

Hydraulics Research Wallingford

RESERVOIR SEDIMENTATION

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ABSTRACT

This report describes work on numerical reservoir sedimentation models to improve the prediction of reservoir sedimentation. Reservoir sedimentation presents a major water resources problem in tropical and sub-tropical regions of the world. Until the development of numerical models reservoir sedimentation could only be predicted using simple empirical methods which have on occasions have proved unreliable. The recent development of numerical models has greatly improved the accuracy and detail with which predictions can be made. The purpose of the work is to enable methods of controlling sedimentation to be studied. The study considers the problems of up-dating sections subject to erosion or deposition, the consolidation of deposited sediments and the definition required to model a combination of silts and sands. A simple method of assessing the economic cost of reservoir sedimentation is presented. The work should enable more accurate predictions of reservoir sedimentation to be made and provides a method of associating a cost with the predicted siltation. This better engineering and economic assessments of reservoir projects will result.

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

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

1.1 Impact of reservoir sedimentation

The adverse effects caused by reservoir sedimentation may include:

- (a) a reduction in the storage available and hence a reduction in the yield provided by the reservoir,
- (b) degradation downstream of the dam. This may threaten structures associated with the dam

and lead to problems at structures further downstream such as bridges or intakes,

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

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

1.2 Trapping efficiency

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

Gottschalk (1948) related the trapping efficiency to the ratio of the storage capacity to the drainage area of the basin. The trapping efficiency, or effectiveness of a reservoir in retaining sediment, however, can only depend upon the nature of the reservoir, the flow in it and the sediment entering. It must be independent of the nature of the catchment In Gottschalk's analysis, therefore, the upstream. drainage basin area must be acting as a surrogate for a more relevant variable such as inflow. Gottschalk appreciated that the ratio of capacity to inflow could be used in place of the ratio of storage capacity to drainage area but preferred the latter as it was amenable to measurement. He was, however, well aware of the shortcomings of using drainage area.

'... a reservoir in an arid or semi-arid region may have a low capacity - watershed ratio yet not receive enough inflow in any one year to cause water to be discharged over the spillway. In contrast, the volume

of mean annual flow from a watershed of equal size in a humid area may be equivalent to 25 times that of a reservoir having the same capacity - watershed ratio. In the drier region 100% of the incoming load is trapped, whereas in the humid area possibly only 70% is trapped.'

Churchill (1948) pointed out that the ratio of capacity to inflow effectively gave the period of retention. Churchill described how, based on their experience, the Tennessee Valley Authority had developed a method relating the trapping efficiency to the ratio of the period of retention to the mean velocity. This ratio was called the sedimentation index. It was based on the observation that the greater the period of retention in a given reservoir and the lower the transit velocity and turbulence, the higher will be the percentage deposition of incoming sediment. Churchill points out that regardless of the period of retention in a reservoir, or equivalently, the capacity - inflow ratio, if the velocity and resulting turbulence are too high no sedimentation will occur.

Borland (1951) analysed data from the Imperial Dam Reservoir and showed how the trapping efficiency for this dam varied with retention time. Though it was appreciated that such a relationship was specific to a particular reservoir and not of general applicability it is interesting that this is an acknowledgement that the trapping efficiency of a reservoir is not constant but varies from day to day as the inflow and storage in the reservoir changes.

The work of Brune (1953) is still frequently referred to though one of his conclusions was that a great deal of additional work is required in the field of reservoir trap efficiency. Brune pointed out the

inadequacies of using the capacity-watershed area ratio and instead analysed data from 44 reservoirs in terms of the capacity inflow ratio.

Since the trapping efficiency must depend upon the sediment size, the flow through the reservoir, the distribution of flows into the reservoir and the way that the reservoir is operated, it follows that such estimates of trapping efficiency can only provide approximate values which on occasions may be seriously in error.

1.3 Distribution of

sediment deposits

Having estimated, however inaccurately, the volume of the material to be deposited, methods were developed for the prediction of the distribution of sediment within the reservoir (Borland and Miller, 1960; Lara, 1962). These methods start at the bottom of the reservoir and work upwards towards the surface determining the reduction of storage due to sedimentation. This completely ignores the fact that material is only deposited in the lower portions of a reservoir if it fails to be deposited in the higher reaches. The proper procedure, therefore, is to progress from the surface downwards.

1.4 Reservoir

half-life

Pitt and Thompson (1984), however, have shown how these approximate methods can be combined with the notion of the half-life of a reservoir to give an initial assessment of the likely significance of reservoir sedimentation. The half-life of a reservoir is that time taken for 50% of the reservoir storage to be lost through sedimentation. This can be rapidly estimated using empirical trapping efficiency curves. The reservoir can be classified accordingly.

- (a) half-life in excess of 100 years reservoir sedimentation is unlikely to cause major problems,
- (b) half-life between 20 and 100 years loss of storage will have an impact on the scheme. Consideration should be given to methods of reducing the amount of sediment entering the reservoir for example:

land management practices, physically preventing the movement of sediment into reservoir by provision of check dams,

encouraging the movement of sediment through the reservoir by flushing or other means. The circumstances under which sediment flushing is feasible have been discussed by White and Bettess (1984)

(c) half-life less than 20 years - sedimentation will be a major problem and methods to conserve storage will be essential.

If such simple, approximate methods suggest that reservoir sedimentation might be a problem then more detailed numerical modelling of the reservoir will be required to provide a more accurate and better defined picture of the likely sedimentation.

As a result of the inadequacies of these empirical approaches based on trapping efficiency the estimates of sedimentation which they provide can be unreliable. There are instances of reservoirs filling with sediment within one or two years of construction.

More recently with the availability of computers it has been possible to develop numerical models of reservoirs. These models calculate the water flow and sediment movement throughout the reservoir. Numerical reservoir models provide a reliable and detailed estimate of the impact of sedimentation on a reservoir.

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

In the present study we have so far considered:

- the way that cross-sections are up-dated following deposition or erosion;
- 2. the consolidation of deposited sediments;
- the amount of detail required to model a combination of silts and sands.

These investigations are described in the following sections.

NUMERICAL MODEL OF SEDIMENTATION IN RESERVOIRS

2

The numerical reservoir model is a time-stepping model. Given prescribed initial conditions the equations are used to predict what happens in the reservoir over a short time period Δt , so that conditions are determined at the end of that timestep. A repetition of the procedure predicts the conditions after a time $2\Delta t$. The process is then repeated a sufficient number of times to make predictions for the required time period. The timestep used depends upon the size and nature of the reservoir but is typically of the order of a day.

To characterise both the reservoir and the nature of the flow and sediment, data must be specified. The geometry of the reservoir is described using cross-sections along the length of the reservoir and continuing for some distance up the incoming river. Flows entering the reservoir may be derived either using a flow exceedance curve or from observed flow records. The nature of the sediment is described by a number of representative sediment diameters.

2.1 Reservoir

storage model

To predict sedimentation in a reservoir a knowledge of how the reservoir level varies through time is required. The velocity of flow, on entering the reservoir, drops dramatically and the flow becomes no longer capable of transporting the coarser sediment fractions which are then deposited. If the water level in the reservoir is near full supply level then the material will be deposited near the head of the reservoir. If the reservoir is partly drawn down then deposition will occur further into the reservoir basin

and at a lower level. It is thus important to predict the reservoir water level. The finer sediment will be carried further into the reservoir where its deposition is controlled by the opposing effects of the particle weight encouraging deposition and turbulence maintaining the material in suspension.

To predict the reservoir water level through time, a storage model is used. The model uses a continuity equation to relate the inflow of water into the reservoir to any outflows plus the change in storage in the reservoir. Hence, the water level in the reservoir may be determined as a function of time. The inflow is provided by the river flow, the outflow is the sum of any evaporation, water releases or abstraction for irrigation or other purposes and spillage from the spillway. A reservoir stage/storage curve is used to determine water levels for a given volume of storage.

2.2 Modelling of flow

A numerical model may be used to determine the proportion of the sediment that is trapped by the reservoir and the distribution of deposited material throughout the reservoir. Since both the trapping efficiency and the location of deposition depends upon the volume of water stored in the reservoir it is necessary to use the storage model, described above, to determine the water level and the volume of water stored in the reservoir.

The water flow in the reservoir and the upstream river is determined using a backwater calculation. The water level calculated by the storage model is used as an initial downstream boundary condition at the dam to enable the backwater calculation to proceed upstream. This calculation provides water depths, velocities and

slopes at each cross-section along the length of the reservoir and up the river upstream of the reservoir.

3 UPDATING SECTIONS

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

Deposition

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

- (a) Raising the section bodily, without any change of shape. Unfortunately where changes in cross-sectional area are large this is not particularly realistic.
- (b) Fill in the section from the bottom.
- (c) Deposition is distributed across the total width of the section, the amount of deposition at each point assumed to be proportional to the depth so that most deposition takes place in the deepest parts of the section with proportionately less in the shallower areas.

Erosion

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

- Lowering the section bodily without any change of shape. Unfortunately this is not particularly realistic for reservoir sedimentation.
- (b) Erosion is simulated by calculating an equilibrium width of the river entering the reservoir and assuming that erosion is confined to that width.
- (c) Erosion takes place across the total width of the section and is taken to be proportional to the depth so that most

erosion takes place in the deepest parts of the section.

For both deposition and erosion extreme types of behaviour have been considered. It is quite possible to consider the continuum of behaviour between these extremes.

To decide how realistic these algorithms are for reservoir sedimentation it was decided to look at cross-sections derived from reservoir surveys. The ODA unit at HR undertook an investigation of reservoir sedimentation in the Tana River Basin, Kenya funded by ODA in collaboration with the Tana and Athi Rivers Development Authority, the Ministry of Water Development, Kenya and the Kenya Power and Lighting Company Limited. As part of the work cross-sections were surveyed on three reservoirs, Kindaruma, Kamburu and Masinga and the cross-sections compared with those derived from earlier surveys (Wooldridge, 1984). Figure 3 shows Kindaruma reservoir and the comparison between some of the measured cross-sections. For the most part the sections appear to demonstrate a gradual filling up from the bottom most akin to (b) of Figure Figure 4 shows Kamburu reservoir and the 1. comparison of some of the measured cross-sections. In the sections from the upper part of the reservoir the original section is almost completely silted but the inflow of water has maintained a much smaller, almost trapezoidal, section. While some of the other sections demonstrate a gradual filling from the base, (b) of Figure 1, others still demonstrate the cf. locations of the original channel in the silted cross-section so that the pattern of sedimentation resembles (c) of Figure 1. The original investigators attribute the differences in the silting of the cross-sections of the two reservoirs to the way that the reservoirs are operated. Kindaruma is presently

operated to maintain the water level at, or near, its maximum water level for long periods resulting in even sedimentation across the section. Kamburu reservoir, however, is subjected to a large range of water levels and this, it is claimed, leads to the preservation of low water channels due to the re-working of sediment when the water level is drawn down (Wooldridge 1983).

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

3.1 Analysis of section updating

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

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

4 COMPACTION OF SEDIMENTS

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

therefore consider information available on the density of sediment deposits in reservoirs.

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

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

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

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

(1)

where

W is the bed density in lbs/cu ft after time T W_l is the bed density in lbs/cu ft after l year K is a constant

T is the age of the bed in years.

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

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

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

where e is the voids ratio, C_F is the coefficient of consolidation, t is time and z is the vertical co-ordinate. Descriptions are being sought for the

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

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

$$e = e_{o} - C_{c} \log_{10} \left(\frac{p_{o} + \Delta p}{p_{o}}\right)$$
 (3)

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

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

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

where ρ_{s} and ρ_{w} are the densities of the solids and water respectively.

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

$$\rho_{soil} = \frac{\rho_{s} + (e_{o} - C_{c} \log_{10} \left[\frac{p_{o} + \Delta p}{p_{o}}\right]) \rho_{w}}{1 + e_{o} - C_{c} \log_{10} \left[\frac{p_{o} + \Delta p}{p_{o}}\right]}$$
(5)

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

We can, therefore, replace
$$\frac{p_0 + \Delta p}{p_0}$$
 by $1 + K^{l}T$,

where $K^{1} = \frac{K}{p_{0}}$

Equation (5) then becomes

$$\rho_{soil} = \frac{\rho_{s} + (e_{o} - C_{c} \log_{10} [1 + k^{1}T]) \rho_{w}}{1 + e_{o} - C_{c} \log_{10} [1 + K^{1}T]}$$
(6)

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

Further work on the density of deposited sediments and their compaction through time has been done by Bolton (1986). After reviewing existing methods for predicting sediment densities and showing that they contain major shortcomings either in their technical or practical aspects he then goes on to consider the possible contribution which could be made to improving the available techniques through numerical modelling, laboratory simulations, empirical formulations and field investigations.

4.1 Modelling
sediment
transport

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

4.1.1 Modelling movement of sand fractions

The transported sand sizes at each section is calculated using the Ackers and White sediment transport theory (1973). In tests on an extensive set of field and flume data this theory produced the most satisfactory predictions of sediment transport (White, Milli and Crabbe, 1973). The movement of non-cohesive sand is dependent upon the sediment diameter. For sediments which do not contain too broad a range of different sizes a representative sediment diameter is selected. In the case of Ackers and White theory for sediment movement the D₃₅ size is chosen (Ackers and White, 1973). For widely graded sediments the range of sediment sizes may be divided into a number of

different classes and a representative diameter used for each class (Day, 1980).

4.1.2 Modelling of silt fractions

The concentrations of the silt fractions on entering the reservoir is based on the sediment yield and total annual run-off. The behaviour of the silt and clay fractions depends upon the fall velocity of the sediment and the turbulence of the flow. The silt is convected with the flow but the concentration reduces as some of the material settles out of suspension onto the bed. The rate of settling is dependent upon the fall velocity. The fall velocity itself varies with the concentration and also with the flow conditions.

If the shear stress is sufficiently high it is assumed that the turbulence generated is sufficient to maintain all the material in suspension but as the shear stress reduces the fall velocity tends to the still-water value.

The silt concentrations are added to the sand transport rates to obtain the total sediment transport rate. A sediment continuity equation is then applied to determine the change in bed level at each section due to the variations in sediment transport rate along the reach.

4.2 Observed

distribution of sediment sizes in reservoir sediments

> Heinemann (1962) took samples of sediment from Sabetha Lake, Kansas, USA and showed that the composition of the sediment deposited varied with distance upstream

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

4.3 Numerical experiments

Numerical experiments were performed using 1 and 5 representative diameters for the silt sizes. After simulating two years of deposition in a reservoir a mean sediment size was calculated for the sediment deposited at each section. This was taken to be the mean of the sediment sizes weighted by the proportion of the material present on the bed. In Figure 9 this mean sediment diameter is plotted against distance upstream of the dam. The distribution of sediment and sediment sizes depends upon a number of factors such as variation of water level in the reservoir and the distribution of inflows throughout the year. It can be seen, however, that using one representative diameter for the sand and one for the silt gives a poor representation of the distribution of sediment sizes. Using five silt diameters improves the

modelling of the silt sizes but the use of only one representative diameter in the sand sizes leads to a loss of definition in that size range. It is, therefore, clear that whereas in calculating sediment transport in a river the use of a representative diameter such as D_{35} has been shown to be satisfactory (White et al, 1973) it is unable to simulate the process at the head of a reservoir whereby the different sand sizes are sorted according to the ability of the flow to transport material.

5 OUTPUT FROM NUMERICAL MODEL

A numerical reservoir sedimentation model can predict:

- volume of sediment deposited over a specified period
- location of sediment deposits
- annual stage/storage curves
- longitudinal profile of the reservoir at specified times

Numerical models can also be used to study the feasibility of using sediment flushing to maintain the storage capacity of the reservoir.

Since the geometry of the reservoir is specified by cross-sections it is simple to calculate the volume of the reservoir below a given level and hence determine the storage. This information can be given either as stage/storage curves at discrete times or by showing the variation of storage with time for a fixed level, most commonly the full-supply level.

Since the variation in bed level is calculated it is simple to provide initial and subsequent longitudinal profiles. It is of interest that the results from numerical models reproduce the classic top-set, fore-set and bottom-set slopes that have long been

observed in real reservoirs. The model calculates the amount of each sediment size that is passing each section. It can, therefore, provide information on the volume, location and composition of deposits.

IMPACT OF RESERVOIR SEDIMENTATION UPSTREAM AND DOWNSTREAM OF THE RESERVOIR

6

6.1 Degradation
 downstream of
 dam

The loss of storage is not the only sediment related problem associated with reservoirs. The trapping of sediment in the reservoir leads to a reduction of the sediment supply to the river reach downstream. This may cause degradation to take place downstream of the dam. This may be a disadvantage if it threatens the dam or other structures or an advantage if it increases the head available for the generation of hydro-power. The amount of degradation that will take place may be predicted using a numerical model (Bettess and White, 1981).

6.2 Increase of

flood levels upstream

> Consideration should also be given to the impact of reservoir sedimentation on the water levels in the rivers upstream of the reservoir. Sediment deposition can lead to increased flood levels in the river upstream of the reservoir. This can be predicted using the numerical reservoir model. An extreme example of the impact of reservoir sedimentation on flood levels upstream occurred during construction of

the Hongshan Reservoir on the Laoha River in China (Sediment Research Laboratory, Tsinghua University, 1985). A violent storm brought 1,750 x 10^6 m³ of water (1.9 times average annual runoff) and 172×10^6 tonnes of sediment (4 times average annual sediment load) into the reservoir. The land inundated by the flood was raised by 1.5 to 2.0m. The bankfull discharge of the river channel was reduced from approximately $1000 \text{ m}^3/\text{s}$ to $40 \text{ m}^3/\text{s}$ so that subsequent floods spilled over onto the flood plain. This provided an ideal environment for weed growth which sprouted to a height of 2 to 3m and formed a vegetative screen 4km wide and 12km long which trapped 90% of the incoming sediment load. The increase in roughness due to the vegetation and the reduction in the capacity of the main channel caused the deposition to extend rapidly upstream. By 1975 the sediment deposits extended to a level almost 10m higher than the water level at the dam.

7 APPLICATIONS

HR has used numerical reservoir sedimentation models to simulate historic sedimentation and also to predict sedimentation in proposed dams. A number of case studies are described.

7.1 Chitowe dam (HR, 1983a)

The feasibility of constructing a dam at Chitowe on the River Sabi in Zimbabwe was being considered. The catchment was approximately $25,650 \text{km}^2$. The total proposed live storage was approximately $25 \times 10^{9} \text{m}^3$. Mean annual run-off is $2.4 \times 10^{9} \text{m}^3$. Figure 10 shows the predicted longitudinal profile for 18, 36, 54 and 72 years. Figure 11 shows the predicted distribution of increases in bed levels. The composition of the deposited material at various locations along the length of the reservoir is shown in Figure 12. A

sensitivity analysis was performed to see the effect of changing the assumed sediment yield from the catchment because of uncertainty in assessing this, but even with the largest assumed sediment yield the results showed that in 72 years only 15% of the live storage would be lost.

7.2 Kamativi dam (HR 1983b and White and Bettess 1984)

> Kamativi mine adjacent to the Gwai river was interested in the feasibility of obtaining its net water requirement of $1.1 \times 10^{6} \text{m}^3$ by constructing a dam on the Gwai river. The area of the catchment is 38,600km² and the mean annual run-off is approximately 580 x 10 6 m³. Thus the water requirement is small in comparison with the total river flow. A range of heights for the proposed dam were considered but all suffered from significant deposition, see for example Figure 13. The loss storage against time for various proposed dam heights is shown in Figure 14. The large ratio of annual flow to storage requirement and the fact that the workings of the mine would tolerate an interruption to the water supply led to a study of the feasibility of using sediment flushing through large low-level outlets to maintain the storage required. This study identified under what conditions flushing is a practical means of maintaining reservoir storage. In the case of Kamativi dam the work showed that storage could be maintained for a considerable period of time, Figure 15.

7.3 Austral Weir (HR, 1985)

As part of the study of sediment yield in Zimbabwe historic sedimentation in six reservoirs is being modelled. From measurements of the deposited sediments and simulations of the sediment deposition, estimates will be made of the sediment yield from the catchments. Results are presented here for one of the reservoirs, Austral Weir, on the Tokwe River. The reservoir has a storage capacity of 2.7 x $10^{6}m^{3}$ and the mean annual run-off is 470 x $10^{6}m^{3}$. During the study samples of deposited material were obtained along the length of the reservoir. Figure 6 shows a comparison of the predicted and observed values for the D₅₀ sediment size.

8 PRESERVATION OF STORAGE IN RESERVOIRS

A number of methods have been used to reduce the amount of sedimentation in a reservoir, these include:

- (a) reducing the inflow of sediment by catchment control,
- (b) preventing the deposition of sediment in the storage part of the reservoir. In certain circumstances this can be achieved by making heavily sediment-laden water by-pass the reservoir or by using off-river storage,
- (c) removal of deposited sediment for example by flushing, dredging or syphonic action.

8.1 Siltation

reduction by

catchment control

Sediment inflows to a reservoir can be significantly reduced by applying soil conservation techniques to the catchment. Techniques which have been used successfully are:

- (a) contour ploughing
- (b) crop control to ensure vegetative cover of soil
- (c) control of animal grazing to prevent over-grazing
- (d) afforestation to control water run-off, improve rain infiltration and protect against soil erosion
- (e) construction of ditches, dams and other structures to encourage filtration of water
- (f) protection of water-courses against erosion
- (g) provision of check dams.

The effectiveness of such methods are hard to quantify. Careful measurements on a number of catchments in Malawi with sizes ranging from 5 to 8 hectares, however, have shown that conservation techniques can lead up to a 100-fold reduction of sediment yield.

8.2 Siltation

prevention

In situations where the majority of the sediment enters the reservoir during a short flood period it may be possible to regulate the flow so as to utilise the sediment carrying capacity of the flow to carry the sediment through the reservoir and downstream. In areas of China where 80% to 90% of the annual sediment load occurs in July and August transported by only 25 to 50% of the annual runoff reservoir levels are

reduced during this period to encourage the passage of this heavily silt-laden water through the reservoir. Adopting this operational procedure at Heisonglin Reservoir on a tributary of the Yellow River reduced the rate of sedimentation from 540,000m 3 /year to 93,000m 3 /year.

8.3 Sediment removal

8.3.1 Sediment flushing

In sediment flushing the flow of water through the reservoir is used to erode deposited sediment and carry it downstream of the dam. In a study of sediment flushing White and Bettess (1984) demonstrated the conditions under which sediment flushing could be effective:

- (a) where there were adequate low-level outlets,
- (b) where low reservoir levels could be maintained during periods of flood flows, this latter condition implying that the required water yield of the reservoir is significantly less than the annual river flow.

Sediment flushing is not appropriate

- (a) where a reservoir is used for over-year storage
- (b) where the required water yield of the reservoir is comparable with the annual river flow,

(c) where periodic interruptions to the use of a reservoir cannot be tolerated.

Sediment flushing has been used successfully to reduce sedimentation at a number of reservoirs. Hengshan Reservoir in China was built with a storage capacity of 13.3 x $10^{6}m^{3}$. After eight years of operation 3.2 x $10^{6}m^{3}$ of storage (24%) had been lost through sedimentation. Subsequent flushing removed 1.03 x $10^{6}m^{3}$ of these sediments thereby regaining 8% of the original storage.

8.3.2 Dredging

Deposited sediments may be removed by dredging. In general this is an expensive method of restoring lost storage and is infrequently resorted to. Dredging may also be used to alleviate problems generated by sedimentation at the head of a reservoir, for example to maintain a navigation channel.

8.3.3 Syphoning

The head difference between upstream and downstream of a dam can be used to drive a syphon. This can then be used in a similar fashion to an ordinary suction dredger. Using a syphon provides a significant reduction in cost over using conventional dredging. Though this method has been used successfully in a number of cases practical considerations, however, normally limit the area of operation to that immediately adjacent to the dam. The method is, therefore, generally only of value for smaller reservoirs. ECONOMIC ASSESSMENT OF RESERVOIR SEDIMENTATION

9

Much of the work described on reservoir sedimentation is directed towards determining the half-life of a reservoir or estimating the loss of live storage after a given period of time. The real concern, however, is the impact that the loss of storage has on the yield from the reservoir and the economic implications of this. Wall Bake (Interconsult) describes a simple method for assessing this.

Yield from a reservoir

The first requirement is to establish how the yield from a reservoir varies as the available storage varies. As the amount of available storage reduces so the quantity of water provided by the dam diminishes. Mitchell (1977) has indicated how the Transition Probability Matrix method can be used to develop sets of curves of storage ratio (storage volume/mean annual runoff) against yield ratio (yield/mean annual runoff) for varying risk levels and varying evaporation rates. In the subsequent analysis Mitchell's cur s will be used but any method of appropriately relating yield to storage may be used. It should be noted that as sedimentation increases not only is storage lost but evaporation losses increase.

In the subsequent calculations, following Wall Bake, we will assume that the risk remains constant and that due to sedimentation the yield is reduced. In practise usually the reverse happens, the yield required remains fixed but the risk that this may not be satisfied increases.

Economic loss

It should be relatively straightforward to assign a value to the yield generated by the reservoir. One can then assign a value to the loss of yield resulting from sedimentation.

An example set of calculations is presented for a reservoir with a storage of $1.5 \times 10^{6} \text{m}^{3}$, a catchment area of 30km^{2} and a mean annual run-off of 100mm. Assuming a sediment yield from the catchment of 600 tonnes/km²/year then over a 20 year period the net yield from the reservoir at a fixed level of risk drops from $330,000 \text{m}^{3}$ to $270,000 \text{m}^{3}$. This implies that on average an extra $13,500 \text{m}^{3}$ loss of yield occurs each year. If one assumes that $7,500 \text{m}^{3}$ of water are required to irrigate one hectare then the loss of yield of $13,500 \text{m}^{3}$ per year implies a reduction each year of the irrigated area by 1.8 hectares.

If one assumes that an average annual income from 1 hectare of land can be increased by £5,000 by irrigating rather than dry-cropping then the cost of this loss of 13,500m³ of water for one year is £9,000. As the loss of water is cumulative through the life of the reservoir this implies that £9,000 is lost in the first year, £18,000 the second and 3 x £9,000 the third year. Over a twenty year period the loss of income due to reservoir sedimentation is £1.89x10⁶. Assuming an annual discount rate of 10% the loss is approximately £0.9x10⁶. This demonstrates that an initial substantial capital expenditure to reduce sedimentation can be justified.

Numerical reservoir modelling offers a significant improvement over other methods for predicting reservoir sedimentation. It can readily take account of:

- variable flows
- variable water levels
- sediment size
- reservoir geometry
- reservoir operating rules

The method can provide:

- volume of sediment deposited over a specified time period
- location of sediment deposits
- annual stage/storage curves
- longitudinal profile of the reservoir

It can be used to study the feasibility of using sediment flushing to maintain storage capacity.

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

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Fig 2 Algorithms for erosion



Fig 3A Kindaruma Reservoir cross-sections

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Fig 3B



Fig 4 A Kamburu Reservoir cross-sections



Fig 4B



Fig 4C







Fig 5 B



Fig 6 Longitudinal profiles for different algorithms



Fig 7 Percentage clay versus density



Fig 8 Percentage clay versus distance upstream from dam



Fig Sediment diameter against distance 9



Longitudinal profile of Chitowe reservoir Fig 10





Chitowe reservoir



Fig 13 Storage against time, sediment yield, silt 50 tonnes km⁻²yr⁻¹ sand 2.5 tonnes km⁻²yr⁻¹ (Runs 1, 2, 6)



Fig 14 Storage againt time



Fig 15

Austral Weir – Mean sediment size against chainage