*Recent Developments in the Explanation and Prediction of Erosion and Sediment Yield* (Proceedings of the Exeter Symposium, July 1982). IAHS Publ. no. 137.

# A proposed method for accurately calculating sediment yields from reservoir deposition volumes

J. P. JOLLY
*10-525 Hilson Avenue, Ottawa, Ontario K1Z 6C3, Canada*

ABSTRACT This paper proposes a means of developing a relation between sediment yield and the hydrological, geological and climatic characteristics of the upstream drainage basin, that can be used worldwide to estimate sediment loads at potential future reservoir sites. The most economical and accurate method of determining sediment volumes deposited in existing reservoirs will be found. This method will be then used to develop a relation between sediment yields and measurable upstream drainage basin parameters using data from many rivers.

## INTRODUCTION

There have been many reservoirs built throughout the world during the past 100 years. In most cases sediment has been deposited in the reservoirs and decreased the volume of live storage; thus decreasing not only the economic value of the reservoirs but also shortening their operational lives. In some cases, the amounts of sediment deposited in reservoirs have been similar to those that the engineers incorporated into their designs, and the reservoirs are functioning adequately. Other reservoirs have had higher rates of sediment deposition than estimated and are either providing smaller volumes of live storage during their design lives or have filled, or will fill, with sediments before the design periods are reached. Both occurrences result in serious economic losses with adverse sociological effects. This has occurred not because of a lack of competence on the part of the reservoir design engineers, but because of a paucity of information on the amounts as well as characteristics of the sediment that enters reservoirs during their design lives.

The world's average yield of sediment and solutes by rivers is equivalent to a lowering of the earth's surface by 3 cm every 1000 years or 42 t km$^{-2}$ of basin per year. The worldwide spatial distribution of the annual average is given in Table 1 which shows a range by continents from 27 t km$^{-2}$year$^{-1}$ in Africa to 600 t km$^{-2}$year$^{-1}$ in Asia. The latter continent's contribution represents 80% of the total. These averages can be misleading when considering individual drainage areas, since there are many streams in Asia that carry relatively little sediment and there are reservoirs in North Africa that have completely filled with sediment.

The magnitude as well as spatial variability of sediment yield can be seen from Table 2 which gives the annual suspended sediment yields of some of the world's major rivers. The average annual

*TABLE 1 Average suspended sediment discharge by continents*

| *Continents* | *Suspended sediment discharge:* (t km$^{-2}$year$^{-1}$) | (10 t year$^{-1}$) |
|---|---|---|
| *Africa* | *27* | *0.55* |
| *Asia* | *600* | *16.16* |
| *Australia* | *45* | *0.23* |
| *Europe* | *35* | *0.33* |
| *North America* | *96* | *1.99* |
| *South America* | *63* | *1.22* |

*Source: Gregory & Walling (1973), p. 342.*

yield varies from 3 to 1568 t km$^{-2}$. Also given in Table 2 are the worldwide rankings of rivers with respect to drainage area and mean annual flow. There is no correspondence between the three statistics. This is indicative of the direct influence of basin physiography and climate on sediment yields and indirectly on reservoir deposition rates.

When the statistics of world maximum average annual suspended sediment loads for individual gauging stations are reviewed (Table 3), it may be seen that the highest annual average is 8040 t km$^{-2}$, and the top 14 are higher than 2292 t km$^{-2}$. Thus reservoirs situated in tributaries and in the headwaters of large rivers may experience large sediment loads, and, because storage volumes are relatively small, the reservoir sediment deposition volumes may be very large.

The influence of physiography on sediment yields is demonstrated in Table 4 where yields are related to lithology for two geographic regions. The more resistant rocks are associated with smaller yields. Sediment yield as a function of climate has been studied by Wilson (1977) who obtained meaningful regression relationships between suspended sediment yield and precipitation, snowfall, thunderstorm occurrences as well as water balance for continental USA.

The preceding is an overview of the magnitude and controls of major basin sediment yields. Once the average annual sediment yield is known, a reservoir deposition volume can be determined by considering the reservoir trap efficiency for various stages of a project life.

If a stream sediment sampling programme has been carried out for a number of years near a proposed reservoir site, the engineer is fortunate. But even then he is usually faced with the problem of extrapolating a sediment discharge rating curve, the measured points of which were determined at low and medium flow rates, to determine sediment transport rates at flood stages when most of the sediment is transported. Some rating curve estimates of suspended sediment load have been found to involve errors of ±50% (Walling, 1977). In many regions sediment surveys have not been carried out or, if they have been, the record lengths are short and sporadic. These may give the

TABLE 2 Suspended sediment yields of selected worldwide major drainage basins

| River | Measurement location | Drainage area ($10^3$ $km^2$) | Ranking (size) | Ranking (flows) | Average annual yield (t $km^{-2}$ $year^{-1}$) |
|---|---|---|---|---|---|
| Ganges | Delta, Bangladesh | 1065 | 17 | 5 | 1568 |
| Yangtze | Chikiang, China | 1953 | 9 | 3 | 549 |
| Indus | Kotri, Pakistan | 932 | 19 | 23 | 510 |
| Mekong | Mukdaham, Thailand | 807 | 23 | 14 | 486 |
| Colorado | Grand Canyon, USA | 634 | (26)* | | 424 |
| Missouri | Hermann, USA | 1377 | (12)* | | 178 |
| Mississippi | Louisiana, USA | 3239 | 3 | 7 | 107 |
| Amazon | Mouth, Brazil | 5810 | 1 | 1 | 67 |
| Nile | Delta, Egypt | 2995 | 4 | 33 | 37 |
| Danube | Mouth, USSR | 820 | 22 | 21 | 27 |
| Congo | Mouth, Congo | 4036 | 2 | 2 | 18 |
| Rhine | Mouth, Holland | 146 | 43 | 38 | 3.5 |
| St Lawrence | Mouth, Canada | 1297 | 13 | 11 | 3.1 |

* Tributary.
Source: Gregory & Walling (1973), p. 333.

*TABLE 3 World maximum recorded suspended yields*

| *River* | *Location* | *Average annual yield ($t\ km^{-2} year^{-1}$)* |
|---|---|---|
| *Ching* | *Changchiashan, China* | *8040* |
| *Lo* | *Chuantou, China* | *7922* |
| *Waipaoa* | *Kanakanaia, New Zealand* | *6982* |
| *Tjatabon* | *Java, Indonesia* | *6250* |
| *Lo-Lo* | *Luyang, China* | *6068* |
| *Marecchia* | *Pietracuta, Italy* | *4570* |
| *Semani* | *Urage, Kucit, Albania* | *4150* |
| *Soldier* | *Pisgash, Iowa, USA* | *4072* |
| *Shkum Bini* | *Paper, Albania* | *3590* |
| *Kosi* | *Chatra, India* | *3130* |
| *Yellow* | *Shenhsien, China* | *2957* |
| *Indus* | *Kalabagh, Pakistan* | *2498* |
| *Santa Anita* | *Arcadia, California, USA* | *2374* |
| *Eel* | *Scotia, California, USA* | *2292* |

*Source: Gregory & Walling (1973), p. 333.*

engineer an approximation of sediment transport rates, but they are not adequate to provide accurate predictions. Moreover, if an adequate sediment sampling programme has been carried out at one location on a river for a long duration, the engineer is still faced with the problem of transferring the data to the proposed reservoir site. These limitations indicate the value of determining the amount of sediment carried by streams by other means, which can be easily used for any reservoir location. The method to be investigated relates sediment yield to the hydrological, geological and climatic characteristics of basins where data are available and applies the results to proposed reservoir locations where the sediment yield data are inadequate or non-existent.

*TABLE 4 Influence of rock type on sediment production estimated from studies of sedimentation in small reservoirs*

| *Lithology* | *Sediment Loss ($m\ km^{-2} year^{-1}$): Utah* | *New Mexico-Arizona* |
|---|---|---|
| *Resistant: conglomerate, limestone and resistant sandstone* | *143* | *95-143* |
| *Medium: friable sandstone* | *571* | *523* |
| *Soft: shale and gypsum* | *1237* | *761* |

*Source: Gregory & Walling (1973), p. 317.*

## METHODOLOGY AND OBJECTIVES

The overall objective is to collect data pertaining to sedimentation in existing reservoirs and then to synthesize the information into a form that can be used by engineers to produce more accurate estimates of sediment inflows. By applying trap efficiencies, the volume of sediment deposited in a proposed reservoir over a design duration can be estimated.

This can be achieved by determining the volume of sediment that has been deposited in a reservoir since it was initially filled. By converting this to a sediment transport rate using a trap-efficiency relation, the average sediment yield can be found. Data from many reservoirs can in turn be related to hydrological parameters that influence rates of erosion. Using this information more meaningful relationships can be found by considering reservoir size as well as shape, the hydrology and geology of the upstream drainage area and the regional climate. The end product will be a family of curves, which an engineer can use when designing a reservoir at a particular location. Hence an engineer by considering the topography of a proposed reservoir, the hydrology and geology of the upstream drainage area, and the regional climate can estimate the average annual rate of deposition and the reservoir's expected useful life.

This can be achieved by four steps which are:

(a) Collect flow and sediment data for existing reservoirs where the volumes of deposited sediments have been measured and information on the hydrology and geology of the upstream drainage area and the climate.

(b) Determine an economical and accurate means of finding the deposition rates of many existing reservoirs.

(c) Using the method established in step (b) above, determine the sediment deposition rates as well as pertinent upstream drainage area characteristics for as many reservoirs as possible, which when combined with existing reservoir data (step (a)) will provide enough information to establish an accurate regression equation for predicting average annual sediment yields.

(d) Using the statistics collected in step (a) and those found in step (c), determine the regression equation or equations that will enable average annual sediment yields to be accurately predicted from upstream drainage area and regional characteristics, and represent the results by design curves.

The reservoirs that will be analysed in step (c) will be some for which the original stage/capacity relations are known and for which recent bathymetric surveys as well as records of water levels are available.

The volume of deposited sediment can be found by a number of means; all are based on determining the reservoir bathymetry and converting the result into a stage/capacity curve. By comparing this curve with the stage/capacity curve derived from topographic surveys carried out before a reservoir was created, the total volume of sediment deposited can be found. From this the average annual sediment deposition rate can be calculated using the density of deposited sediment, which can be found from the grain size distribution and the duration that the sediment has been deposited.

There are currently four means of determining reservoir bathymetry. They are:

*Depth sounding survey* This consists of electronic echo sounding and positioning from a small boat. This method has been undertaken on a number of reservoirs and has been found to give precise, accurate results. The cost per reservoir is relatively high.

*Depth sensing method* Another means of determining reservoir volumes depleted by sediment deposition is by using Landsat spectral data to obtain information on reservoir surface area at different dates when the water surface is at various levels throughout the operating range. By delineating the surface areas of a reservoir and using the water surface elevations, incremental reservoir volumes can be calculated. By adding these incremental volumes a new stage/capacity curve can be determined, and by comparing it with the original one, the volume of sediment deposited can be found. This may be the most promising method, since most hydroelectric and irrigation reservoirs have water levels that vary over a wide range each year thus providing incremental volume determinations over the operating range.

*Numerical modelling* The one-dimensional equations governing sediment transport and deposition are those of continuity, momentum and sediment continuity. This system of equations has been incorporated into a computer model by the US Corps of Engineers known as HEC6 (Chen *et al.*, 1978). For determining the volume of sediment that has been deposited in a reservoir in which sediment inflow concentrations are not known beforehand, the model will be run with discharges specified, and when the calculated depths of deposited sediment at four locations along the longitudinal axis match the measured depths, the calculated depths at other grid points representing the reservoir longitudinal profile will be used to determine the volume of deposited sediment.

*Empirical area reduction method* Another method of determining reservoir sediment deposition volume is to use the US Bureau of Reclamation empirical area reduction method (Borland & Miller, 1960) obtained from resurveys of 30 US reservoirs. The results indicated that a relationship between water depth as a % of total reservoir depth and sediment deposition depth as a % of total reservoir sediment volume exists for each of four different reservoir shapes. From the initial depth/capacity curve for a reservoir and graphs relating relative cross sectional areas and deposition volumes to relative depths as well as a few current point depth measurements, the volume of deposited sediment and its distribution within a reservoir can be found.

## PROPOSED STUDY PROCEDURE

Information on reservoirs which have been used in previous sediment yield equation development will be collected and studied. Also data on reservoirs where recent bathymetric surveys have been conducted will be obtained so that those that will be studied can be selected.

For step (b) it is recommended that five medium-sized reservoirs which have been in existence for more than 30 years and which have good inflow data should be selected. Reservoir deposition rates will be established by the depth sensing, numerical modelling and empirical area reduction methods. The results will be compared with the depth sounding results, and the average annual sediment transport rates related to inflow hydrological characteristics. When this has been done, the relative costs as well as the accuracies of the sediment deposition determinations can be assessed and the graphical relationships studied in order to obtain a first indication of the results which are sought. Once this has been done a programme can be developed, using the most feasible method of determining deposition rates, to provide data for a sufficient number of existing reservoirs in drainage areas of various geological types to define an accurate regression relationship between average annual sediment transport rate and hydrological as well as other basin characteristics.

The study procedure for each reservoir would be:

(a) Obtain statistics on reservoir characteristics and operating procedures as well as information on drainage area hydrology, geology and climate.

(b) Select Landsat scene dates when the reservoir water levels were at various levels throughout the operating range and the reservoir area was cloud-free (it is desirable to obtain six scenes).

(c) Obtain Landsat spectral data for these dates and carry out multi-spectral analyses to determine reservoir surface areas and in turn determine the reservoir stage/capacity relationship. Using the original storage/capacity curve, compute the volume of deposited sediment.

(d) Using five bathymetric measurements along the reservoir longitudinal axis and the numerical model, compute the existing reservoir bathymetry and from it the stage/capacity relationship as well as the volume of deposited sediment.

(e) Using the original stage/capacity curve for the reservoir and the five bathymetric measurements, estimate the volume of deposited sediment using the empirical area reduction method.

After this has been completed for five reservoirs, the sediment deposition results will be compared with regard to accuracy and costs of each of the three methods, with the results of the recent depth sounding surveys. The results will be converted into average annual sediment yields and related to known hydrological, geological and climatic characteristics in order to study in a preliminary way the relationship between sediment yield and upstream parameters.

After the above analyses have been carried out and the most accurate and economical method of determining annual average sediment deposition rates has been found, the procedure can be used to provide data from a sufficient number of reservoirs to derive a meaningful regression relationship between average annual sediment yield and drainage basin characteristics:

(a) Convert the sediment volume to t by using the density and the deposited sediment which has either been measured directly or determined from the proportion of sand, silt and clay in the deposits.

(b) Divide by the duration that the reservoir has been operating to determine the average annual deposition rate.

(c) Considering the size of reservoir and its mode of operation, determine the average trap efficiency applicable for the deposition period.

(d) From (b) and (c) above determine the average annual sediment yield entering the reservoir;

(e) Study the hydrology of the drainage area, in particular the inflow characteristics during the reservoir deposition period, and the geology and the regional climate and relate the annual sediment yields to hydrological, geological and climatic variables by regression techniques.

## USE OF RESULTS

The main objective of this study is to analyse the accuracy and economics of four methods of determining reservoir deposition rates and in turn sediment yields. Another objective is to study the obtainable relation between sediment yield and hydrology, geology and climate in a preliminary way in order to assess whether, if an accurate and economically feasible means of determining sediment yield is found, sediment yields for many drainage areas can be related to easily obtainable drainage basin parameters.

Once the sediment transport rates are found, then hydrological parameters, such as average wet season flow or average annual flow, can be obtained by studying the records from streamgauging stations located upstream, but near the reservoir, or by considering the records of reservoir outflow and changes in reservoir water level. Once a number of reservoir surveys and hydrological analyses have been carried out, a regression analysis can be undertaken to determine the best equation to describe the relationship between the variables.

The output of the two proposed studies will be curves of annual sediment transported in a stream versus measurable hydrological characteristics of the drainage basin. Different curves will represent various basin geologies and climates. The data will be obtained from various parts of the world; hence the relations should be useful to an engineer faced with estimating sediment deposition rates for proposed reservoirs in any geographical region.

## REFERENCES

Borland, W.M. & Miller, K.R. (1960) Distribution of sediment in large reservoirs. *Trans. ASCE* 125, 160-180.

Chen, Y.H., Lopez, J.L. & Richardson, E.V. (1978) Mathematical modeling of sediment deposition in reservoirs. *J. Hydraul. Div. ASCE* 104 (HY12).

Gregory, K.J. & Walling, D.E. (1973) *Drainage Basin Form and Process*. Edward Arnold, London.

Jansen, J.M.L. & Painter, R.B. (1971) Predicting sediment yield from climate and topography. *J. Hydrol.* 21, 371-380.

Walling, D.E. (1977) Limitations of the rating curve technique for

estimating suspended sediment loads, with particular reference to British rivers. In: *Erosion and Solid Matter Transport in Inland Waters* (Proc. Paris Symp., July 1977), 34-48. IAHS Publ. no. 122.
Wilson, L. (1977) Sediment yield as a function of climate in United States rivers. In: *Erosion and Solid Matter Transport in Inland Waters* (Proc. Paris Symp., July 1977), 82-92. IAHS Publ. no. 122.