PHYSICAL PROCESSES GOVERNING RESERVOIR SEDIMENTATION

by

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ABSTRACT

Reservoir sedimentation results from the interaction of several physical processes governing the upstream sediment supply and the reservoir trap efficiency. The sediment supply depends on the sediment source from upland areas and the sediment yield is controlled by the channel system that conveys the sediment load to the reservoir. The trap efficiency depends on the physical characteristics of the reservoir and the particle size distribution of the incoming sediment load. The life expectancy of a reservoir is usually calculated from the ratio of the storage capacity to the mean annual sediment yield trapped in the reservoir.

The analysis of reservoir sedimentation requires understanding of the governing physical processes to predict possible changes in sediment yield during the lifetime of a reservoir. Foreseeable perturbations to the hydrologic and hydraulic regime caused by changes in land use can trigger future increases in sediment supply, thus reducing the life expectancy of a reservoir. GIS-based soil erosion models assist engineers in the analysis of increased sediment supply related to demographic expansion, deforestation, altered land use and agricultural practices. Sediment conveyance in the drainage network can be determined through comparative analyses of sediment rating curves for different periods, increasing vs decreasing discharge, and washload vs bed material load. A risk analysis of extreme events capable to fill the entire reservoir within a short period of time is particularly important in the design of small reservoirs. Finally, flocculation can largely increase the trap efficiency of the fine sediment load over standard calculations based on experiments without flocculation. Conversely, sediment consolidation can extend the life expectancy of a reservoir.

INTRODUCTION

Man-made reservoirs usually satisfy multiple objectives including flood control, irrigation, hydro-power generation, water supply, boating, fishing and recreation, etc. Since most surface waters also carry substantial amounts of sediment, large reservoirs induce sedimentation which depletes the reservoir storage capacity over several years. Reservoir sedimentation rates result from the complex interrelationships between climate, drainage basin, fluvial system and human activities (Simons and Senturk, 1992). Proper determination of the future reservoir capacity becomes a difficult task for an engineer dealing with the design, maintenance and operation of a reservoir normally built with a life expectancy of more or less 100 years. In relation to the sediment regime, the engineer has to determine: 1) the "usable life" of a reservoir

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defined as the period through which the capacity of a reservoir occupied by sediment does not affect the primary purpose; and 2) the "full life" defined as the number of years for the capacity to be fully depleted by sedimentation. The challenge in predicting the water and sediment supply to reservoirs emerges from understanding the physical processes governing the river response to a watershed environment detrimentally affected by demographic expansion.

The main reservoir sedimentation concern relates to estimating the life expectancy of a reservoir. With reference to Figure 1, life expectancy depends on the number of years necessary to deplete the dead storage capacity (useful life) or full capacity (full life) of a man-made lake. However, the storage capacity depends in the first place on the engineers themselves, i.e. upon dam site, reservoir configuration, type of dam, operating schedule, possibility of sediment flushing, etc. Secondly, it depends on the whole fluvial system as it changes with time, on which the engineers have less influence: variability in water and sediment inflow, development of natural resources, changes in land use in the drainage basin, natural hazards, etc. Sediment eroded from upland areas, gullies, streambanks and stream beds are transported with different time intervals in the fluvial system depending on runoff, flow discharge and size of sediment, until the hydraulic conditions are conducive to sedimentation. Sediment is carried either as bedload or suspended load. As the stream approaches the reservoir, the sediment transport capacity decreases due to flow deceleration, resulting in sedimentation. Coarse material forms a delta at the head of a reservoir; the suspended sediment load settles throughout the reservoir and clay fractions usually form a density current which generally moves slowly through the reservoir toward the foot of the dam. Therefore, storage losses over time, in terms of active or dead storage, are normally simultaneous, as delta formation at the head of the reservoir directly affects the active storage and the river upstream from the reservoir, while the finer particles usually settle in the dead storage. This means that, from technical, economical and environmental points of view, not only the full life of a reservoir must be considered, but also each phase of life in regard to each purpose.

The Molineros project in Bolivia illustrates the importance of reservoir sedimentation (Frenette et al., 1983). Located on the Caine River in the Bolivian Andes south-east of Cochabamba, the site, head and discharge were suitable for hydropower production. The reservoir itself would have been 45 km long in a narrow gorge. In 1970, the first feasibility studies guaranteed a life time exceeding 50 years based on the average sediment supply. In 1983, the reevaluation of the project consisted of a 132 MW surface powerhouse with a 200 m high dam and 1.98 km3 of live storage and 2.98 km3 of total storage. The concern was a steep watershed covering 9530 km2 with only 20% ground cover, easily eroded sandstone, siltstone, shales and marls responsible for a large sediment load in the Caine River. Two tributaries, the Tapacari and the Arque Rivers, drained 35% of the total basin but contributed to 60% of the sediment load. With an average sediment load estimated at 110 million tons per year, the life expectancy had to be reduced to about 35 years. This example illustrates the importance of sedimentation problems through time in the design of large dams. Typically, four aspects need to be considered: 1) the sediment source from the drainage basin; 2) the sediment yield from the inflowing rivers; 3) the reservoir characteristics; and 4) the possible changes of these conditions during the expected life time of a reservoir.
Figure 1. Typical flow and deposition pattern in a reservoir.
SEDIMENT SOURCE

To understand the problem, one must recall that during a basin's geological history, the climatic variables operating on complex physiographic and geologic variables, have shaped the basin and established an equilibrium between the nature, type and quantity of sediment available for transport and conveyance through the river channels. Those processes are highly variable, responding to ever-changing climatic input and to variations in erodibility of the geologic formations. Throughout history, mankind has altered land use, resulting in accelerated erosion rates. Climate and now mankind determine the character and the behavior of a drainage basin by operating on its complex physiographic and geological parameters. Man's interaction with drainage basins is relatively recent and may cover a moment of time compared to changes at geological time scales, but the changes can nevertheless be significant.

Upland erosion can be investigated as a probabilistic problem (Julien and Frenette, 1985; Julien and Dawod, 1987), but the Universal Soil-Loss Equation (USLE) remains the primary method to calculate average soil erosion losses. The USLE relates mean annual soil erosion losses $A$ to the physical characteristics of upland areas in terms of rainfall erosivity $R$, soil erodibility $K$, surface runoff length $L$ and slope steepness $S$, cropping-management factor $C$ and soil conservation practice $P$:

$$A = R K L S C P$$ (1)

The evaluation of mean annual soil erosion losses on a watershed is straightforward as long as the six parameters on the right-hand side of (1) can be determined on the entire watershed (e.g. Frenette and Julien, 1986a; 1987). Models have been developed in which the spatial distribution in mean annual soil losses can be evaluated and soil erosion maps can be plotted. Mapping soil erosion losses primarily depends on the combination of two factors: 1) topography described by slope steepness; and 2) vegetation cover characterized by forest versus agricultural and pasture land. Correction factors for different grid sizes were developed by Julien (1979, 1982) and Julien and Frenette (1987). For instance, the model of Julien and Frenette (1986) was first developed for large watersheds at a 2 km resolution (see Figure 2). The model has also been used in Europe at a 250 m resolution by Julien and Gonzalez del Tanago (1991). Nowadays, results at a 30 m resolution are possible as shown in Figure 3 from Noss and Julien (1996). Developing trends in this field are linked to: 1) rapid developments in computer technology and increased computational speed; 2) the availability of large data bases through Geographic Information Systems (GIS) with fine spatial resolution at 30 m for topography, soil type, land use and vegetation; 3) availability of spatially distributed rainfall data from polarized dual-Doppler radars with rainfall precipitation fields every five minutes; and 4) the development of two-dimensional algorithms for the calculation of surface runoff and sediment transport for moving rainstorms. Recent advances in this field can be found in Julien et al. (1995) where two-dimensional simulation of surface runoff generated from rainstorms is possible with radar-rainfall data and a spatial distribution of the watershed parameters.

Predicting the future trends in reservoir sedimentation from existing sediment data requires consideration of possible changes in drainage basin characteristics, such as demographic expansion, uncontrolled deforestation, forest fires, overgrazing, improper tillage methods, unwise agricultural practice, natural hazards and future programs of soil conservation. Man-made lakes
invariably imply technical, environmental and economical concerns for each phase of development, i.e. periods of construction, water and sediment storage, exploitation and post-exploitation. Consideration must also be given to possible changes in the soil erosion parameters over the expected life of the reservoir. From the six parameters of the USLE in (1), one may expect some parameters to remain fairly constant like the soil type and topography in slope length and steepness. The climate may change but it remains to be demonstrated that significant climatic changes from humid to dry climate or desiltification is possible during the life time of a reservoir. On the other hand, changes in cropping-management factor and soil conservation practice can be significant and the time response is almost immediate. Deforestation, increased agricultural use and change in soil conservation practices directly increase soil losses from upland areas. Changes by up to an order of magnitude are possible, considering that the parameter $C$ for forested land is about 0.01 as compared to $C=1$ for bare soils. The consequences of deforestation can be devastating if one considers that not only the upland erosion losses will locally increase by up to two orders of magnitude, but the peak runoff discharges will also increase in the drainage system to accelerate the delivery of sediments.

Peligre Dam in Haiti was built in 1956 on the Artibonite River basin covering 6615 km$^2$ (Frenette et al., 1982a; 1982b). The planners had estimated an annual silting rate of 3.5 hm$^3$/yr, corresponding to a life expectancy of 180 years. A quick drawdown in 1977 showed a total stockage of sediment higher than expected. The sediment load estimated between 1977-79 exceeded 9.9 million tons per year. The analysis showed that the actual sedimentation rate in the reservoir had gradually increased from 3.3 hm$^3$/yr in 1956-61 to 10 hm$^3$/yr in 1977-79. A comparison of areal photographs during the same period showed significant deforestation of the river basin and a corresponding increase in agricultural land with rill and gully erosion in steep areas (Figure 4). Values of the mean annual flow from 1944 to 1977 increased as shown in Figure 5. Sediment discharge since 1956 steadily increased at an average rate of 18% per year. The rate of sediment accumulation in the reservoir almost tripled within 20 years as shown in Figure 6. As a consequence, 50% of the active storage was now expected to be depleted by 1995 instead of year 2039 predicted from design conditions, as shown in Figure 7.
Figure 2. Map of soil erosion on a large watershed in kt/km\(^2\) at a 2 km resolution.

Figure 3. Goodwin Creek erosion rates at a 30 m resolution.
Figure 3: Goodwin Creek erosion rates at a 30 m resolution
Figure 4. Change in land use between 1956 and 1978, Artibonite Watershed, Haiti.

Figure 5. Mean annual flow at the dam site: 78 m$^3$/s and average progression since 1944.
Curve no. 1: sediment inflow considered for the design ($Q_s = 3.3 \text{ hm}^3/\text{yr}$);

Curve no. 2: accumulated volume of sediment in the reservoir taking into consideration the progressive degradation of watershed, excluding the compaction of the sediment deposit (e.g. real conditions (T.V. = 187 hm$^3$);

Curve no. 3: idem to Curve no. 2, including compaction (T.V. = 135 hm$^3$);

Curve no. 4: historical progression of silting obtained by the model following a quadratic form.

Figure 6. Simulation of the accumulation of sediment in reservoir since 1956: a) increasing of specific degradation, b) rate of reservoir sedimentation.
Figure 7. Life exceedancy of the active storage versus time.
SEDIMENT YIELD

There is no uniformity in the assessment of methods used to predict the life expectancy and the environmental effects of a reservoir. Normally, surveys and observations made before construction are used to evaluate the foregoing risk, mainly based on average data generally obtained during record periods as short as a few years. Due to lack of information, often the practice is to proceed by statistical or regression analysis, relating the short sediment concentration or sediment load record to a normally longer flow discharge record. The incoming sediment load is usually measured at gaging stations. Flow and sediment measurements define the sediment-rating curve. The sediment-rating curve is typically highly scattered and daily sediment discharge covers several orders of magnitude. It is important to realize that a single point on the upper part of the sediment-rating curve can correspond to a daily sediment load in excess of 10,000 times the daily sediment load at low discharge.

The example of the Chaudière River in Canada in Figure 8 illustrates the scatter related to daily sediment discharges. The sediment-rating curve is widely scattered and the highest daily sediment load at 70,000 tons far exceeds the low values around 3 tons. The extremely high sediment load during a single day is thus equivalent to the extremely low daily sediment load of about 20,000 days!

The annual suspended sediment yield is obtained from the sediment-rating curve and the flow-duration curve. Experience indicates that the method is not reliable when: 1) the period of record is too short; 2) insufficient data at high flow is available; and 3) the sediment-rating curve shows considerable scatter. Often, rating curves are different during the rising limb than the recession limb of the hydrograph. Different sediment-rating curves have also been observed between low flows and high flows.

The Indus River supplies water and sediment to Tarbela Reservoir in Pakistan (Lowe and Fox, 1982; Julien, 1995). The reservoir spans over 80 km and the storage capacity is 13.9 km³. Surface runoff and sediment load depend primarily on melting snow and the sediment load varies monthly as shown in Figure 9. Sediment-rating curves are also shown to vary on a monthly basis in Figure 10.

The importance of extreme events is well-illustrated with the example in Tunisia in 1969 where three consecutive floods with a period of return of 40, 46 and 60 years respectively carried the equivalent of 20 years of sediment in the Zerou and Merguellel rivers in only 13 days.

Hurricanes usually have devastating consequences on reservoirs. For instance, hydrologic studies estimated the mean annual flow at 4.9 m³/s and the 100 year flood at 350 m³/s on the Ravine du Sud in Haiti. Since 1980, four extreme events including hurricanes Allen in 1980, Gilbert in 1988 and Gordon in 1994 flooded the river at a discharge exceeding 500 m³/s, with Gordon estimated at 700-800 m³/s. Compared with sediment loads ranging from 1000-1500 m³/year prior to 1980, single extreme events added 300,000-500,000 m³ to the sediment load within a few days. Consequently, the River du Sud doubled its width since Gordan and aggraded about 3 m in 2 years. Floods affected 800,000 people and the irrigation network in operation since 1759 had to be abandoned.
Figure 8. Sediment-rating curve of the Chaudière River.

Figure 9. Discharge and sediment load, Indus River.
Figure 10. Sediment-rating curve, Indus River.
The time pattern of sediment graphs shows that most of the sediment load is transported during floods with devastating consequences during extreme events. In order to give full weight to the total sediment inflow, observations must be concentrated during high flows. Unfortunately, in too many cases, field measurements are not available during extreme periods.

Difficulties arise in measuring bedload transport and more than often one must rely on bed load equations. Armored beds in mountain streams are frequent and the composition of bedload is different from that of the bed material. In some cases, consolidated clays are found underneath a thin layer of alluvium covering the bed and easily washed out at high flows. The calculated load can be very different from the actual load. The bedload is often arbitrarily assumed to be 10% of the total load.

Long-term sampling of the sediment load is required for a statistically reasonable prediction of the mean annual sediment load. Yet for most rivers, the correlation coefficient between water and sediment discharge is low. The discharge record is usually longer than the sediment record and the missing sediment record is estimated from the poorly correlated sediment-rating curve. With significant dispersion around the average value and the correction factor for log-transformed data, the lack of reliable sediment data can yield inadequate long-term estimates of the mean annual sediment load.

The Oldman River in Alberta has been monitored for twelve years. Water and sediment discharge data are shown in Figure 11. The variability in sediment discharge far exceeds the variability in water discharge. For instance 63% of the total sediment volume was measured in only three years (about one year out of four). In 1975, the sediment load was 350% of the mean annual sediment load estimated at 340,000 tons for the 12 years of record. Comparatively, the liquid volume during the same year was only 30% greater than average. Based on extreme values of sediment load, the life expectancy of a reservoir would be underestimated by 200 to 300%. Conversely, when the extreme values of sediment load are not considered, the life expectancy would now be overestimated by 200 to 300%. The variability in the annual sediment load cannot be neglected in the analysis of the life expectancy of reservoirs.

Provided that a sufficiently long sediment record is available, the period of return of annual and daily sediment load can be determined. As an example, the case of the Oldman river in Alberta is given. A good agreement with the log-normal distribution is shown in Figure 12 with annual sediment load data. A complete analysis of the life expectancy of a reservoir must include a risk analysis of the probable occurrence of extreme events during the construction phase as well as during the early life of a reservoir. For instance, the annual sediment load with a period of return of 100 years (P=0.01) of the Oldman river in Figure 8 is approximately 4 million tons, which is more than ten times the mean annual sediment load. In other words, the 100 year sediment load is equivalent to about ten years of mean annual sediment load. The occurrence of a single extreme event, and sometimes a single flood, can have a detrimental impact on the life expectancy of reservoirs designed for a "short" period of time, e.g. 30 years. For a reservoir with a 30 year life expectancy, one must face the possibility, albeit of low probability, that the 100 year sediment supply may occur in the next three years, in which case about a third of the storage capacity could be depleted sooner than anticipated.
Figure 11. Flow and sediment discharge between 1967 and 1978, Oldman River.
Figure 12. Probability vs. annual sediment load, Oldman River, Brocket station.
Recent advances in the analysis of sediment-duration curves is presented by Julien (1996). Accordingly, daily sediment load data can be plotted as (- ln P) versus ln Q_s where P is the exceedance probability and Q_s is the daily sediment load. A linear fit on this diagram gives a transform exponent \( \hat{b} = 2 \) and it is demonstrated that the value of the daily sediment load with exceedance probability P can be approximated by:

\[
Q_s \approx \left( \frac{\ln(P)}{2} \right)^2 \bar{Q}_s
\]

(2)

where \( \bar{Q}_s \) is the mean sediment load. An example is given in Figure 13 for the Colorado River at Lee's Ferry based on five years of daily records from 1955-59.

For the Molineros project in Bolivia, the analysis of extreme events in Figure 14 showed that 95% of the sediment load corresponds to a water discharge that is exceeded only 8% of the time; and 50% of the sediment load corresponds to a discharge that is exceeded only 2% of the time (Frenette and Julien, 1986).

**RESERVOIR CHARACTERISTICS**

Sedimentation in many reservoirs encroaches on the active storage, thus reducing the flood attenuation capacity. This eventually interferes with flood control objectives. Therefore, the operation of the dam should be expected to change over time. Future investigations could prove that the sedimentation rate is much higher than estimated during the design phase.

Churchill (1948), Brune (1953), Brown (1958) and others have shown that the trap efficiency of any reservoir, defined as the ratio of the deposited sediment to the total sediment inflow, is guided by two dominant factors: 1) the relation of capacity to inflow; and 2) the inflowing sediment content. The capacity-inflow relation corresponds to the detention time, highly dependent upon the upstream river regime and the size and geometry of a reservoir. It also depends on its age since the reservoir storage capacity decreases with time. Among other factors affecting the long-term storage capacity, one can cite the pattern of deposition through time, consolidation effects, density currents, sediment flushing, and dam operation. Hence, on a long-term basis, the trap efficiency of a reservoir gradually decreases.

Borland (1971, 1975) introduced a new approach showing the relation between the fraction of material deposited, the settling velocity of the suspended material and the capacity-inflow of a reservoir:

\[
T \ E = 1 - e^{-1.055 \frac{L \omega}{v d}}
\]

(3)

where TE is the fraction of sediment deposited in the reservoir; L is the total length of the reservoir; \( \omega \) is the fall velocity of the sediment; \( V \) is the mean flow velocity in the reservoir; and \( d \) is the flow depth.
Figure 13. Exceedance probability plot for daily sediment discharges in the Colorado River at Lee’s Ferry.

Figure 14. Flow duration curve and inflow of sediment, Molineros project, 1972-1982.
The conversion of the incoming sediment weight to volume requires knowledge of the specific weight of the material. This poses no problem for material coarser than 0.1 mm as the specific weight does not vary significantly around 1300 kg/m³. The presence of finer material, however, causes consolidation over time. The method of Miller (1953) has been widely used. It is important to note that the process of consolidation may increase the life expectancy of a reservoir by as much as 20%.

The deposition pattern in Peligre Reservoir in Figure 15 showed that about 85% of the sediment deposited in the downstream reservoir was clay. While it was expected that only 50 to 60% of the incoming clay sediment load would settle in the reservoir, field observations showed that about 100% of incoming clay particles settled between 1956 and 1979. Laboratory tests of sedimentation versus detention time in Figure 16 show very different results between flocculated versus deflocculated rates of silting depending on water quality and sediment concentration. Water quality tests of the reservoir water confirmed that the potential for flocculation is high because of the calcareous content of inflowing waters. The phenomenon of consolidation of sediment accumulated in the reservoir can extend the life expectancy of a reservoir. This effect can only be substantial for fine sediments (silts and clays) after a long period of time. Sediment consolidation is most effective when the reservoir operation includes frequent drawdowns. The example of the Peligre Reservoir in Figure 6 shows that the life expectancy could be extended five years after a period of 20 years, as viewed by comparing curves #2 and #3 in Figure 6.

CONCLUSIONS

The challenge in predicting the water and sediment supply to reservoirs emerges from understanding the physical processes governing the river response to a watershed environment detrimentally affected by demographic expansion. Reservoir sedimentation is the result of the combination of volume of sediment supplied to a reservoir and the ability of a reservoir to trap the incoming sediment load. The sediment supply depends on the sediment source from upland areas and the sediment yield depends on the efficiency of the channel system to convey the sediment load to the reservoir. The life expectancy of a reservoir is calculated from the ratio of the reservoir storage capacity to the mean annual sediment yield trapped in the reservoir.
Figure 15. Deposition patterns of Peligre Reservoir.

Figure 16. Settling of sediment with time.
The analysis of sedimentation in several reservoirs indicates that improvements over existing methods are possible through better understanding of the governing physical processes, particularly those related to possible future changes in sediment source available for sediment transport. Foreseeable changes in land use with time can trigger significant increases in incoming sediment source, hence reducing the life expectancy of a reservoir. GIS-based hydrologic and sediment transport models can assess the effects of expected changes in land use due to expected demographic expansion in the reservoir drainage basin. Improved analysis of sediment-rating curves is warranted, particularly those comparing substantial data bases for different periods, increasing vs decreasing discharge, and washload vs bed material load. A risk analysis is required for extreme events conducive to fill small reservoirs within a short period of time. Finally, the trap efficiency of fine sediment in reservoirs deserves careful consideration of possible flocculation and consolidation.

REFERENCES


