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Hydrolink

PREDICTING RESERVOIR CAPACITY LOSS FROM SEDIMENTATION AT LARGE INDIAN DAMS

BY DAVID C. FROEHLICH

Eroded sediment transported by natural streams tends to settle out when it enters the comparatively calm water of an artificial lake (a reservoir) created by a dam. The rate of water storage loss depends on the annual sediment load carried by the streams and the extent to which that material is kept in the reservoir. The amount of sedimentation is controlled by a number of factors including the area and geologic origin of the catchment, the land uses (cultivation practices, grazing, logging, construction activities, and conservation practices), the amount of rainfall, the reservoir storage capacity, the duration of storage in relation to the sediment load of the stream, the particle size distribution of sediment, the planform configuration of the reservoir, the location and size of sluices and other outlet works at the dam, and the method and purpose of water releases through those outlets.

As time passes, a reservoir continues to fill with sediment, which reduces the available storage volume and may interfere with the operation of dam outlet works and hydropower intake structures (Figure 1). The question that needs to be answered is: How long will it take before the functions of the dam and its reservoir are so severely affected by sedimentation that continued operation becomes untenable? The rate of sedimentation in a proposed or existing reservoir may be estimated in the following ways[1]:

1. From sediment discharge rating curves combined with flow-duration relations on significant streams entering the reservoir. The sediment discharge rating curves may be prepared using measured or calculated values of sediment loads.
2. From calculations of the total amount of land surface erosion, the ability of the sediment to be transported to the impoundment, and the reservoir trapping efficiency.
3. From predictions based on sedimentation in existing reservoirs in which the accumulated deposits have been surveyed over a lengthy period.

It is the third approach that is followed here. The data are obtained from a compendium of storage loss from siltation at 243 reservoirs in India[2]. Mathematical models are developed that relate reservoir capacity loss to catchment area, reservoir surface area, the original storage volume, and the time since the first filling of the impoundment. Models prepared for sedimentation of reservoirs found on the eastward and the westward-flowing regions differ significantly. The formulations give good fits to the assembled data and allow an uncomplicated calculation of the half-life of reservoirs (that is, the time needed for the storage capacity to be reduced by 50%), which offers a measure of when sedimentation will have a significant adverse impact on functioning.

Analysis of Reservoir Capacity Loss and Half-Life

Estimating the amount of sedimentation in a reservoir could require extensive calculations of the sediment yield from the catchment, the amount of eroded soil that is transported to a reservoir, the additional sediment inflow contributed by stream channel bank and bed erosion, and the quantity of water that flows into the impoundment. However, a more simple and faster approach to estimating reservoir sedimentation is developed here by analyzing

Figure 1. Sediment accumulation reduces storage volume and may interfere with the operation of dam outlet works. Removal of sediment by dredging or excavation (as shown in the photograph of the Maneri Bhali Stage 1 dam during maintenance of the spillway.) may be needed to enable the dam to function.

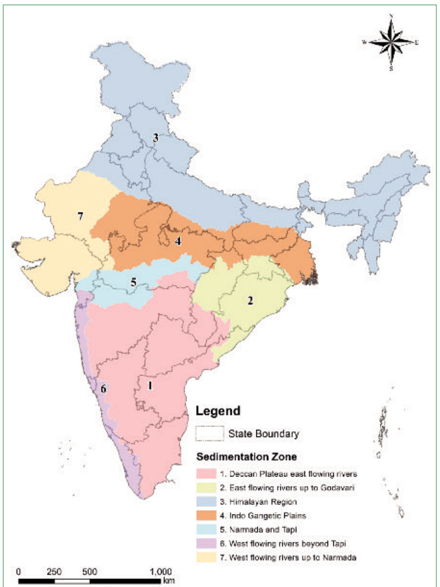


Figure 2. Sedimentation Zones of India[2]

data from the compendium of siltation in reservoirs at large Indian dams[2] where the accumulated deposits have been surveyed over a suitable period. The compilation divides India into seven sedimentation zones as shown in Figure 2. Zones 1, 2, 3 and 4 cover geographic regions in which rivers flow eastward to the Bay of Bengal, while Zones 5, 6 and 7 encompass areas where rivers flow westward into the Arabian Sea. After filtering the data, 130 reservoirs on eastrward-flowing rivers and 90 reservoirs on westward-flowing rivers were analyzed.

Reservoir Capacity-Loss Calculation

For both eastward and westward-flowing rivers, a general mathematical model of the form:

$$\ln\hat{Y} = \theta_1 + \theta_2 \ln A_c + \theta_3 \ln A_r + \theta_4 \ln C_o + \theta_5 \ln T \quad (1)$$

provides a linear relation for $\ln\hat{Y}$ with constant variance and good fits to the assembled data, where $\hat{Y}$ expected value of reservoir capacity loss in Mm³, A_c = catchment area in km², A_r = surface area of the reservoir when filled to the controlled retention level (FRL) in km², C_o = initial storage capacity of the impoundment in Mm³, and T = time in years since the initial filling of the reservoir. Values of the parameters θ_1 to θ_5 were found using multivariate optimization and were slightly rounded to obtained the following relations (after transformation from logarithms) for $\hat{Y}$:

$$\hat{Y} = \begin{cases} 0.0064 A_c^{0.10} A_r^{0.05} C_o^{0.8} T^{0.90}; & \text{eastward flowing rivers} \\ 0.030 A_c^{0.15} A_r^{0.30} C_o^{0.5} T^{0.65}; & \text{westward flowing rivers} \end{cases} \quad (2)$$

The coefficient of determination of Eq. (1) fit to the 130 reservoirs on eastward-flowing rivers is 0.929, and the residual standard error is 0.600. Predicted Y_{east} values are plotted against measured values in Figure 3. Similarly, for the 90 reservoirs on westward-flowing rivers, the coefficient of determination is 0.880, and the residual standard error is 0.496. Predicted values of Y_{west} are plotted against measured values in Figure 4.

The expression for the loss of reservoir storage volume on westward-flowing rivers Y_{west} varies significantly from the equation for Y_{east}. While the relative influence of A_c is the same, the remaining independent variables have different effects on reservoir capacity loss. The most significant difference is related to time. All other factors being the same, capacity loss of reservoirs on westward-flowing rivers is considerably slower than on eastward-flowing streams resulting in a comparatively longer half-life. Regional reservoir sedimentation differences are the result of combined meteorological and geological influences on land surface runoff and sediment yield.

Reservoir Half-Life Calculation

Reservoir half-life is determined from Eq. (2) by setting Y/C_o = 0.5 and solving for T to obtain

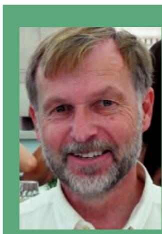
$$T_{50\%}(\text{years}) = \begin{cases} [74.2 A_c^{-0.15} A_r^{-0.1} C_o^{0.3}]^{1.11}; & \text{eastward flowing rivers} \\ [16.6 A_c^{-0.15} A_r^{-0.3} C_o^{0.5}]^{1.54}; & \text{westward flowing rivers} \end{cases} \quad (3)$$

The regional difference in the calculated half-life is shown by considering the value found for a proposed reservoir where C_o = 80 Mm³, A_c = 200 km², and A_r = 5 km². Inserting variables in Eq. (3) gives $T_{50\%}$ = 178 years for the reservoir built on an eastward-flowing river and 309 years on a westward-flowing river.

Summary and Conclusions

Mathematical models are presented, relating reservoir capacity loss at large Indian dams to catchment area, reservoir surface area, initial storage volume, and time since the initial filling of the impoundment. Two models are developed, one for reservoirs on eastward-flowing rivers and one for westward-flowing regions. The expressions for the loss of reservoir storage volume in the two regions differ significantly because of the joint meteorological and geological influences on land surface runoff and sediment yield.

The models give good fits to the assembled data and allow an uncomplicated calculation of the half-life of reservoirs (that is, the time needed for initial storage capacity to be reduced by 50%), which provides a measure of when sedimentation will have a significant adverse impact on functioning. The relations provide a straightforward and rapid means of estimating the loss of reservoir storage capacity caused by sediment deposition. ■



Specializing in complex and computationally-intensive designs and plans for water resource engineering projects, **Dr. Froehlich** has accumulated more than four decades of domestic and international knowledge in design, research, teaching, project management, and institutional counseling.

References

1. Bureau of Indian Standards (1992). Indian Standard IS 6518:1992c.
2. Central Water Commission (2015). Compendium on silting of reservoirs in India, Ministry of Water Resources, Watershed and Reservoir Sedimentation Directorate, New Delhi, India.

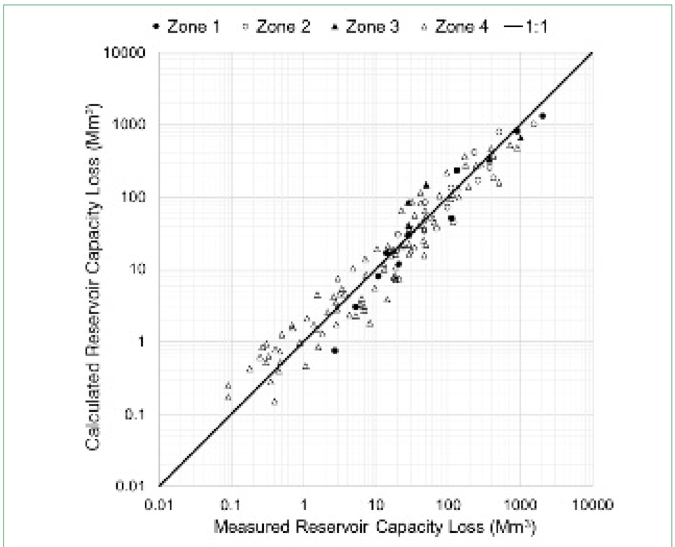


Figure 3. Comparison of measured and calculated reservoir capacity losses in 130 reservoirs on eastward-flowing rivers in sedimentation zones 1, 2, 3 and 4

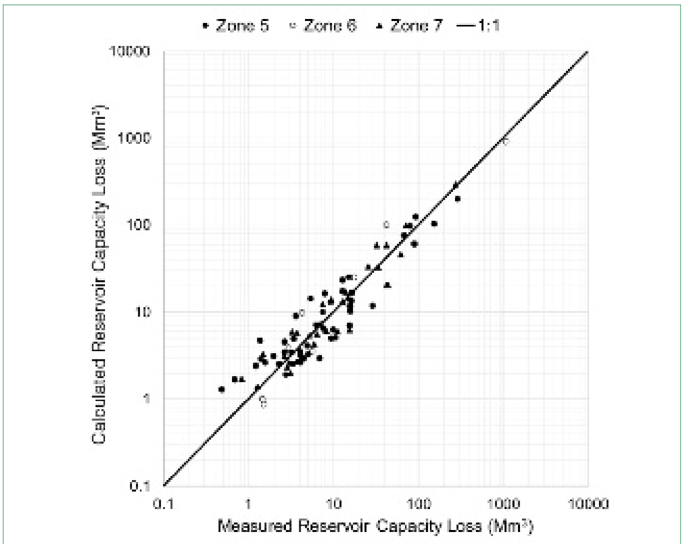


Figure 4. Comparison of measured and calculated reservoir capacity losses in 90 reservoirs on westward-flowing rivers in sedimentation zones 5, 6 and 7