Beijing, China.

YOON, Y N, 1992. The state and the perspective of the direct sediment removal methods from reservoirs. International Journal of Sediment Research, Vol. 7, No. 2.

ZHANG QISHUN and LONG YUQIAN, 1980. Sediment problems of Sanmenxia reservoir. Paper D1, Preprints of the International Symposium on River Sedimentation, March 1980, Beijing, China.

Figures



EA/1/11-95/ f.line

Figure 1 Approximate limit of scour upstream from low level outlets in static water (from White and Bettess, 1984)

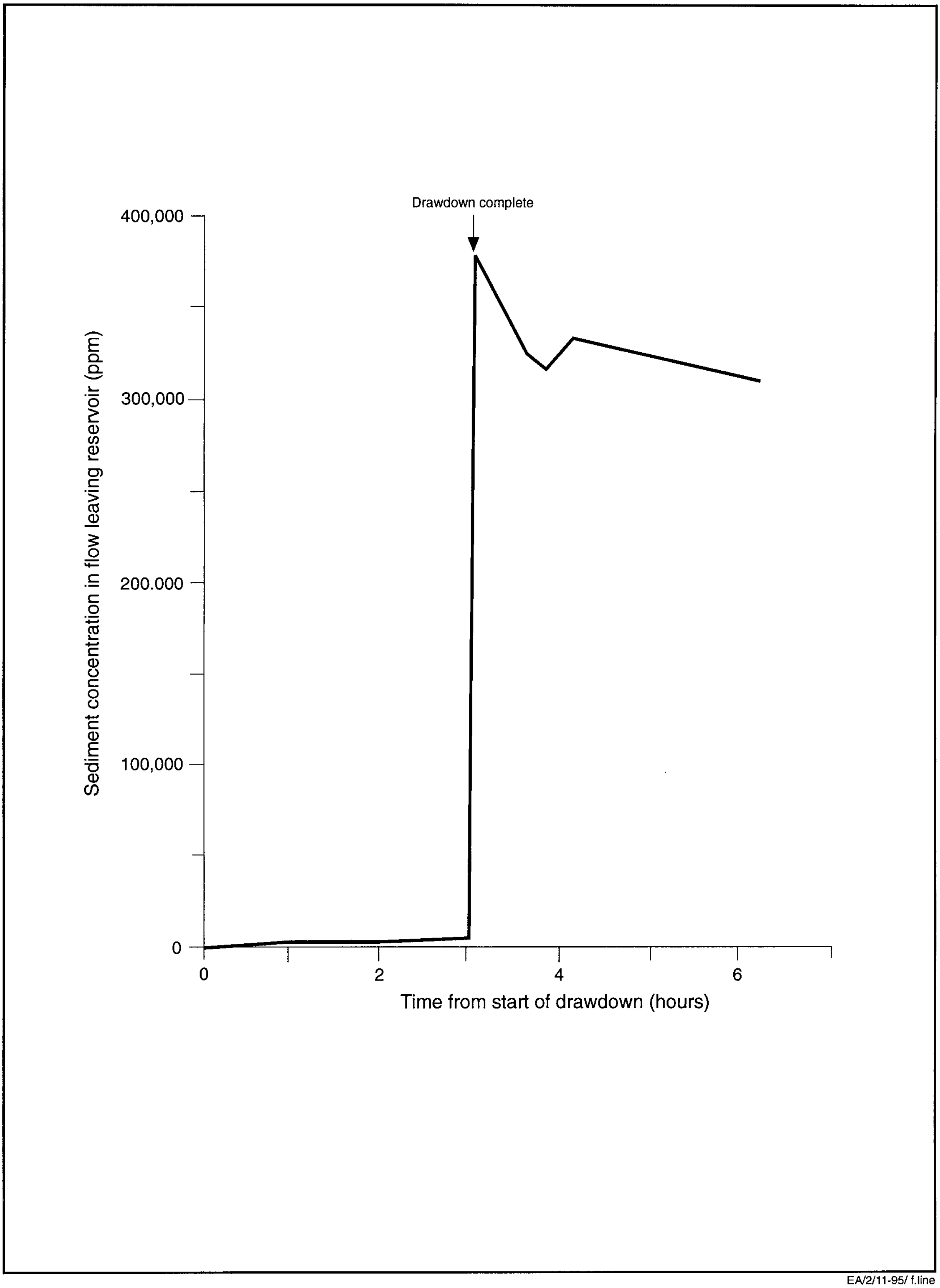
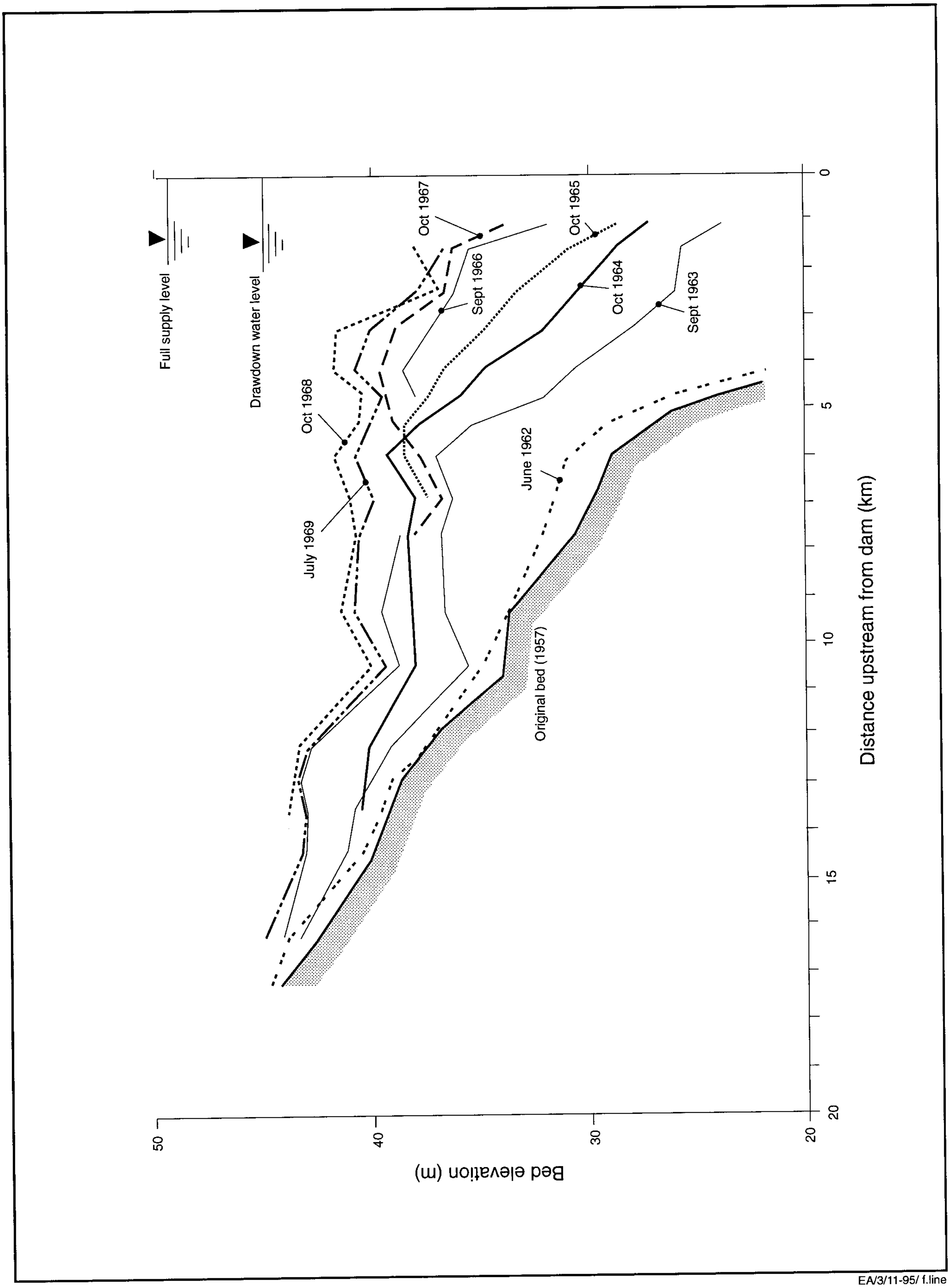
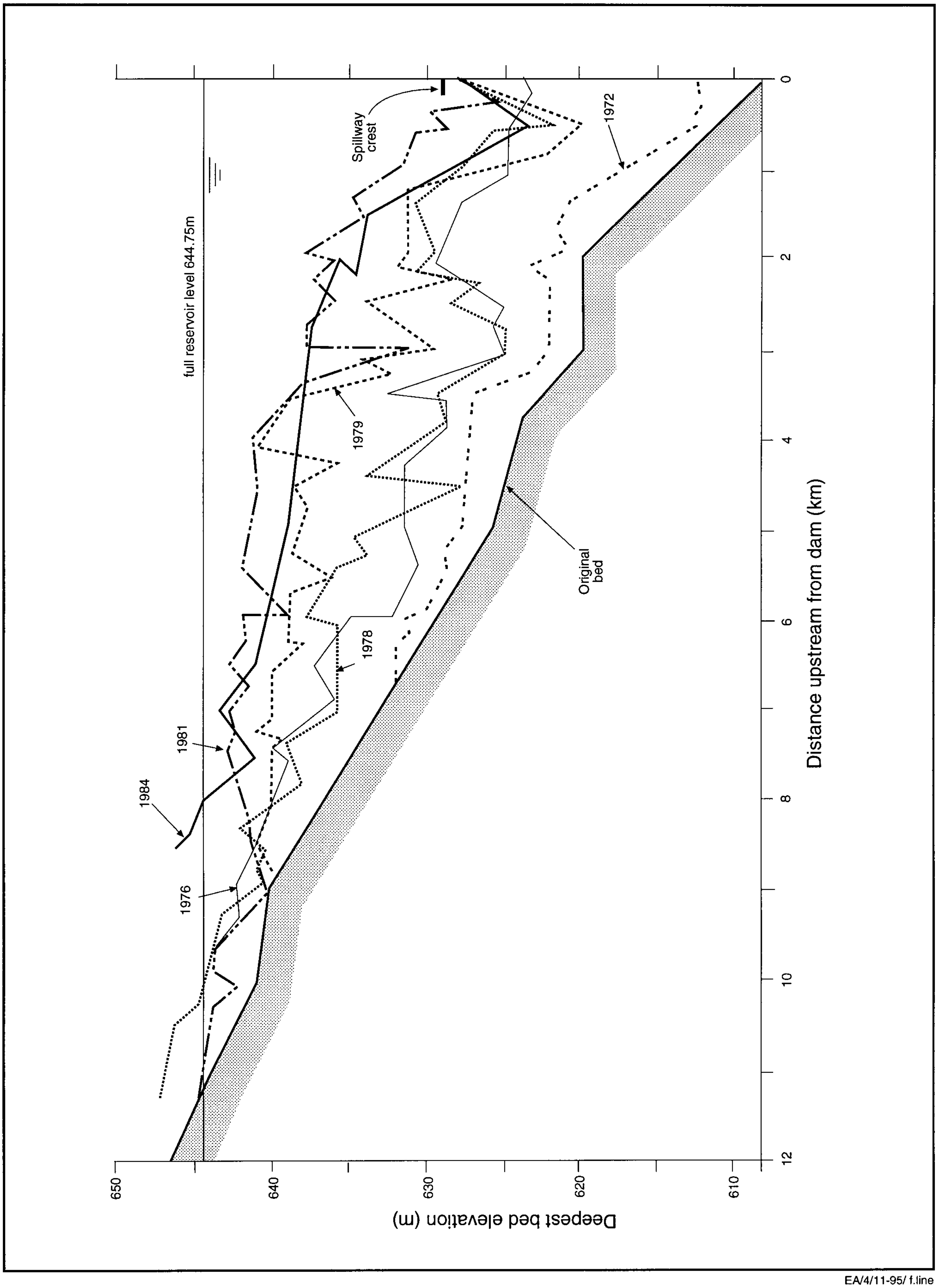


Figure 2 Sediment concentration during drawdown of Baira Reservoir



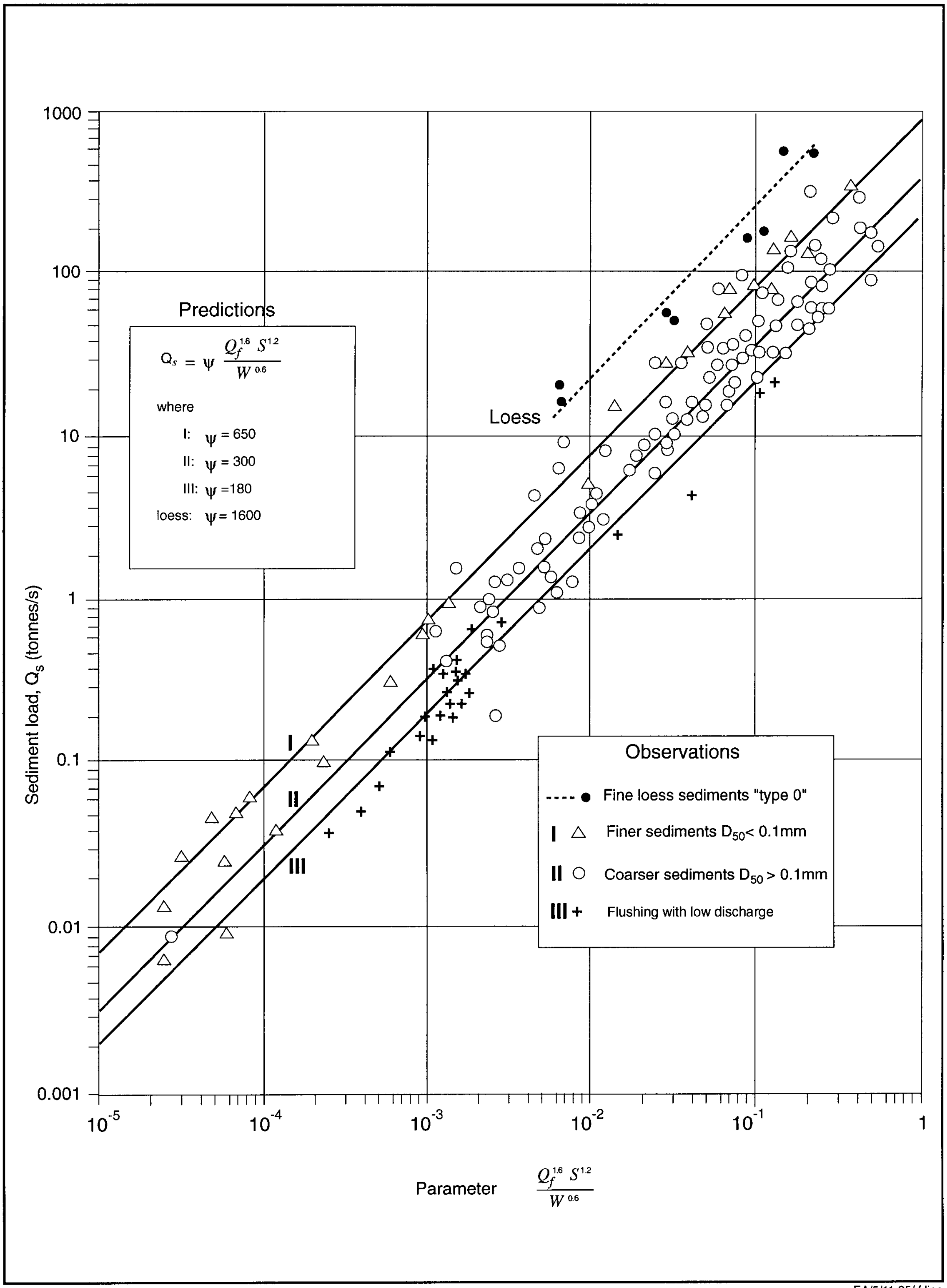
EA/3/11-95/ f.line

Figure 3 Bed elevations in Ouchi-Kurgan reservoir



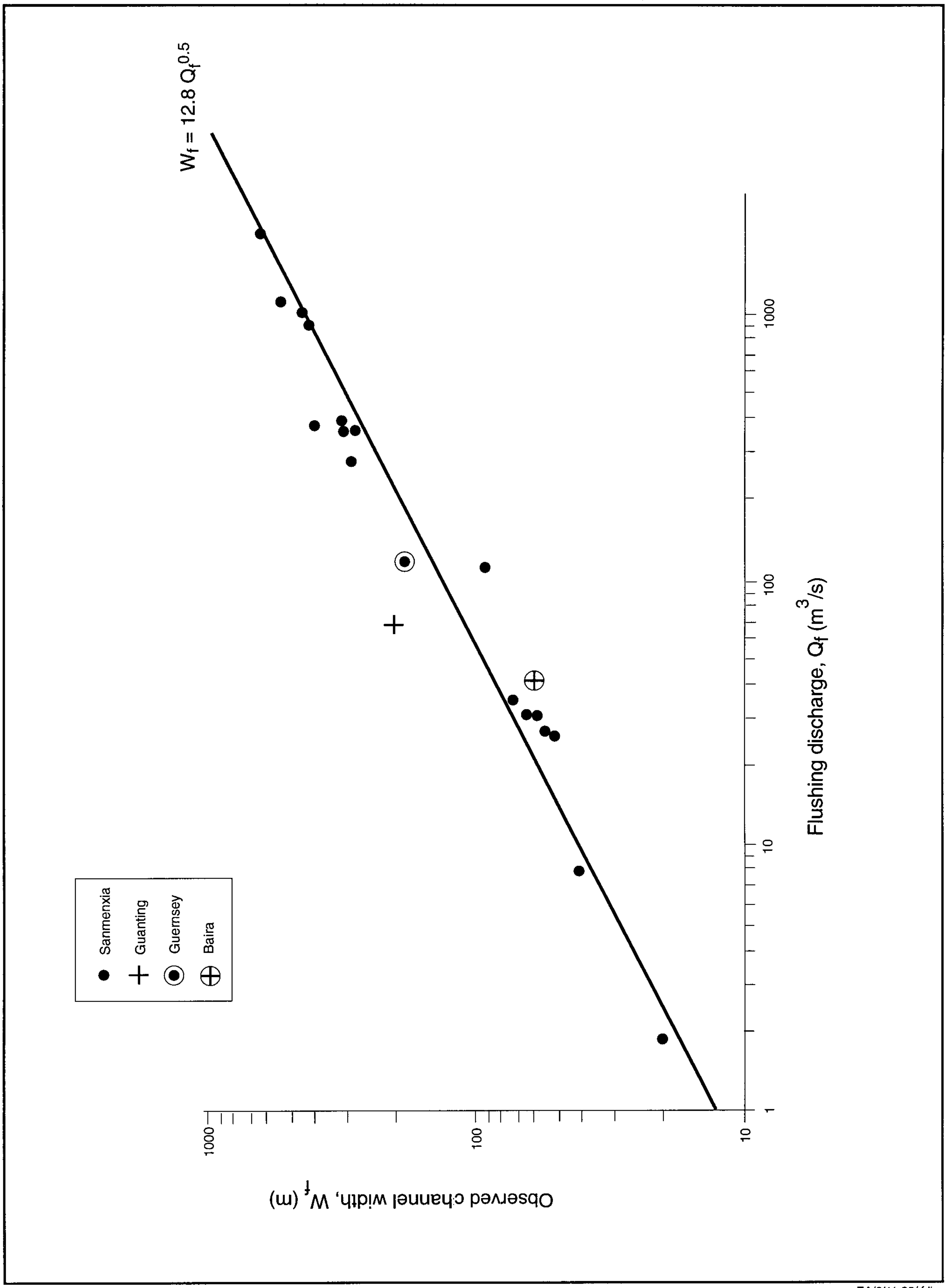
EA/4/11-95/ f.line

Figure 4 Bed elevations in Ichari reservoir



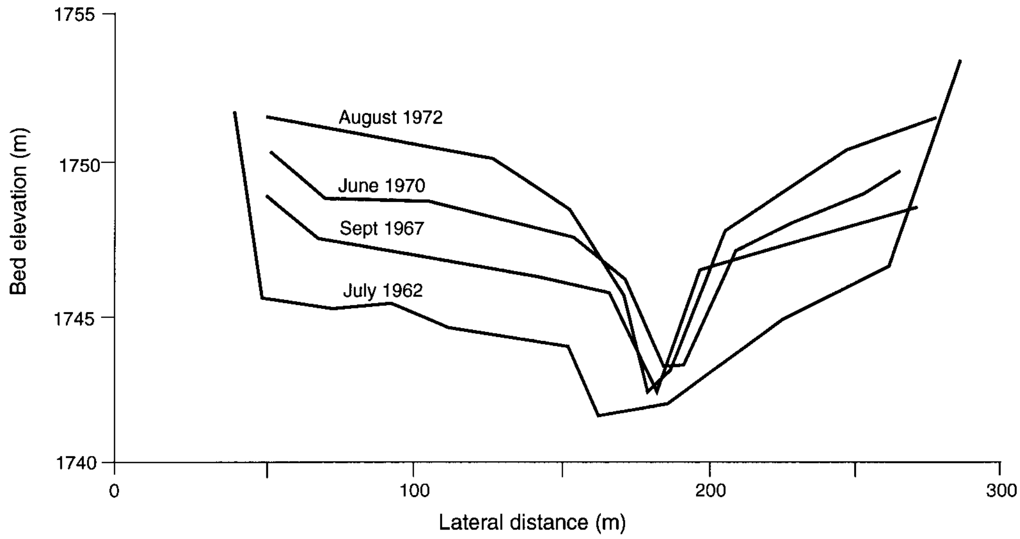
EA/5/11-95/ f.line

Figure 5 Sediment transport capacity of flushing flow in a reservoir, Tsinghua University method, Chinese data used

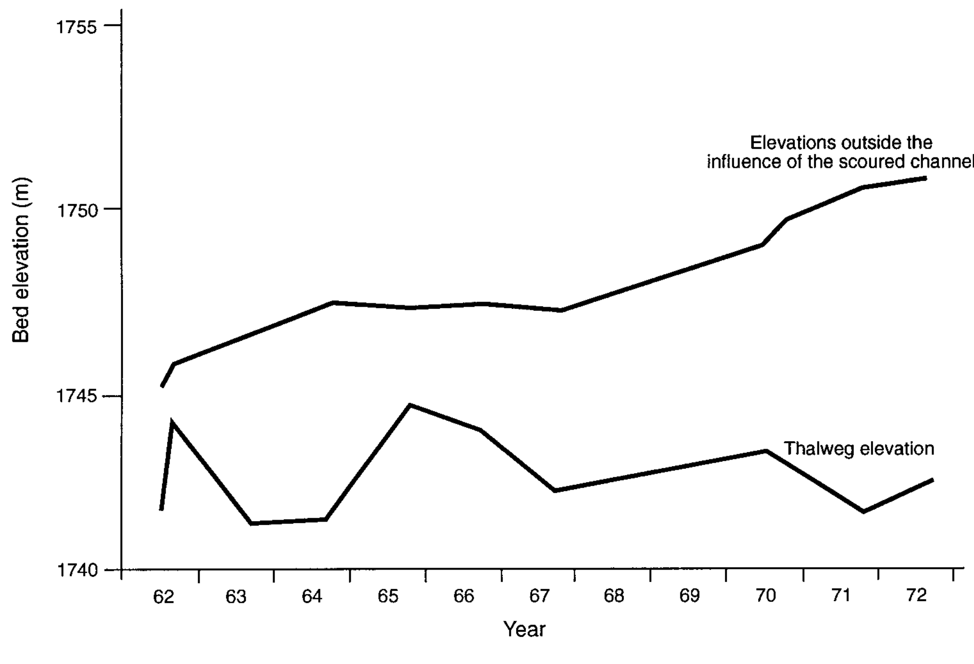


EA/6/11-95/ f.line

Figure 6 Widths formed in reservoir deposits by flushing flows



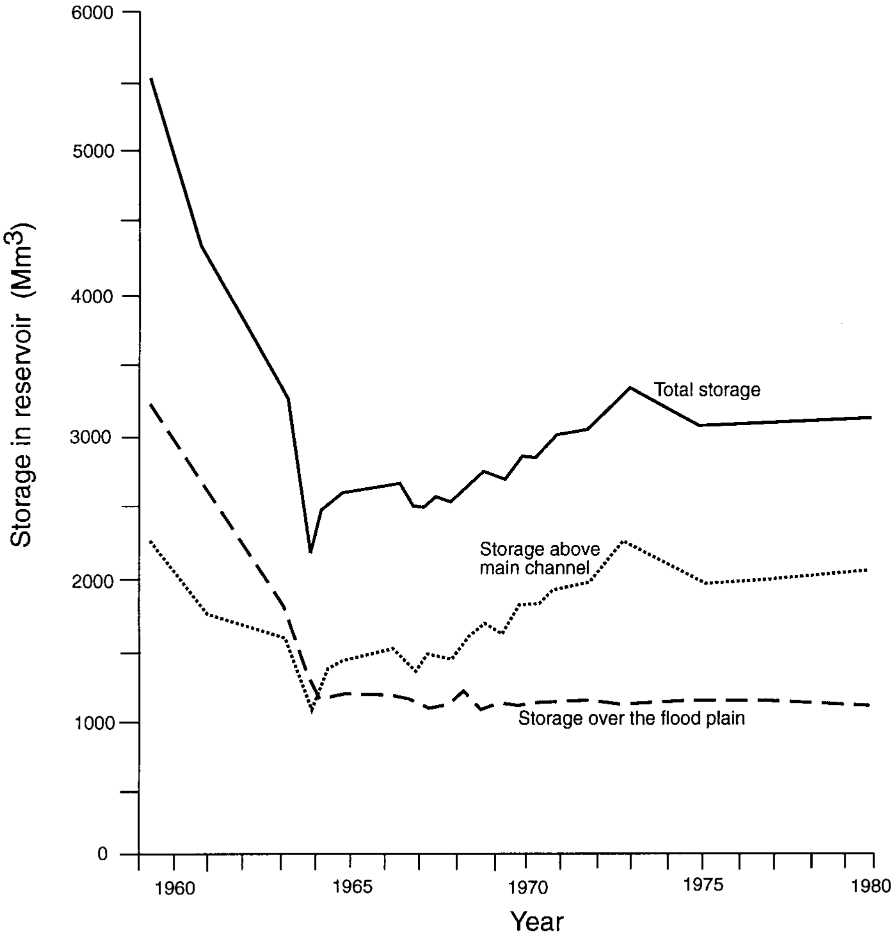
(a) Cross sections showing channel formed by flushing



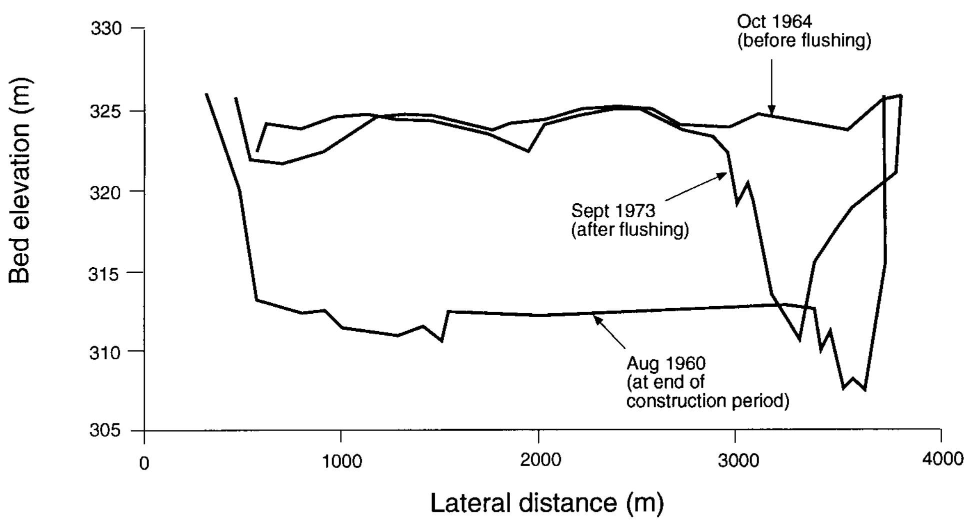
(b) Variation of elevation with time

EA/7/11-95/ f.line

Figure 7 Sediment deposition pattern in the Heisonglin reservoir, 180m upstream from dam



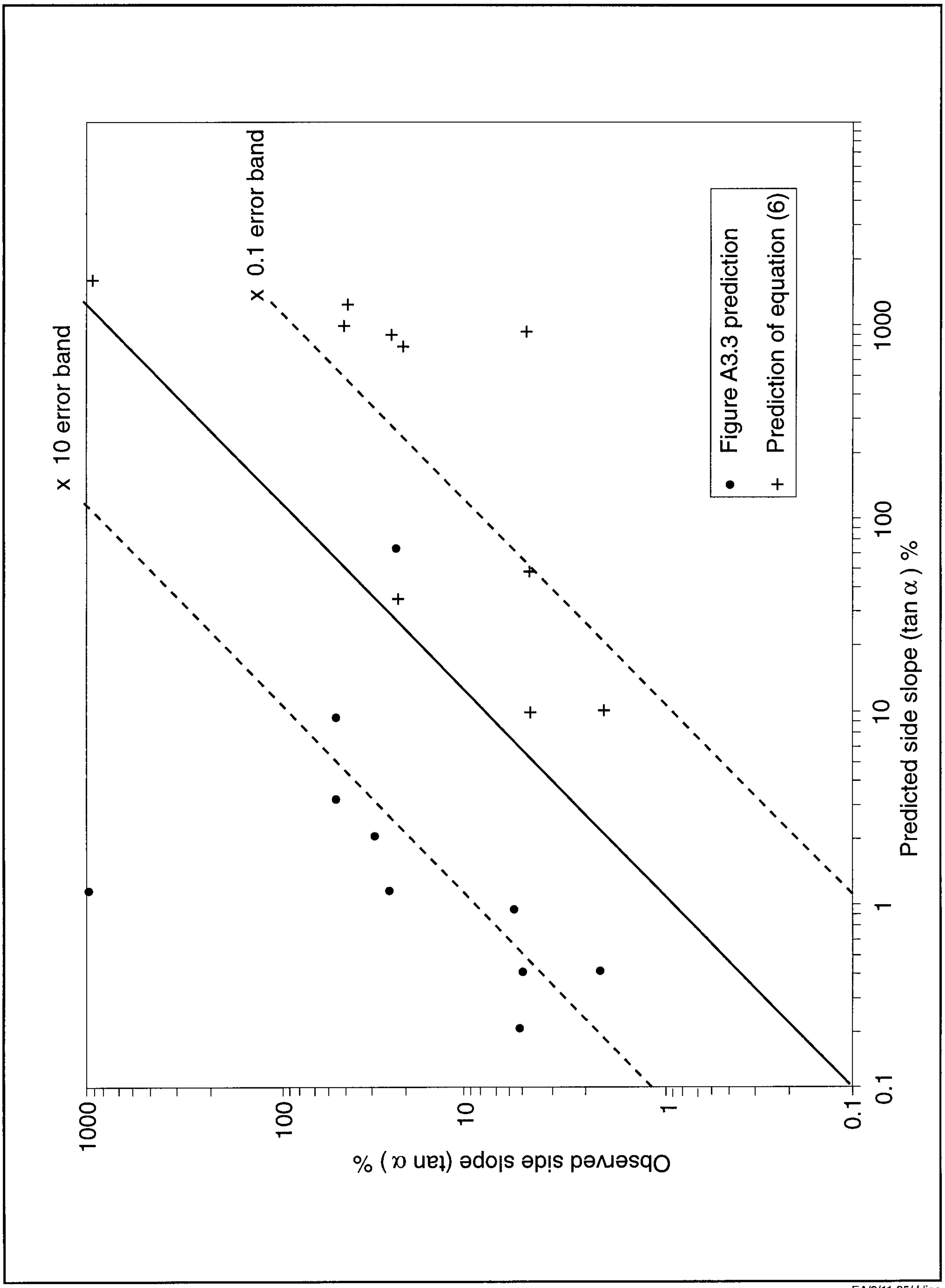
(a) Storage changes



(b) Bed elevations at a cross section

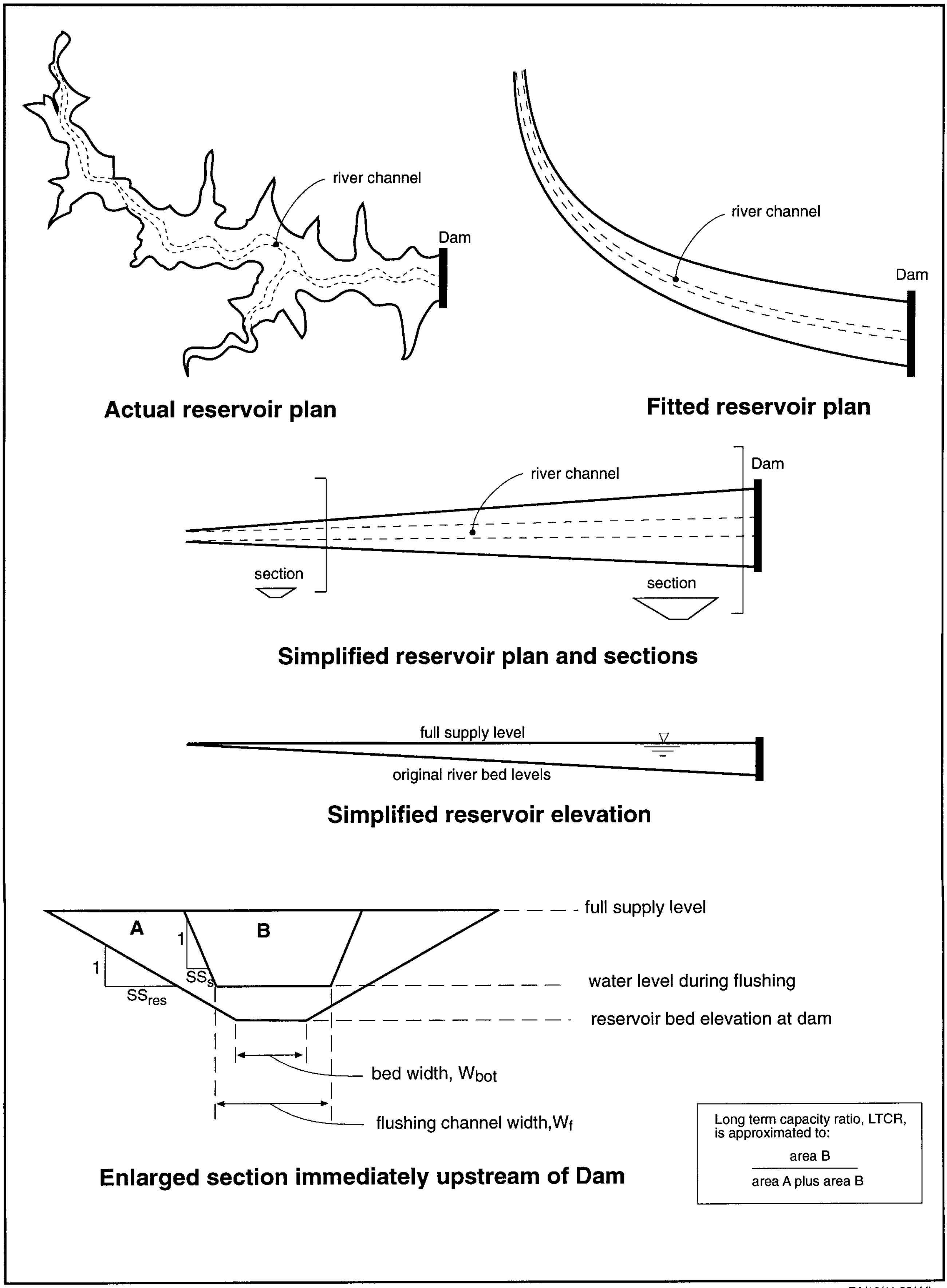
EA/8/11-95/ f.line

Figure 8 Deposition and scour in the Sanmenxia reservoir



EA/9/11-95/ f.line

Figure 9 Comparison between observed and predicted side slopes in reservoir deposits after flushing



EA/10/11-95/ f.line

Figure 10 Simplified reservoir geometry for application of capacity criterion

Appendices

Appendix 1

Numerical model simulations of flushing without full drawdown

Appendix 1 Numerical model simulations of flushing without full drawdown

When low level outlets in a dam are first opened large flow velocities are developed in the immediate vicinity of the outlet. Sediment deposits are scoured from a region close to the outlets but flow velocities further away from the outlets are small and hence no scour occurs. White and Bettess (1984) investigated flushing before complete drawdown by applying a simple inviscid flow model. The reservoir geometry considered was a flat horizontal bed, with an outlet specified as a sink, and the criterion for effective flushing was that the velocity of the flow near the bed should exceed 0.1m/s. Their results have been reproduced as Figure 1 (in the main report).

The purpose of this appendix is to confirm White and Bettess's results with numerical model simulations.

A three dimensional model based on the PHOENICS computational fluid dynamics code was used. The model simulates flow, turbulence, and boundary effects, by solving the Navier-Stokes equations for fluid flow on a numerical grid of cells in three dimensions (Atkinson, 1995). The code used has been applied previously to the flow in lakes and reservoirs (Svenson, 1985 and Neve and Gusbi, 1991). Turbulence was simulated using the k-epsilon turbulence model which has wide acceptance and gives accurate results in similar applications (Rodi, 1984).

The geometry that was modelled is shown in Figure A1.1. The figure also shows a plot of the variation in bed shear stress along the reservoir centreline, where bed shear was greatest. (Shear stress was computed in the model using an assumed bed roughness height of 1m. The choice of roughness height adopted is justified later.)

The bed shear stress required to produce significant erosion of deposited sediments depends on the size range of the sediment deposits. In reservoir deposits fine material and coarse material may co-exist in horizontal layers, or may be intermixed. To be effective, flushing must remove consolidated sediments in the cohesive size range, for which a much larger tractive force is needed for re-entrainment than to prevent deposition (Mahmood 1987). An estimate of critical shear stress for fine sediments can be derived from research into silt movement in estuaries. This indicates that there is a relationship between the density of silt deposits and the shear stress at a threshold for erosion (HR Wallingford, 1992).

If it is assumed that annual flushing is being considered, and so the deposit age is one year, then Lane and Koelzer's (1953) method predicts a minimum density of 481kg/m^3, close to the minimum in situ density of 500kg/m^3 reported for Indian reservoirs by Chandra (1986).

The general formula suggested in HR Wallingford (1992) for the erosion threshold is:

$$\tau_{cr} = 0.0012 \ \rho^{1.2} \qquad \text{(A1)}$$

where τ_{cr} is the critical bed shear stress and
ρ is density in kg/m^3

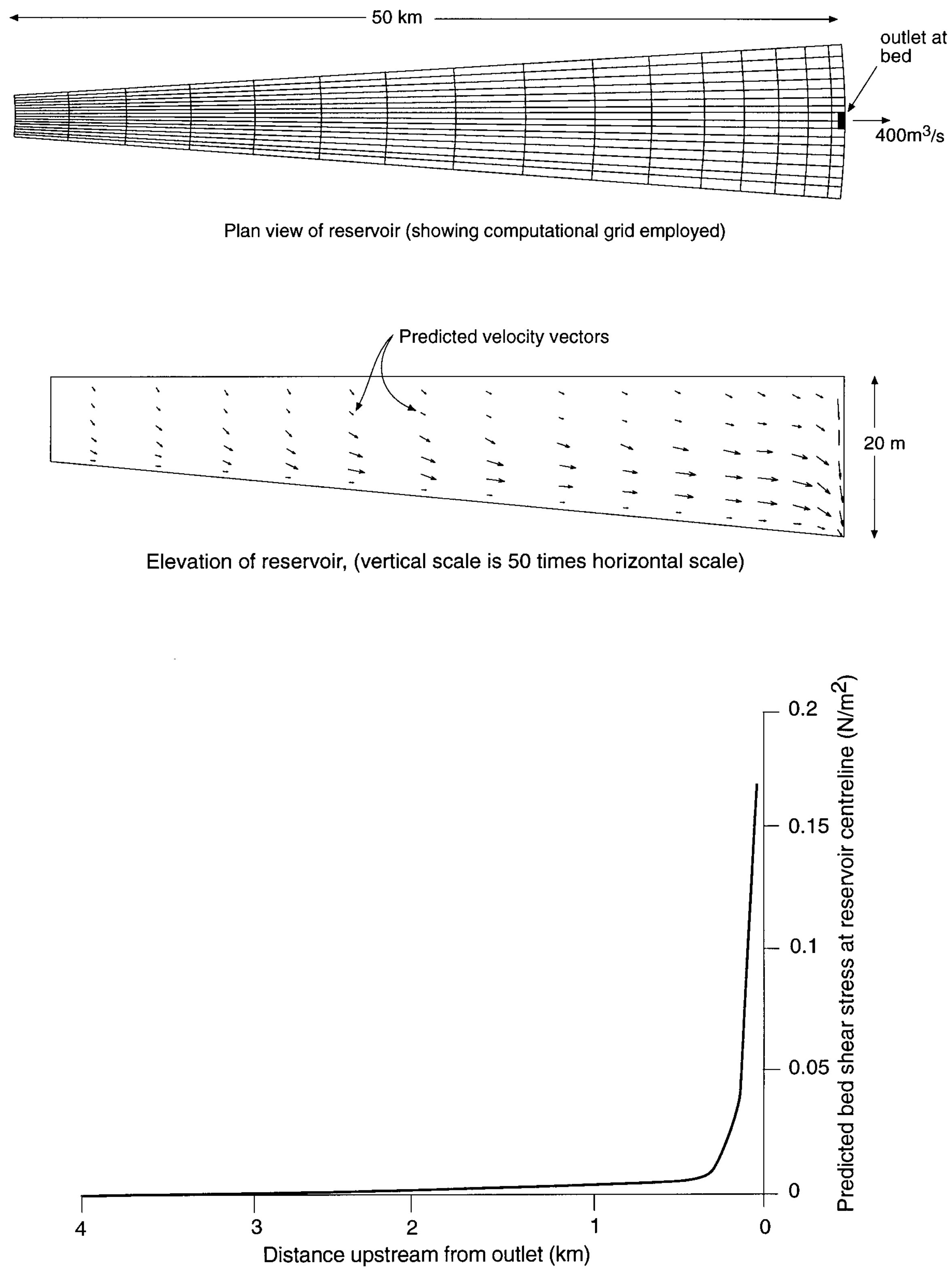
Equation A1 yields a minimum shear stress value for erosion of $2N/m^2$. This value appears low when compared with Mahmood's observation that significant erosion commences in the shear stress range of 5 to $10N/m^2$ (Mahmood, 1987). Therefore $2N/m^2$ has been taken because it will produce conservatively large values for the extent of scour.

Figure A1.1 shows that for the reservoir geometry tested, the minimum shear stress for erosion of $2N/m^2$ was not exceeded in the bulk of the reservoir. The shear stress would exceed that threshold very near to the outlet, but this was so close to the dam that it was not within the resolution of the model, which had a cell sizes near the outlet of about 30m.

White and Bettess' method, Figure 1 in the main report, gives a scour limit of about 60m for the conditions tested in the numerical model. The model predicts bed shear stress at 60m of $0.16N/m^2$, which is only 8% of the threshold shear value derived above. Similar results for other conditions confirm that Figure 1 will provide optimistic values for the scour limit.

In conclusion, Figure 1 of the main report can be used to make a conservatively large estimate of the extent of scour during flushing without drawdown. In most cases it will indicate that such flushing will be too localized in its effect to reclaim significant storage capacity.

Finally, an observation given by Scheurlein (1987) is worth reporting. Scheurlein observed that a funnel shaped crater develops upstream from the low level outlets, and that its slope is similar to the angle of repose for that soil. For quartz sand the angle of repose is about 30^o and it will be less for poorly consolidated deposits. The angle of repose is unlikely to be sufficiently shallow to cause large areas upstream from the dam to be within Scheurlein's 'funnel'.



EA/A1.1/11-95/ f.line

Figure A1.1 Predicted bed shear stress in a reservoir of idealized shape

Appendix 2

Estimation of variables to test the Tsinghua University Method for sediment load prediction

Appendix 2 Estimation of variables to test the Tsinghua University Method for sediment load prediction

A2.1 Baira Reservoir, India

The data were derived from the paper by Jaggi and Kashyap (1984).

A discharge of 44m^3/s was estimated from the sediment concentration data and the reported total sediment quantity removed from the reservoir. The width of the eroded channel was taken as 60m, which is the highest value from the cross sections shown, narrower sections were assumed to be due to the gorge narrowing near the dam site.

The bed slope was reported as 0.02 .

The high sediment concentrations during the first 4 hours of flushing were used. The sudden drop in concentration at 4 hours was assumed to be due to the reservoir bed elevations reaching the original river bed elevations. Subsequent sediment loads were therefore assumed to be limited by the sediment supply from side slope slumping in the empty reservoir.

There was no information on the sediment sizes.

Flushing was performed 18 months after impoundment.

A2.2 Guernsey Reservoir, USA

Data are given in Jarecki and Murphy (1963).

Free flow did not extend right down the reservoir during flushing, so data were taken from station V rather than the dam itself. Data were taken for conditions on the day when sediment concentrations rose appreciably as water levels were drawn down, concentrations later dropped and this was probably due to the removal of the freshly deposited sediment. The days chosen were then: 13th July 1960, 26th July 1961 and 29th July 1962.

The discharges were read from Table 2 and the sediment concentrations from Table 1 of Jarecki and Murphy. The channel slope was estimated from their Figure 3.

The widths were derived from Equation 3 of this report, which was developed using data from the Guernsey reservoir, see Section (2.4).

Sediment deposits in the reservoir were largely silts and clays (80%).

Impoundment of Guernsey reservoir took place in 1927, while the first flushing was attempted 33 years later in 1960. Thalweg elevations were still appeared to be dropping year by year at the end of the period reported: 1962.

A2.3 Ichari Reservoir, India

The data were derived from Bhargava et al (1987).

Bhargava et al report that free flow flushing was attempted on just one day, in 1981, when the sediment concentration produced was 91 000ppm.

The discharge on that day is not given, but we may assume that it was appreciably more than the annual mean discharge of about 150m^3/s and less than the peak discharge for that year 1623m^3/s. Computations were made for discharges of 400m^3/s and 1 000m^3/s.

The channel slope was estimated from Figure 2 (reproduced as Figure 4 in this report) and the width was taken as 83m using Figure 1 in Bhargava et al (1987).

Although no size grading curves are given, the sediment probably consisted largely of sand because the bed load was in some years more than 10% of the total load and the maximum size entering the power intake was 0.5mm.

Flushing of some kind appeared to be attempted more than once each year, however consolidation effects can be expected to have little significance due to the predominance of sand in the deposits.

A2.4 Zemo-Afchar Reservoir, in the former USSR

Data has been taken from IRTCES (1985).

It is reported that the most active erosion occurred during the first 8 to 10 hours of flushing, therefore only data from flushings lasting less than 10 hours were used. Longer flushings may not have been suitable for comparison with a sediment transport predictor as sediment supply may have been a factor. Flushings on 8th November 1950 and 12th February 1961 were therefore used.

Discharges and sediment concentrations were taken from Table 7 on page II-39 of IRTCES (1985). Channel slope was estimated from the range in water surface elevations at the dam (17m) and reservoir length (8km).

Channel widths are not reported, estimates from Equation 3 of this report were used. This implies an assumption that the gorge did not restrict channel widths despite the full drawdown of the reservoir to form a channel at the original river bed.

No information on sediment sizes is reported, but sediment type 1 or 2 can be assumed due to the larger flows.

Flushing was carried out approximately every six months.

Appendix 3

Prediction of the side slope which will develop in exposed reservoir deposits

Appendix 3 Prediction of the side slope which will develop in exposed reservoir deposits

An analysis for predicting side slopes can be based on the simplifying assumption of a long slope, so that the downslope gravity forces can be equated with a frictional force parallel to the slope. A sketch showing the force balance is given in Figure A3.1.

If the deposit consists of pure sand, and there are no pore pressures (which occurs when deposits are submerged), then the force balance yields $\alpha = \phi$ where α is the angle of slope which is just stable, and ϕ is the angle of friction for the sand. ϕ has a value of around 40^o for quartz sand, corresponding to slopes of between 1:1 and 1:1.5.

Concepts of friction can also be applied to cohesive soils (for a discussion on this see Bolton, 1979, chapter 5), however the force balance must include the effect of pore water pressures. The total compressive pressure within the deposit at any point is termed the total stress, it is partly borne by the pore water pressure, and the remaining pressure is termed the effective stress. Effective stress is related to the forces between particles in a soil, so the more compact a soil the greater the effective stress which it can bear and so the steeper the slope at which it lies.

As a deposit consolidates in a reservoir under its own weight, pore water is squeezed out from between the particles, and both the effective stress and density increase. Numerical models of self consolidating sediments in reservoirs and estuaries assume a unique relationship between density and effective stress (Wooldridge, 1984, Appendix 4, and Ginger, 1987). The relationship is derived, for a particular sediment, from laboratory tests in a consolidation column, such tests are described by Been and Sills (1981), and Ginger (1987).

Figure A3.2 shows a mean curve drawn through the test results derived at HR Wallingford (HR Wallingford, 1990) and by Been and Sills (1981), all data apply to estuarine sediments. The curve has been extended up to densities for fully consolidated silts and clays, using the typical range of water contents found at the Atterberg test liquid limit. Bolton (1979) states that soil shearing strength at the Atterberg liquid limit is roughly $2kN/m^2$, which for a typical friction angle of 30^o is equivalent to an internal effective stress of $3.5kN/m^2$.

The relationship of Figure A3.2 between effective stress and dry density can be used in the side slope analysis reported above. The force balance, per unit area on the slope, is

$$\rho_{bulk} \ x \ g \ \sin\alpha = \sigma' \ \tan\phi \qquad \text{(A3.1)}$$

where
- ρ_{bulk} is bulk density,
- x is deposit depth,
- g is gravitational acceleration, and
- σ' is effective stress.

Slopes at the limit of stability, as predicted by Equation A3.1 with ϕ taken as 30^o and the relationship of Figure A3.2 assumed, are plotted on Figure A3.3. The figure also includes predictions of the stable slope before a deposit is exposed by reservoir drawdown, for which a submerged bulk density is used in the force balance. Slopes which are just at the limit of stability when submerged appear to be approximately five times steeper than the equivalent slopes when the deposits are exposed.

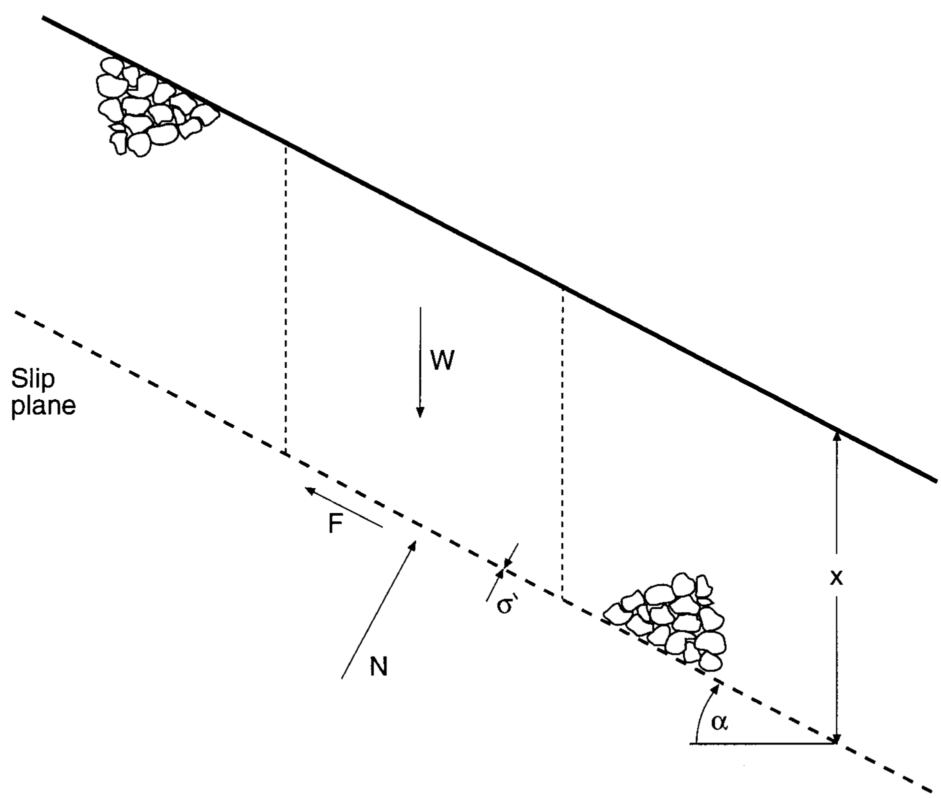
Figure A3.3 also shows a prediction equation for submerged slopes presented by Teisson (1991), which he attributed to Migniot (1981). The equation gives similar predictions to the force balance method when the deposit depth is around 0.1m.

Thus there are two methods for side slope prediction which can be proposed: the prediction chart of Figure A3.3, and Migniot's equation with the multiplying constant reduced fivefold (to account for the difference between submerged and exposed deposits):

$$\tan \alpha = \frac{31.5}{5} \rho_d^{4.7} \qquad \text{(A3.2)}$$

where

ρ_d is dry density in t/m^3.



weight W $= \rho_{bulk} \times g$ (N/m²)

normal force N $= W \cos \alpha$

friction force F $= N \tan \phi$ if no pore water pressures

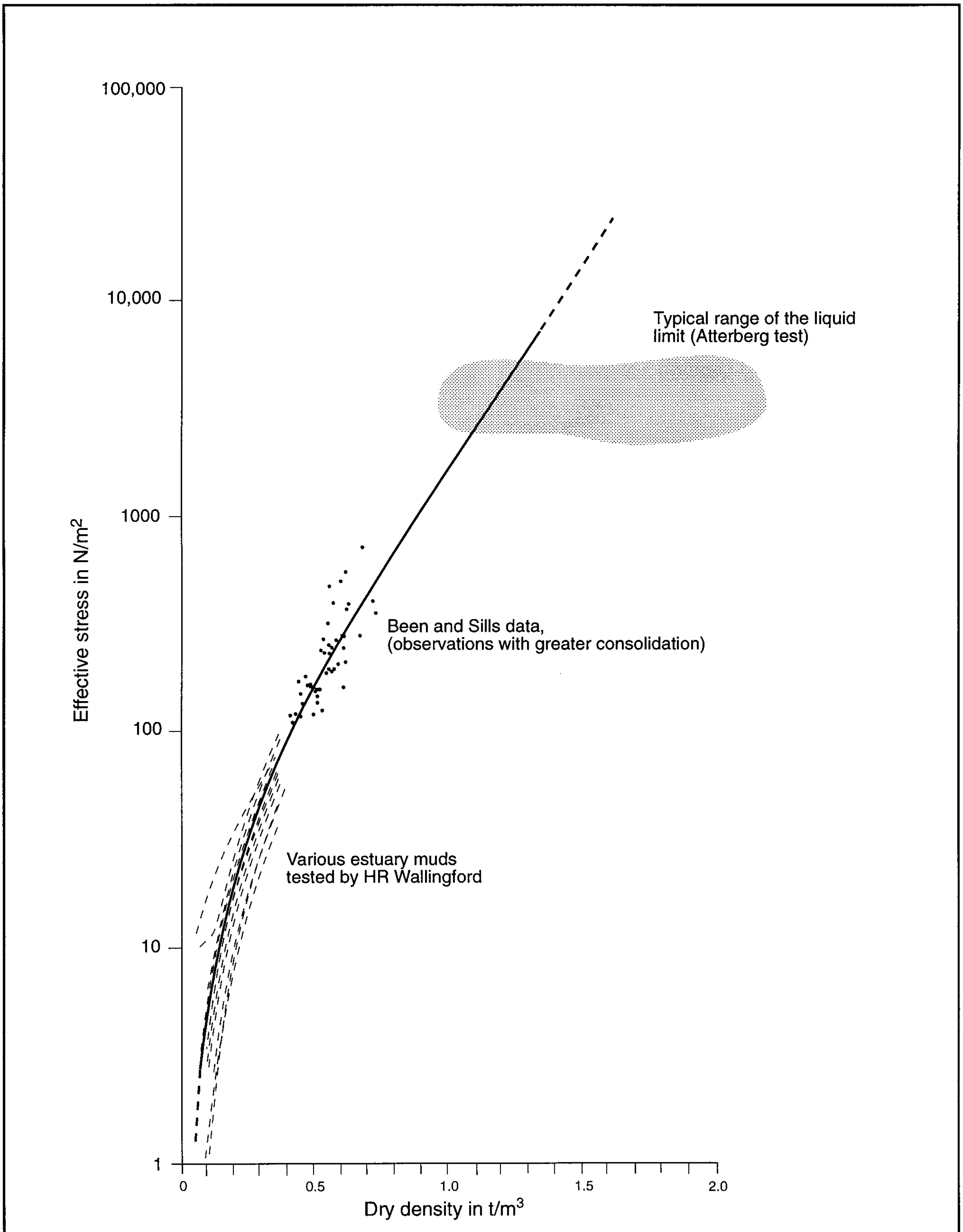
ϕ is angle of friction

$F = \sigma` \tan \phi$, where $\sigma`$ is effective stress

force balance gives $F = W \sin \alpha$

EA/A3.1/11-95/ f.line

Figure A3.1 Force balance on a side slope



EA/A3.2/11-95/ f.line

Figure A3.2 Effective stress in a soil related to density

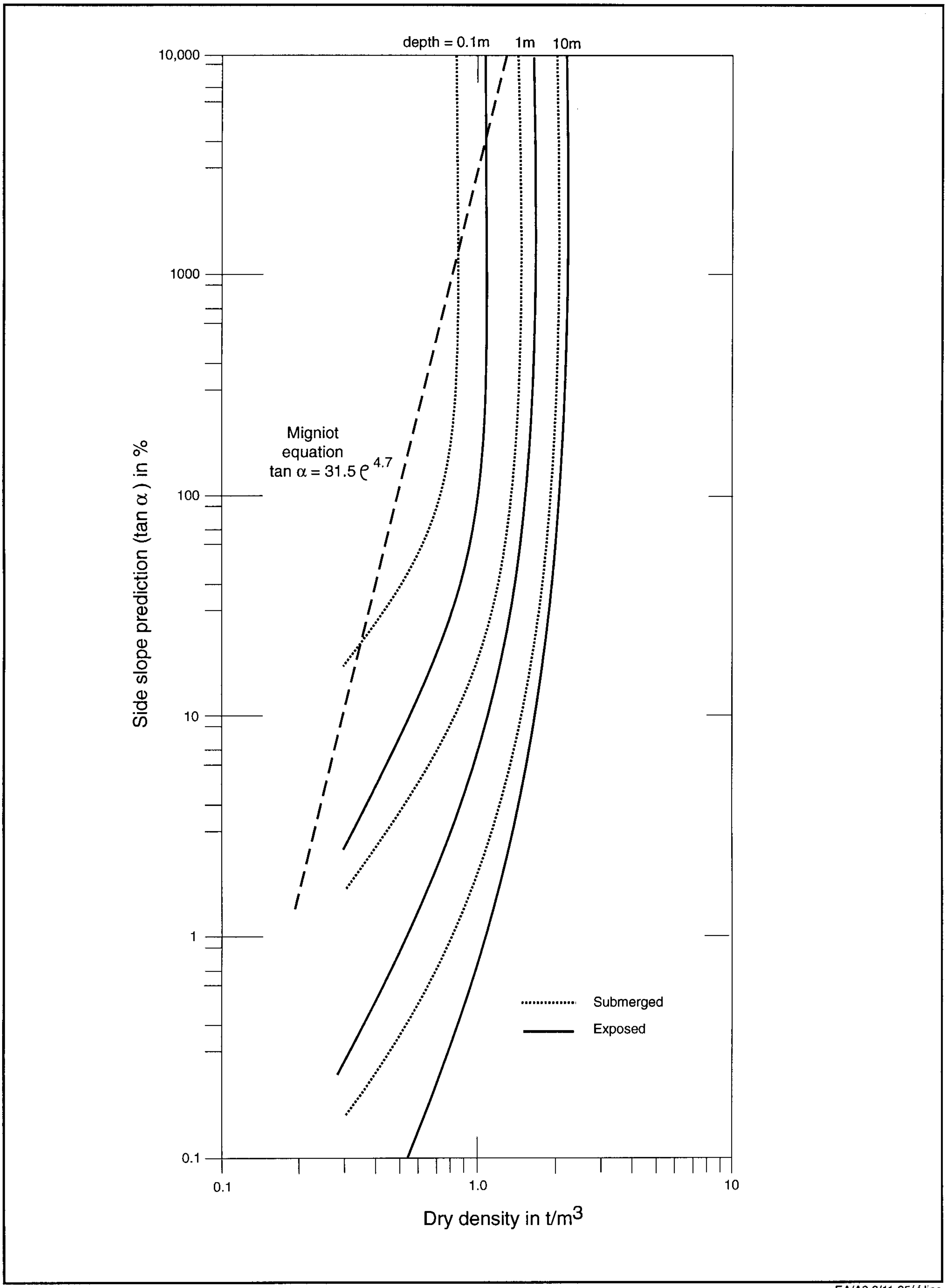


Figure A3.3 Predicted slopes at the limit of stability

Appendix 4

Definition and calculation of ratios used in the feasibility criteria

Appendix 4 Definition and calculation of ratios used in the feasibility criteria

The ratios defined in the main text of the report, and listed in this Appendix, can be calculated using the following parameters:

C_o - the original storage capacity of the reservoir (m^3)

L - reservoir length (m)

El_{max} - elevation of top water level (m)

El_{min} - the minimum bed elevation, which is usually the river bed elevation immediately upstream from the dam (m)

W_{bot} - a representative bottom width for the reservoir (m)

SS_{res} - a representative side slope for the reservoir

SS_s - a representative side slope for the deposits exposed during flushing, it can be derived using Equation 6 with density computed using Lane and Koelzer's (1953) method (the method is reported by Vanoni, 1975)

V_{in} - mean annual inflow volume (m^3)

M_{in} - mean annual sediment inflow (tonnes)

Q_f - representative discharge passing through reservoir during flushing (or sluicing if appropriate) (m^3/s)

T_f - duration of flushing (days)

El_f - water surface elevation at the dam during flushing, derived from Q_f, outlet sill elevation and outlet design (m)

Type - sediment type for the Tsinghua University method for predicting sediment loads in flushing flows

A4.1 Sediment Balance Ratio

The sediment balance ratio, SBR, is defined

$$SBR = \frac{M_f}{M_{dep}}$$

where

M_f - the mass of sediment flushed annually from the reservoir, and
M_{dep} - the mass of sediment which deposits annually in the reservoir

The sediment masses M_f and M_{dep} are mean values which would apply to a typical year.

The calculation of SBR is performed as follows:

i) Derive a representative reservoir width in the reach upstream from the dam at the flushing water surface elevation:

$$W_{res} = W_{bot} + 2 \; SS_{res} \; (El_f - EL_{min})$$

ii) Calculate the flushing width using Equation 3:

$$W_f = 12.8 \; Q_f^{0.5}$$

iii) Take the minimum of W_{res} and W_f as the representative width of flow for flushing conditions, W.

iv) Estimate the longitudinal slope during flushing

$$S = \frac{El_{max} - El_f}{L}$$

v) Determine the parameter ψ in the Tsinghua University method for sediment load prediction

ψ = 1600 for fine loess sediments

ψ = 650 for $D_{50} < 0.1$mm

ψ = 300 for $D_{50} \geq 0.1$mm

ψ = 180 if the flushing discharge is low (say less than $50m^3/s$)

vi) Calculate the sediment load during flushing

$$Q_s = \psi \frac{Q_f^{1.6} \; S^{1.2}}{W^{0.6}}$$

Reduce Q_s by a factor of 3 for reservoirs where conditions are dissimilar to those in China.

vii) Determine the sediment mass flushed annually (86,400 is the number of seconds in a day)

$$M_f = 86{,}400 \; T_f \; Q_s$$

viii) If the reservoir is sluiced, ie a long draw down period to pass the high sediment loads without deposition, then a trapping efficiency, TE, of 100% should be selected, otherwise predict TE using Brune's curves (Brune, 1953, copied here as Figure A4.1) and the values for C_o and V_{in}.

ix) Calculate the mass depositing annually which must be flushed.

$$M_{dep} = M_{in} \; TE / 100$$

x) Determine SBR

$$SBR = \frac{M_f}{M_{dep}}$$

A4.2 Long Term Capacity Ratio

The long term capacity ratio, LTCR, is defined using a simplified reservoir geometry shown in Figure 10 of the main report. Firstly the reservoir is assumed to approximate to a prismatic shape with trapezoidal cross sections. Therefore, a reservoir cross section at the dam site is representative of conditions within the reservoir. At this section, the ratio of cross sectional area for the channel formed by flushing to the original reservoir cross sectional area is determined. The ratio is taken to be indicative of the capacity ratio for the entire reservoir.

LTCR can be calculated from these parameters: EL_{max}, El_{min}, W_{bot}, SS_{res}, SS_s and El_f used as input to the procedure, from W_{res} and W derived in steps (i) and (iii) of the SBR calculation.

The calculation of LTCR is performed as follows:

i) Determine the scoured valley width at the top water level

$$W_{tf} = W + 2\ SS_s\ (El_{max} - El_f)$$

ii) Determine the reservoir width at this elevation for the simplified geometry assumed

$$W_t = W_{bot} + 2\ SS_{res}\ (El_{max} - El_{min})$$

iii) If $W_{tf} \leq W_t$ then the reservoir geometry does not constrict the width of the scoured valley and so scoured valley cross sectional area, A_f, is calculated

$$A_f = \frac{W_{tf} + W}{2} (El_{max} - El_f)$$

iv) However if $W_{tf} > W_t$ then the scoured valley will be constricted as shown in Figure A4.2

Referring to the figure

$$h_m = \frac{W_{res} - W}{2\ (SS_s - SS_{res})}$$

$$h_l = El_{max} - El_f - h_m$$

$$h_f = El_{max} - El_f$$

and A_f is the sum of area C, areas D and areas E

$$A_f = W\ h_f + (h_f + h_l)\ h_m\ SS_s + h_l^2\ SS_{res}$$

v) Estimate the reservoirs cross sectional area

$$A_r = \frac{W_t + W_{bot}}{2} (El_{max} - El_{min})$$

vi) Determine LTCR

$$LTCR = \frac{A_f}{A_r}$$

A4.3 Drawdown Ratio

This ratio, termed DDR, is defined

$$DDR = 1 - \frac{El_f - El_{min}}{El_{max} - El_{min}}$$

A4.4 Sediment Balance Ratio with Full Drawdown

This ratio, SBR_d is defined and calculated in the same manner as SBR, Section (A4.1). The only difference is in steps (i) and (iv) which use El_f; its value for full drawdown should be used. That is

$$El_f = El_{min}$$

A4.5 Flushing Width Ratio

The flushing width ratio, FWR, is

$$FWR = \frac{W_f}{W_{bot}}$$

where

W_f is calculated in step (ii) of Section (A4.1), and
W_{bot} is an input parameter

A4.6 Top Width Ratio

The top width ratio for a flushed reservoir, TWR, is calculated:

$$TWR = \frac{W_{td}}{W_t}$$

where

W_{td} is the value for scoured valley width at top water level if complete drawdown is assumed, and

W_t is the reservoir top width calculated in Section (A4.2), step (ii).

W_{td} and hence TWR are calculated as follows:

i) Determine W_{bf} the bottom width of the scoured valley at full drawdown. It is the minimum of W_{bot} and W_f which are defined in Section (A4.1).

ii) Calculate W_{td} from the side slope SS_s which is discussed in Section (A4.2)

$$W_{td} = W_{bf} + 2 \; SS_s \; (El_{max} - El_{min})$$

Both El_{max} and El_{min} are defined in the input to the calculations of Section (A4.1).

iii) Determine TWR

$$TWR = \frac{W_{td}}{W_t}$$

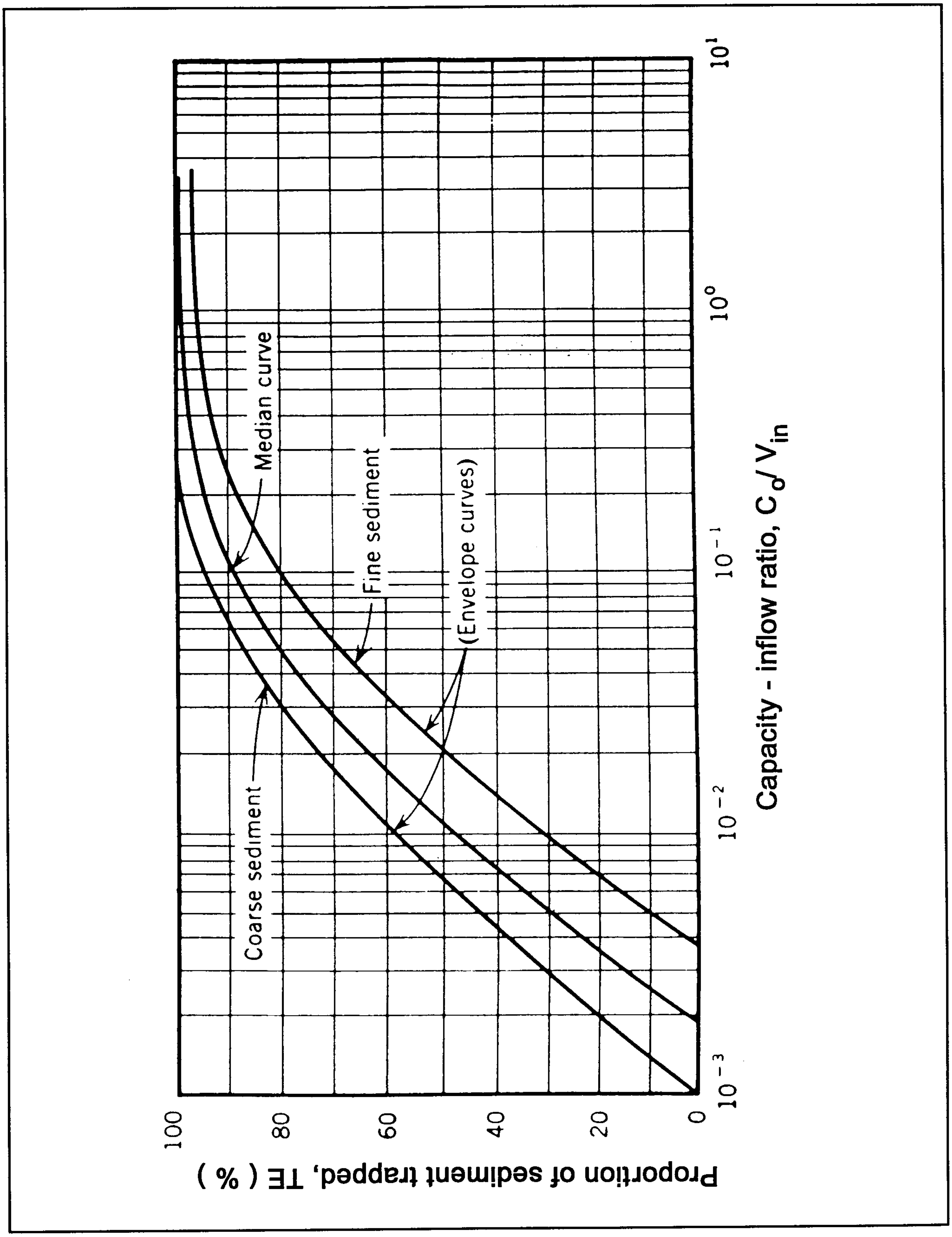
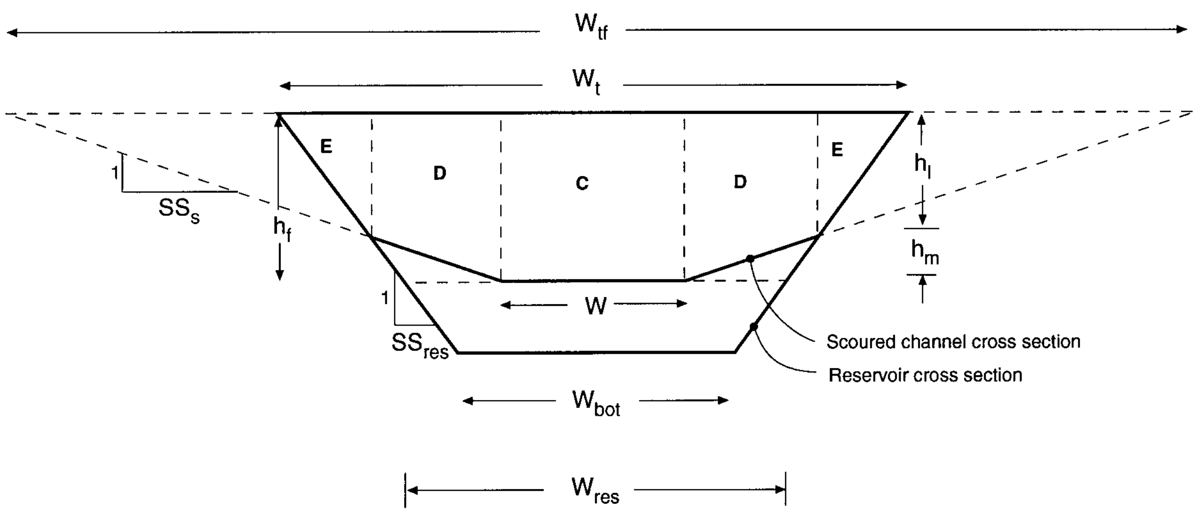


Figure A4.1 Brone's curve for estimating reservoir tracking efficiency



ED/A4.2/11-95/ f.line

Figure A4.2 Cross section immediately upstream of dam for simplified reservoir geometry and the scoured channel constricted by reservoir sides

Appendix 5

Example application of the feasibility criteria, Baira reservoir

Appendix 5 Example application of the feasibility criteria, Baira reservoir

The following parameters are used as input, they have been taken from Table A6.1 in Appendix 6:

$C_o = 9.6Mm^3$

L = 4,100m

$El_{max} = 1123m$

$El_{min} = 1072m$

$W_{bot} = 25m$

$SS_{res} = 1 : 2$

$SS_s = 1 : 3.3$

$V_{in} = 1,900Mm^3$

$M_{in} = 300,000t$

$Q_f = 44m^3/s$

$T_f = 1.29$ days (31 hours)

El_f is calculated from outlet sill elevation, 1072 + 16.4 = 1088.4m, plus the water depth above that sill at the flushing discharge, $Q_f=44m^3/s$:

$$El_f = 1088.4 + \frac{(Q_f/C)^2}{2\,g}$$

where C is the outlet rating constant, $C=24m^2$

$$El_f = 1088.4 + \frac{(44/24)^2}{19.62} = 1088.57m$$

Sediment type for the Tsinghua University method for predicting sediment loads in flushing flows is taken as III due to the relatively low flushing discharge.

A5.1 Sediment Balance Ratio

The calculation of SBR is:

i) The representative reservoir width at the flushing water surface elevation is:

$$W_{res} = 25 + 2 \quad 2 \; (1088.57 - 1072)$$

$= \quad 91.28m$

ii) Flushing width is:

$W_f = 12.8 \quad 44^{0.5}$

$= \quad 84.9m$

iii) The minimum of W_{res} and W_f is the representative width for flushing conditions is:

$W = 84.9m$

iv) Longitudinal slope during flushing is:

$$S = \frac{1123 \;-\; 1088.57}{4100}$$

$S = 0.008398$

v) The parameter ψ is 180, the value for low flushing discharge.

vi) The sediment load during flushing is:

$$Q_s = 180 \quad \frac{44^{1.6} \quad 0.008398^{1.2}}{84.9^{0.6}}$$

$= \quad 17.24t/s$

Divide by 3 because Baira reservoir does not have conditions typical of those found in China: $Q_s = 5.75t/s$

vii) The sediment mass flushed annually is:

$M_f = 86{,}400 \quad 1.29 \quad 5.75$

$= \quad 641{,}000t$

viii) Brune's median curve is selected due to uncertainties in the sediment size (Figure A4.1). The capacity-inflow ratio, C_o / V_{in}, is 9.6/1900 = 0.005, which gives TE = 30%.

ix) The mass depositing annually is then:

$M_{dep} = 0.30 \quad 300{,}000$

$= \quad 90{,}000t$

x) Determine SBR

$$SBR = \frac{641{,}000}{90{,}000}$$

$= \quad 21.3$

This value is acceptable, it exceeds the required value comfortably.

A5.2 Long Term Capacity Ratio

i) The scoured valley width at the top water level is:

$$W_{tf} = 84.9 + 2 \ 3.3 \ (1123 - 1088.57)$$

$$= 312.1\text{m}$$

ii) The reservoir width at this elevation is:

$$W_t = 25 + 2 \ 2 \ (1123 - 1072)$$

$$= 229\text{m}$$

iii) and

iv) $W_{tf} > W_t$ so:

$$h_m = \frac{91.28 - 84.9}{2 \ (3.3 - 2)}$$

$$= 2.454\text{m}$$

$$h_l = 1123 - 1088.57 - 2.454$$

$$= 31.98\text{m}$$

$$h_f = 1123 - 1088.57$$

$$= 34.43\text{m}$$

$$A_f = 84.9 \ 34.43 + (34.43 + 31.98) \ 2.454 \ 3.3 + 31.98^2 \ 2$$

$$= 5{,}506\text{m}^2$$

v) The reservoirs cross sectional area is:

$$A_r = \frac{229 + 25}{2} \ (1123 - 1072)$$

$$= 6{,}477\text{m}^2$$

vi) Hence:

$$\text{LTCR} = \frac{5506}{6477}$$

$$= 0.85$$

This value for long term capacity ratio is good, it indicates that the majority of the original capacity can be maintained in the long term.

A5.3 Drawdown Ratio

DDR is:

$$DDR = 1 - \frac{1088.57 - 1072}{1123 - 1072}$$

$$= 0.68$$

The value for DDR is just below our (arbitrary) threshold of 0.7 as acceptable for successful flushing. However, in view of the high values for the width ratios below and the still fairly high value for this ratio, the criterion can be considered as satisfied.

A5.4 Sediment Balance Ratio with Full Drawdown

The calculation of Section A5.1 is repeated with El_f now set to 1072m.

i) The reservoir width is now for the minimum elevation:

$$W_{res} = 25m$$

ii) Flushing width is still: W_f = 84.9m.

iii) The minimum of W_{res} and W_f is now 25m.

iv) Longitudinal slope during flushing is:

$$S = \frac{1123 - 1072}{4100}$$

$$S = 0.01244$$

v) The parameter ψ is still 180.

vi) The sediment load during flushing is now:

$$Q_s = 180 \frac{44^{1.6} \quad 0.01244^{1.2}}{25^{0.6}}$$

$$= 57.5t/s$$

Divide by 3 as before, Q_s = 19.2t/s

vii) The sediment mass flushed annually is:

$$M_f = 86{,}400 \quad 1.29 \quad 19.2$$

$$= 2{,}140{,}000t$$

viii) and

ix) TE = 30%, giving M_{dep} = 90,000t, as before.

x) SBR_d is then:

$$SBR_d = \frac{2,140,000}{90,000}$$

$$= 23.8$$

As for SBR in Section A5.1, this value is acceptable as it comfortably exceeds the required value.

A5.5 Flushing Width Ratio

The flushing width ratio, FWR, is

$$FWR = \frac{84.9}{25}$$

$$= 3.4$$

The ratio is well above unity and so the criterion is comfortably met.

A5.6 Top Width Ratio

i) W_{bf}, bottom width of the scoured valley at full drawdown, is the minimum of W_{bot} (25m) and W_f (84.9m), it is then 25m.

ii) Scoured valley width at the top water level is:

$$W_{td} = 25 + 2\ 3.3\ (1123 - 1072)$$

$$= 361.6m$$

iii) Finally TWR is

$$TWR = \frac{361.6}{229}$$

$$= 1.58$$

Again, this ratio is above unity and the criterion is met.

All the criteria were considered as satisfied. Therefore, on the basis of these calculations, flushing is expected to be successful at this site.

Appendix 6

Tables listing data on the reservoirs where flushing was successful

Table A6.1 Summary data on Baira Reservoir India

Reference:	Jaggi and Kashyap, 1984
Original storage capacity :	1.56Mm^3 dead storage (total storage not given, but the geometry estimated below suggests 9.3Mm^3)
Reservoir length:	4.1km (estimated from dam height and river slope)
Elevation of top water level above river bed at dam :	51m
Representative bottom width :	25m (estimated from Plates A and C)
Representative side slope :	1 : 2 (estimated from photographs)
Annual water inflow :	1900Mm3 (estimated from typical discharges for monsoon and non-monsoon periods)
Annual sediment inflow :	0.3Mt (from siltation after 18 months)
Sill height of outlet relative to base of dam :	16.4m (base of dam elevation was derived from dam height quoted)
Outlet rating constant defined: discharge / (2g water level above sill)$^{0.5}$	24m^2 (derived from rating curves)
Typical flushing discharge :	44m^3/s (derived indirectly from sediment concentrations and sediment loads)
Typical duration of flushing :	31 hours
Sediment type in Tsinghua University method:	No information, type III taken due to low flows
Typical side slope in reservoir deposits after flushing :	1 : 3.3 (Plate C)
Estimated long term capacity :	Close to original (85% of deposited silt removed by first flushing, despite a relatively low discharge)

Table A6.2 Summary data on Gibidem Reservoir, Switzerland

Reference:	Dawans et al, 1982
Original storage capacity:	9Mm^3
Reservoir length:	1.4km
Elevation of top water level above river bed at dam :	113m (assuming top level is 2m dam crest)
Representative bottom width :	6m (estimated from photographs)
Representative side slope :	1 : 1.3 (estimated from dam design)
Annual water inflow :	420Mm^3
Annual sediment inflow :	0.5Mt
Sill height of outlet relative to base of dam :	8m
Outlet rating constant defined: discharge / (2g water level above sill)$^{0.5}$	4m^2 (from discharge capacity at top water level)
Typical flushing discharge :	10m^3/s
Typical duration of flushing :	45 hours
Sediment type in Tsinghua University method:	deposits are non-cohesive granite material, type III taken due to low flows
Typical side slope in reservoir deposits after flushing :	1 : 2 (estimated from photographs)
Estimated long term capacity :	Close to original (no net deposition trend was observed after 10 years of operation)

Table A6.3 Summary data on Gmund Reservoir, Austria

Reference:	Rienossl and Schnelle, 1982
Original storage capacity:	0.93Mm^3
Reservoir length:	0.93km
Elevation of top water level above river bed at dam :	37m
Representative bottom width :	6m (estimate)
Representative side slope :	1 : 3 (chosen to match original storage capacity of 0.93Mm^3)
Annual water inflow :	200Mm^3
Annual sediment inflow :	0.2 Mt before 1967, 0.07 Mt/year after 1967 (an estimate for bulk density of deposits was used to derive these values)
Sill height of outlet relative to base of dam :	3m (elevation of base of dam was estimated from the maximum reservoir depth)
Outlet rating constant defined: discharge / (2g water level above sill)$^{0.5}$	3m^2 (estimate)
Typical flushing discharge :	6m^3/s (derived from mean inflow rate)
Typical duration of flushing :	1 week
Sediment type in Tsinghua University method:	appears to be sands and gravels, type III taken due to relatively low flows
Typical side slope in reservoir deposits after flushing :	1 : 4 (estimated)
Estimated long term capacity :	about 0.8Mm^3 (Figure 9 of the paper. Flushing steadily reduced the sedimentation volume from over 0.2Mm3 to a stable value of about 0.14Mm^3

Comments: After 1967 the upstream Durlassboden reservoir was operated, which reduced the sediment loads entering Gmund and made flushing marginally more effective. The observations given in this table, and the calculations reported in the text of this report, all refer to the period before 1967.

Table A6.4 Summary data on Hengshan Reservoir, China

Reference:	IRTCES, 1985
Original storage capacity:	13.3Mm^3
Reservoir length:	1.0km
Elevation of top water level above river bed at dam :	65m
Representative bottom width :	200m (estimate from photographs)
Representative side slope :	1 : 1 (estimate from photographs)
Annual water inflow :	15.8Mm^3
Annual sediment inflow :	1.18Mt (derived using an estimate for density of deposits)
Water surface elevation relative to base of dam during flushing:	15m (Fig 45)
Typical flushing discharge :	around 2m^3/s (hydrographs given in the reference, show values in range 1.8 to 58m^3/s)
Typical duration of flushing :	a few weeks every two or three years
Sediment type in Tsinghua University method:	$D_{50} \approx$ 0.02mm near dam, becoming coarser remote from dam. Type III taken
Typical side slope in reservoir deposits after flushing :	1 : 18 value quoted for conditions near to the dam
Estimated long term capacity :	about 10Mm^3 (estimated from deposit volumes remaining after flushing)

Table A6.5 Summary data on Palagnedra Reservoir, Switzerland

Reference:	Swiss National Committee on Large Dams, 1982 and Liechti and Haeberli, 1970
Original storage capacity:	5.5Mm^3
Reservoir length:	2.6km
Elevation of top water level above river bed at dam :	55m
Representative bottom width :	10m (value near dam)
Representative side slope :	1 : 1
Annual water inflow :	304Mm^3
Annual sediment inflow :	0.08Mt (derived using an estimate for density of deposits of 1t/m^3)
Sill height of outlets relative to base of dam :	12m upper outlet, 0m lower outlet. (Only the more effective flushing using the lower outlet has been analysed here)
Outlet rating constant defined: discharge / (2g water level above sill)$^{0.5}$	1m^2 (estimated from geometry of upper outlet)
Typical flushing discharge :	0.3m^3/s upper outlet then 1.25m^3/s lower outlet (flushings undertaken in 1978-1979)
Typical duration of flushing :	1.5 months upper outlet, 3 months lower outlet (flushings undertaken in 1978-1979)
Sediment type in Tsinghua University method:	Largely silts with some coarser material, material removed in 1978-1979 also contained 1.4% wood
Typical side slope in deposits after flushing:	1 : 1 (derived from photographs)
Estimated long term capacity :	Same as initial capacity 5.5Mm^3 (allowing from some sediment clearance by bulldozer, see discussion below.)

Comments: It is the first reference which reports the flushing at Palagnedra, the second reference gives further information on the dam design and reservoir dimensions. flushing of the reservoir was required following an extreme event in August 1978. An unusually large flood caused 1.8Mm^3 of deposition in the reservoir which was equivalent to 33% of the original storage volume, flushing from mid November 1978 to March 1979 successfully removed these deposits and a further 0.6Mm^3. The entire original capacity of the reservoir was restored. In order to provide comparison between the predictions of the methods presented in this report and the data from Palagnedra, the sedimentation and flushing discharges relevant to the August 1978 to March 1979 period have been used in this table. Regular drawdown flushing at the reservoir is reported by neither the Swiss National Committee nor by Liechti and Haeberli. It should be noted that heavy machinery was used to assist flushing, this was partly due to the need to remove wood buried in the deposits.

Table A6.6 Summary data on Santo Domingo Reservoir, Venezuela

Reference:	Krumdiek and Chamot, 1979
Original storage capacity:	$3Mm^3$
Reservoir length:	1.0km Santo Domingo river, 0.7km Aracay river
Elevation of top water level above river bed at dam :	47m
Representative bottom width :	approx 20m for Santo Domingo river, 10m for Aracay river
Representative side slope :	1 : 1
Annual water inflow :	$450Mm^3$
Annual sediment inflow :	0.2Mt (based on a value adopted for design purposes, but the value is in keeping with observed deposition)
Sill height of outlets relative to base of dam :	0m
Outlet rating constant defined: discharge / (2g water level above sill)$^{0.5}$	$3.7m^2$ Santo Domingo side, $1.9m^2$ Aracay
Typical flushing discharge :	$5m^3/s$ Santo Domingo side, $3m^3/s$ Aracay
Typical duration of flushing :	3 days, followed by 3 weeks with bulldozer operations
Sediment type in Tsinghua University method:	Suspended loads have particles finer than 0.1mm, type III taken due to low flushing discharges
Typical side slope in reservoir deposits after flushing :	1 : 2 (derived from photograph)
Estimated long term capacity :	$2.9Mm^3$ (see discussion below)

Comments: The analysis has used data from the larger Santo Domingo branch of the reservoir. Krumdiek and Chamot report only one flushing operation at the reservoir. The flushing conditions and results given here refer to that operation. About 40% of the material was removed with the aid of two bulldozers, however Krumdiek and Chamot report that the reason for their use was to accelerate the sediment removal as well as to clear deposits not within reach of the flushing flow. The authors suggest that bulldozers should not normally be necessary if the reservoir is flushed during periods of higher flow. It appears, therefore, that the majority of the capacity could be maintained by hydraulic flushing alone.

Appendix 7

Tables listing data on the reservoirs where flushing was not successful

Table A7.1 Summary data on Guanting Reservoir, China

Reference:	IRTCES, 1985
Original storage capacity:	2,270Mm^3
Reservoir length:	30km
Elevation of top water level above river bed at dam :	43m
Representative bottom width :	about 3000m
Representative side slope :	1 : 7
Annual water inflow :	1530Mm^3
Annual sediment inflow :	60Mt
Water surface elevation relative to base of dam during flushing:	8m
Typical flushing discharge :	80m^3/s
Typical duration of flushing :	5 days
Sediment type in Tsinghua University method:	loess
Typical side slope in reservoir deposits after flushing :	1 : 20
Estimated long term capacity :	Very low, only one flushing (in October 1954) is reported, however only about 10% of the annual sediment inflow was removed by the flushing

Table A7.2 Summary data on Guernsey Reservoir, USA

Reference:	Jarecki and Murphy, 1963
Original storage capacity:	91Mm3
Reservoir length:	23.5km
Elevation of top water level above river bed at dam :	28.6m
Representative bottom width :	100m (central reach of reservoir appears much wider)
Representative side slope :	1 : 5 (taken from range 21 data only)
Annual water inflow :	about 2,100Mm^3 (estimated as 50% more than the controlled releases for irrigation)
Annual sediment inflow :	about 1.7Mt (derived from predictions of trapping efficiency and deposit density)
Sill height of outlet relative to base of dam :	10m
Outlet rating constant defined: discharge / (2g water level above sill)$^{0.5}$	11.4m^2
Typical flushing discharge :	125m^3/s
Typical duration of flushing :	5 days
Sediment type in Tsinghua University method:	about 20% fine sand, 60% silt, 20% clay, type I
Typical side slope in reservoir deposits after flushing :	vertical
Estimated long term capacity :	Low (the channel scoured by flushing was much narrower than reservoir width, and thalwegs were well above the original river bed. Only about 2% of the annual sediment inflow was being flushed.)

Table A7.3 Summary data on Heisonglin Reservoir, China

Reference:	Xia and Ren, 1980 and IRTCES, 1985
Original storage capacity:	8.6Mm3
Reservoir length:	2.9km
Elevation of top water level above river bed at dam :	30m
Representative bottom width :	200m (taken from two cross sections)
Representative side slope :	1 : 2 (taken from two cross sections)
Annual water inflow :	14.2Mm^3
Annual sediment inflow :	0.70Mt
Sill height of outlet relative to base of dam :	7m
Outlet rating constant defined: discharge / (2g water level above sill)$^{0.5}$	1.8m^2 (estimated as the product of cross sectional area and a coefficient of discharge of 0.6)
Typical flushing discharge :	0.8m^3/s
Typical duration of flushing :	3 days
Sediment type in Tsinghua University method:	loess
Typical side slope in reservoir deposits after flushing :	1 : 4
Estimated long term capacity :	2 to 3Mm^3

Comments: Flushing is not the only means of sediment removal at Heisonglin. Immediately after a large flood has filled the reservoir, sediment laden water is released through the outlet thereby preventing much of the sediment from depositing. Also sediment laden density currents are allowed to pass through the outlets in the dam when possible. These measures ensure that less than half of the sediment entering the reservoir actually deposits. The analysis of chapter 4 of this report has allowed for the reduced sedimentation; an overall trapping efficiency of 40% has been used on the basis of the field observations.

Table A7.4 Summary data on Ichari Reservoir, India

Reference:	Bhargava et al, 1987 and Mohan et al, 1982
Original storage capacity:	11.55Mm^3
Reservoir length:	11.3km
Elevation of top water level above river bed at dam :	36.75m
Representative bottom width :	approximately 60m (derived from relationship between bed levels and storage)
Representative side slope :	approximately 1:05 (derived from relationship between bed levels and storage)
Annual water inflow :	5300Mm^3
Annual sediment inflow :	5.7Mt (derived using an assumed density of 1t/m^3
Spillway crest elevation relative to base of dam :	20.8m
Spillway rating constant defined: discharge / {(2g)$^{0.5}$ (water level above crest)$^{1.5}$}	52.5m
Typical flushing discharge :	2,160m^3/s
Typical duration of flushing :	1 day (an estimate based on peak flow to mean flow ratio)
Sediment type in Tsinghua University method:	sand and some silt, type II taken
Typical side slope in reservoir deposits after flushing :	1 : 1 (estimated value for a site where sand predominates in deposit)
Estimated long term capacity :	about 4Mm^3 (derived from extrapolating observed storage losses, the data covered 1976 to 1984)

Comments: Observations at Ichari included the monitoring of reservoir trap efficiency. Brune's curves were found to grossly underpredict the reservoir's trapping efficiency: they indicate a 20% while observations show 85%. The sediment is presumably coarser than is implied by Brune's curve for 'coarse material'. The observed trapping efficiency has been used in chapter 4 of this report.

Table A7.5 Summary data on Ouchi-Kurgan Reservoir, USSR

Reference:	IRTCES, 1985
Original storage capacity:	56.4Mm^3
Reservoir length:	17km
Elevation of top water level above river bed at dam :	35m
Representative bottom width :	200m (estimate)
Representative side slope :	1 : 12 (estimated from water surface widths, however this gives an original reservoir capacity of 143Mm^3)
Annual water inflow :	about 15,000Mm^3
Annual sediment inflow :	13Mt
Sill height of outlet relative to base of dam :	0m
Outlet rating constant defined: discharge / (2g water level above sill)$^{0.5}$	at least 206m^2 (outlets could pass 5,000m^3/s with a head of 30m)
Typical flushing discharge	2000 to 5000m^3/s for a year with higher flows, about 500 to 1000m^3/s for other years. (There was an inconsistency in the data on this matter)
Typical duration of flushing :	3½ months
Sediment type in Tsinghua University method:	No information, type II taken
Typical side slope in reservoir deposits after flushing :	1 : 1 (estimate)
Estimated long term capacity :	A low value can be anticipated because, despite flushing, bed levels at the dam rose 23m after 12 years, which is 66% of the dam height

Comments: Data reported in IRTCES (1985) on this reservoir is not comprehensive and contains some inconsistencies, so the results should be considered with caution. However the results are of qualitative interest. The reservoir is sluiced: it is drawn down for three to four months annually as the high river discharges pass through the reservoir.

Table A7.6 Summary data on Sanmenxia Reservoir, China

Reference:	Zhang and Long, 1980, and IRTCES, 1985
Original storage capacity :	9,640Mm^3
Reservoir length :	120km
Elevation of top water level above river bed at dam :	45m
Representative bottom width :	about 2,500m (estimated from three cross sections)
Representative side slope :	1 : 1 (estimated from three cross sections)
Annual water inflow :	43,000Mm^3
Annual sediment inflow :	1,600Mt (using an estimate for sediment density of 1t/m^3)
Sill height of outlets relative to base of dam :	10m (approximate value, there were sets of outlets at differing elevations)
Outlet rating constant defined: discharge / (2g water level above sill)$^{0.5}$	488m^2 (from sluicing capacity of 9,660m^3/s at a water surface elevation 20m above base of dam)
Typical flushing discharge :	1000m^3/s to 4000m^3/s
Typical duration of flushing :	4 months
Sediment type in Tsinghua University method:	loess
Typical side slope in reservoir deposits after flushing :	approximately 1 : 20
Estimated long term capacity :	3,000Mm^3

Comments: The Sanmenxia reservoir was originally designed to store 64 000Mm^3 of water at a maximum water surface elevation of 340m. However severe siltation and channel accretion upstream from the reservoir necessitated a reduction in the maximum water level by 30m, thus reducing the storage before siltation to 9 600Mm^3. Rehabilitation of the reservoir also involved construction of larger low level outlets in the dam. The observations and calculations for Sanmenxia refer to the reservoir's condition after rehabilitation.

Table A7.7 Summary data on Sefid-Rud Reservoir, Iran

Reference:	Tolouie et al, 1991
Original storage capacity :	1,760Mm^3
Reservoir length :	25km, a minor branch is about 8km long (the analysis of chapter 4 has used the main branch)
Elevation of top water level above river bed at dam :	82m
Representative bottom width :	500m (estimated from plan of reservoir)
Representative side slope :	1 : 13 (derived from bed width and water surface widths)
Annual water inflow :	5,000Mm^3, about 24% enters the branch
Annual sediment inflow :	50Mt
Sill height of outlets relative to base of dam :	20m right bank and 23m left bank
Outlet rating constant defined: discharge / (2g water level above sill)$^{0.5}$	10.5m^2 and 13.7m^2 respectively
Typical flushing discharge :	about 100m^3/s (derived from proportion of inflow which occurs during flushing period)
Typical duration of flushing :	4 months
Sediment type in Tsinghua University method:	approximately 33% sand, 47% silt, 20% clay, type I taken
Typical side slope in reservoir deposits after flushing :	1 : 1 (estimated from brief description of "bank sliding")
Estimated long term capacity :	A low value can be expected, flushing for 7 years caused only 26% of lost storage to be recovered.

Comments: 26% can be considered an overestimate of the long term capacity remaining because the initial deposits are likely to form a relatively narrow flood plain at the bottom of the reservoir. Further recovery of lost capacity has been achieved by a novel technique for washing flood plain deposits into the main flushing channel. The technique involves raising pore water pressures within the deposit by pumps. The analysis reported here assumes that only gravity flushing is employed at the reservoir.

Table A7.8 Summary data on Shuicaozi Reservoir, China

Reference:	IWHR, 1983 and IRTCES, 1985
Original storage capacity :	9.58Mm3
Reservoir length :	6km
Elevation of top water level above river bed at dam :	28m
Representative bottom width :	90m (estimated from original bed elevations and the estimate for side slope)
Representative side slope :	1 : 1 (estimate)
Annual water inflow :	514Mm3
Annual sediment inflow :	0.63Mt
Crest elevation of spillway relative to base of dam :	17m
Spillway rating constant defined: discharge / $\{(2g)^{0.5}$ (water level above crest)$^{1.5}\}$	11.3m
Typical flushing discharge :	$50m^3/s$
Typical duration of flushing :	1 to 2 days
Sediment type in Tsinghua University method:	Silt, type I taken
Typical side slope in reservoir deposits after flushing :	1 : 4 (estimated from descriptions of unconsolidated silt sliding towards the flushing channel)
Estimated long term capacity :	Low, observations of thalweg after flushing show bed levels at the dam only 7m below the impounding level

HR Wallingford is an independent company that carries out research and consultancy in civil engineering hydraulics and the water environment. Predictive physical and computational model studies, desk studies and field data collection are backed by large scale laboratory facilities and long term programmes of advanced research. Established in 1947 as a Government research centre, the Company now employs more than 200 engineers, scientists, mathematicians and support staff, many of whom are recognised international experts. Based on a 36 hectare site near Oxford, HR Wallingford has extensive national and international experience, with offices and agents around the world.

HR Wallingford

Address and Registered Office: **HR Wallingford Ltd,** Howbery Park, Wallingford, Oxon OX10 8BA, UK
Tel:+44 (0) 1491 835381 Fax:+44 (0) 1491 832233 Internet Server: http://www.hrwallingford.co.uk

Registered in England No. 2562099. HR Wallingford Ltd is a wholly owned subsidiary of HR Wallingford Group Ltd