Reservoir sedimentation and flushing

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ABSTRACT This paper is concerned with the engineering assessment of the deposition and re-erosion of sediments in reservoirs. This deposition and re-erosion can be assessed by methods which vary in their complexity. Historically, simple empirical methods have been used which require only a limited amount of data and analysis. More recently, however, computer models have been developed which can simulate the mechanics of sediment movement within the reservoir as flows and levels change. These are used to predict sedimentation patterns and also to look at the possibility of the strategic flushing of sediments through the dam in order to extend the useful life of the scheme.

An assessment of catchment sediment yield is a prerequisite to any consideration of sediment problems in reservoirs and this has been shown to be difficult and often imprecise. Sediment yields vary with climate, the geology of the catchment and land-use practices.

INTRODUCTION

Reservoir sedimentation and the consequent loss of valuable water storage is becoming increasingly important in tropical countries. High sediment yields are natural in the tropics and are balanced by the high rates of erosion and soil production. When this balance is disturbed by man's activities then the sediment yield is dramatically increased at the expense of soil renewal. The steady rise in soil erosion in tropical countries due to increased cultivation has endangered reservoir projects and caused doubts about the viability of existing and future schemes. The impoundment of water for potable and irrigation supplies, hydro-power, and flood control is a necessary step towards improved national incomes. Untimely sedimentation may reduce the benefits and, if it is ignored, remedial measures may become prohibitively expensive.

ASSESSMENT OF RESERVOIR SEDIMENTATION

The assessment of the deposition of sediments can be made using simple empirical desk calculation techniques or more sophisticated numerical modelling. In the case of existing reservoirs these estimates can be improved by measuring sedimentation during the early life of the
reservoir and using these base-line data to help with predictions of future deposition.

**Survey and computation of reservoir sedimentation**

Figure 1 shows sediment yields derived from recent reservoir surveys carried out by Hydraulics Research in Indonesia, the Philippines and East Africa. The order of magnitude difference in annual sediment yield is due to the large differences in soil erosion between the sites in the humid, steeply sloping drainage basins of south east Asia and those in the drier, less steep areas of central Kenya. In addition sediment yields fluctuate annually due to variations in rainfall intensity and distribution, and over longer time periods due to changes in land use and runoff. The important point to note is that all the sediment yields measured by means of these reservoir surveys (after allowing for errors in survey and computation) are several times higher than the figures used during the design of the dams. In the absence of reliable sediment transport data and sediment yield estimates from tropical areas, designers have had to use data from temperate regions.

<table>
<thead>
<tr>
<th>Reservoir</th>
<th>Country</th>
<th>Drainage Area</th>
<th>Annual Sediment Yield</th>
<th>Survey Period</th>
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<tr>
<td></td>
<td></td>
<td>km²</td>
<td>tonnes/km²</td>
<td></td>
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<td>4200</td>
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<td>&quot;</td>
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<td>4660</td>
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<td>1370</td>
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<td>4200</td>
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<td></td>
<td></td>
<td>4123</td>
<td>3800</td>
<td>1982 - 84</td>
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</table>

**FIG. 1** Sediment yields based on recent HR reservoir surveys.

However, not all the variation in sediment yield can be explained as a change in rainfall and runoff. The accuracy of the result depends upon the detail of previous basin surveys. The volume of deposited sediment is generally obtained as the difference between the total reservoir capacity at the time of survey and the capacity at some time in the past (usually pre-impoundment). In this way the result is obtained by taking the difference of two, large, approximately equal numbers. A small error in the calculated reservoir capacity may give rise to an error up to two orders of magnitude different from the calculated volume of deposited sediment.

Research at Hydraulics Research has focused on examining suitable methods for surveying and computing deposited volumes. The aim has been to provide information on the most appropriate method for the accuracy of result required.
Survey techniques

There are numerous ways of surveying a reservoir to determine the elevation of the bed and hence the total storage and sediment volume; and the method and equipment chosen should reflect the nature of the reservoir project. The method of data processing and volume calculation should be decided first since this will constrain the choice of equipment. In many cases estimation of design capacity is based upon small-scale mapping, whereas later range line surveys give more detailed information. Combination of these two types of data, particularly when pre-impoundment data are sparse, can lead to poor estimates of sediment volume.

Traditionally survey data are collected along pre-determined range lines which can be re-surveyed so that the changes of sectional shape can be noted directly. Depth measurement is obtained by using an echo-sounder (sonar) with a chart or digital readout. From our experience, more discrepancies in cross-section data can be attributed to errors in the initial triangulation than any other source.

Computational techniques

The literature contains details of a variety of techniques for computing the volume of deposited sediment but gives little guidance on their relative merits. Reservoir managers with limited financial and skill resources need to know how the choice of method will affect the accuracy of the results. Studies undertaken by HR have gone some way in identifying suitable methods. These are categorised into three groups:

- End-area methods (based on range line surveys)
- Contour methods (based on contour information)
- Combined methods (based on range line and pre-impoundment contour information)

Terrain models (see Figure 2)

The use of Digital Terrain Models (DTMs) has increased dramatically over the last few years. They are used to model ground surfaces and can be used in processing reservoir survey data and in calculating the volume of deposited sediment.

FIG. 2 Three-dimensional representation of DTM, Manjirenji reservoir, Zimbabwe.
Use of DTMs necessitates investment in expensive surveying equipment with integrated data collection in a form which is readily transferable to a computer for processing. The high cost of DTMs means that their use for reservoir surveys in the developing world will for some time be limited to specialist survey companies. The advantages of DTMs are the improved accuracy, speed of computation, and reduction of preparatory work (setting up range line beacons). The accuracy of the results depends heavily on the adequacy of the surveys, in particular the pre-impoundment survey.

EMPIRICAL METHODS OF PREDICTING SEDIMENTATION

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

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

After analysing several reservoirs in the USA, Churchill came to the conclusion that along with the retention time, the transit velocity, i.e., the velocity with which the water flows in the reservoir, governs the trap efficiency. If the water held in the reservoir is moving fairly rapidly in the reservoir, very little sedimentation will occur because the turbulence associated with the higher velocity hinders settling, even though the retention time may be high. He introduced a parameter known as sedimentation index which is the ratio of the period of retention to the mean transit velocity. The trap efficiency of the reservoirs was found to increase with increase in the sedimentation index.

If a large percentage of the sediment in the stream is moving in the form of density currents, then the concept of mean transit velocity introduced by Churchill is questionable. In such a case, the velocity of density currents may be very different from the mean transit velocity of the flow.

Brune analysed the records of 44 different reservoirs in the USA (41 of which were normal ponded reservoirs) and found that the capacity to inflow ratio gives better correlation with trap efficiency than the capacity to watershed area ratio. Figure 3 shows Brune's plot of the trap efficiency against capacity to inflow ratio.

Pitt and Thompson (1984) developed the methodology proposed by Brune and used the concept of "reservoir half life" (i.e., the time taken to fill 50 percent of the reservoir storage with sediment). Figure 4, based on Brune's curve, shows that reservoir half life varies roughly in proportion to reservoir size and the inverse of the sediment concentration. Assuming an average sediment inflow concentration in the range 1000-4000ppm, most reservoirs with storages in excess of 50% of the mean annual inflow will have half lives
measured in hundreds of years. For storages in the range 5-50% of the mean annual inflow, half lives will be measured in decades whilst for the smaller reservoirs the half life may be less than 20 years.

Kabell (1984) presented a similar methodology based on observations of sedimentation in reservoirs in Zimbabwe. Figure 5 shows how the reservoir half life depends on the initial storage rates and the concentration of fine sediments entering the reservoir. Kabell used the curves given in Figure 5 and suggested that all reservoirs with an initial storage ratio of less than 0.10 are uneconomic. Furthermore, in areas of poor land use practices, a minimum economic initial storage ratio of 0.25 is likely to apply.
FIG. 5 The influence of the initial storage ratio and the mean sediment concentration of the reservoir inflow on reservoir half life after Kabell (1978).

HR has recently carried out work to provide a method of estimating reservoir sedimentation which was simple to apply but took account of the size and shape of the reservoir, the nature of the sediment and the hydraulics of the flow.

Rather than consider trapping efficiency to be a yearly average an instantaneous trapping efficiency was defined. By dimensional analysis it was concluded that the instantaneous trapping efficiency was a function of three non-dimensional variables

\[ Z_1 = \frac{bdw}{Q} \]
\[ Z_2 = \frac{b}{L} \]
\[ Z_3 = \frac{d}{L} \]

where

- \( b \) = mean width
- \( d \) = mean depth
- \( L \) = length
- \( w \) = fall velocity
- \( Q \) = discharge

By using a numerical reservoir sedimentation, see next section, the variation of trapping efficiency with these variables was determined.

The instantaneous trapping efficiency can then be determined for different times during the year and integrated to give the annual trapping efficiency.

NUMERICAL MODELS FOR PREDICTING SEDIMENTATION

Recently, with the availability of computers, it has been possible to develop numerical models of reservoir sedimentation. These models
calculate the water flow and sediment movement throughout the reservoir and can provide a reliable and detailed estimate of the impact of sedimentation.

Reservoir sedimentation results from a complex interaction of a number of physical phenomena. While water flow can be satisfactorily described our understanding of the movement, settlement and consolidation of sediment is not complete. Despite this, it is certainly possible to improve on how these processes are described in existing numerical models.

Most numerical reservoir models are time-stepping models. For given initial conditions, the equations are used to predict what happens in the reservoir over a short time-step. The process is then repeated a number of times over the required time period. The time-step used depends upon the size and nature of the reservoir but is typically of the order of a day. Once the geometry of the reservoir and incoming river, and the nature of the flow and sediment are specified, three modelling stages can be carried out: firstly of the reservoir’s storage, secondly of its flow and thirdly of the sediment transport within it.

Modelling reservoir storage

When flow enters a reservoir, its velocity drops dramatically and it is no longer capable of transporting the coarser sediment fractions. If the water level in the reservoir is near full supply level the sediment will be deposited near the head of the reservoir. If the reservoir is partially full then deposition will occur further into the reservoir basin and at a lower elevation. It is thus important to model the reservoir water level. The finer sediment will be carried further into the reservoir where its deposition is controlled by the opposing effects of particle weight and turbulence. To predict the reservoir water level a storage sub-model is used. The sub-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.

Modelling of flow

The water flow in the reservoir and the upstream river is determined using a backwater calculation. The water level predicted in the reservoir storage simulation, described above, 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 incoming river.

Modelling sediment transport

In modelling sediment movement the primary concern is deposition. The trapping efficiency and the location of the deposition depend on the volume of water stored in the reservoir. Since, however, the water level in the reservoir fluctuates and the inflowing discharge varies, sediment that has previously been deposited may be subsequently eroded. It is necessary, therefore, to be able to model both the
deposition and erosion of sediment. In performing such calculations, which are of a volumetric nature, due allowance is made both for initial density, and for subsequently increased density due to compaction by overlying deposition. From the calculated velocities, depths and slopes, the sediment concentrations at each section may be calculated, but when modelling the sedimentation process it is necessary to treat the sand and silt fractions separately. This is because sand movement depends only upon local hydraulic conditions, whereas silt movement is also influenced by preceding flow history.

Sand movement The transported sand sizes at each section are calculating using one of the many established sediment transport theories for non-cohesive materials, eg, Ackers and White (1973). The movement is dependent upon the sediment diameter. For sediments which do not contain too broad a range of different sizes a representative sediment diameter, D_{35}, is often used. For widely graded sediments the range of sediment sizes is divided into a number of classes each with a representative diameter.

Silt movement The concentrations of the silt fractions entering the reservoir depend on the drainage basin’s sediment yield and total annual runoff. The silt is convected with the flow but its concentration reduces as some of the material settles out of suspension onto the bed. The rate of settling is dependent upon the fall velocity which in turn is dependent on concentration and flow conditions. The calculation of the silt concentrations requires more closely spaced sections than for flow. The resulting transport rates of the silt fractions at each section are added to the sand transport rates to obtain the total sediment transport rate. The change in bed level at each section due to the variations in sediment transport rate along the reach can then be determined.

At the head of a reservoir different sediment sizes are sorted according to the ability of the flow to transport the material. Studies at HR have shown that to represent conditions in this region it is best to use a number of representative sand and silt sizes.

Predicting reservoir sedimentation using numerical modelling offers a significant improvement over other methods based on simple estimates of trapping efficiency. The method can readily take account of:

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

and can provide:

- volume, location and compaction of sediment deposited over a specified time period
- annual stage-storage curves
- longitudinal profile of the reservoir at any given time
- effectiveness of using sediment flushing to maintain storage capacity
FLUSHING SEDIMENTS THROUGH RESERVOIRS

Sediment flushing refers to the method of hydraulically clearing accumulated sediments from a reservoir, usually by releasing flow through low-level outlets at the dam.

As the low-level outlets are first opened in a reservoir with a high retention level, the local concentration of flow entrains the fine material deposits close to the outlet. This gives a false impression to a lay observer of extensive desilting of the reservoir. As soon as the local deposits are removed, this action stops. The velocity of flow away from the outlet decreases very quickly so that, in a relatively short distance, the velocity becomes too small even to move the fine material.

Sediment flushing is not effective unless the reservoir is drawn down to an extent that flow velocities over large areas of the deposited material are sufficient to create high sediment transport rates. Even then these hydraulic conditions have to be maintained for a significant period of time in order to remove the high volumes of sediments which will have been deposited over the previous months or years.

In practice this means that reservoirs have to be drawn down to a relatively low level for an extended period of time and for this reason the trend in recent years has been towards larger and larger low-level outlets. The proposed dam at Kalabagh on the River Indus, for example, has low-level outlets with a capacity of more than 4000 m³/s.

Whether sediment flushing is a practicable, economic proposition at particular reservoir sites depends on many factors:

(a) The ratio of the annual run-off to the reservoir volume must be high in order to provide the "extra" water required for flushing

(b) A climate with distinct wet and dry seasons is an advantage because flushing can take place early in the wet season and the

![Graph showing storage volume decrease over time for Kamativi, Zimbabwe.](image-url)
reservoir can be refilled to supply water through the following dry season
(c) Flushing is more likely to be an economic proposition for water supply schemes than for hydro-electric schemes because the need to draw down the reservoir for extended periods can have a major impact on power output.

Hydraulics Research's numerical reservoir sedimentation model was recently used (White and Bettess (1984)) to investigate whether the net annual water requirement \((1.1 \times 10^6 \text{m}^3)\) of the Kamativi Mine in Zimbabwe could be obtained by constructing a dam on the adjacent Gwai river. A range of heights for the proposed dam were considered, but all suffered from significant deposition.

The loss in storage against time for various proposed dam heights is shown in Figure 6. The large ratio of annual flow \((580 \times 10^6 \text{m}^3)\) 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 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, and in the case of Kamativi dam, showed that storage could be maintained for a considerable period of time, Figure 7.

![Figure 7: Effect of flushing on storage, Kamativi, Zimbabwe.](image)

REFERENCES


