Tarbela dam: a numerical model for sediment management in the reservoir

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Abstract:
Tarbela dam plays a vital role in Pakistan’s economy as it is a major resource of irrigation water and electricity generation. Its reservoir has been rapidly filling since its start due to sediment transported and deposited by Indus River. In this study, a numerical model is realized taking into account different morphologic parameters and hydrodynamic processes to predict the evolution of sediment deposits due to river bed erosion and settling velocity in the reservoir.

Keywords:
Sediment transport – Numerical model – Reservoir sedimentation – Tarbela dam – River Indus – Pakistan

1. Introduction
Tarbela Dam (figure 1), the main resource of Pakistan in terms of electricity generation and irrigation supplies was impounded by the waters of Indus River in 1974 and within 25 years it has reached a state where major problems have occurred due to rapid deposit of sediment in the reservoir. The accumulation of deposited sediment thus forms a delta which has been travelling towards the main dam (10.6 km away in 2006) which endangers all the low level outlets including the power station which could be blocked by the liquefaction of the sediment under the severe earthquake.

The source of Indus River is situated in the Tibetan Plateau, at an elevation of 5500 m above sea level. Length of river upstream of Tarbela dam is 1127 km with an area of 169650 km² out of which, 10% of the basin just above Tarbela is subjected to both; rainfall in winter and the heavy rainfall during the monsoon season from July to September. The remaining 90% of the basin lies between the Karakoram and Himalayas mountain ranges (WAPDA, 2005). Primary source of surface water is precipitation in the form of rainfall and snow and the glacier melt. Snowmelt contribution is greater than rainfall. Nevertheless, rainfall is directly linked with peak values. Mean annual inflow calculated by TAMS & HR WALLINGFORD (1998) is 80920 million m³ which varies from year to year due to different temperature ranges and rainfall. The sediment load from the glaciers and the eroded sediment from the river banks thus travel with river and reach the reservoir. Here, the sediment deposits due to insufficient velocity
that generates favourable conditions for particle settling such that important storage
capacity is lost. Sediment carried by Indus is deposited in the reservoir at an annual rate
of about 200 million tons, corresponding to about 98% of the sediment inflow. The
average composition of the deposits is 28% sand, 55% silt and 17% clay (TAMS & HR
WALLINGFORD, 1998). The predicted rate of sediment inflow was 0.294 billion m$^3$
anually but the actual sediment inflow rate has been significantly lower with an
average rate of 0.106 billion m$^3$ which is 36% of the predicted rate (WCD, 2000). The
minimum reservoir drawdown level was raised from initial 396 m to 417 m until 2006.
Raising the minimum reservoir level will let sediment to deposit in upstream thus
reduce the delta advancement. Consequently, it reduces the live storage and water
availability in dry season. Length and area of reservoir are 97 km and 260 km$^2$
respectively. Gross storage capacity is $14.3 \times 10^9$ m$^3$ and original live storage capacity
was $11.93 \times 10^9$ m$^3$ which was reduced to $8.55 \times 10^9$ m$^3$ until 2006. Average annual
sediment deposit is $0.134 \times 10^9$ m$^3$ and sediment volume up to 2006 was $4.23 \times 10^9$ m$^3$.

2. Methods

Methods to lessen the problem of sedimentation are usually based on reduction of the
inflow of sediment, the manipulation and control of the reservoir processes and the
mechanical removal of deposits. Experimental work of SERAJI (1992) related to
flushing of the sediment was thoroughly studied. A numerical model is being realized
taking in account different transversal sections of the reservoir up to 100 km, annual
hydrological cycle, monthly reservoir storage levels, rate of erosion, rate of deposition,
granulometric distributions and settling velocity to define and explain the
morphological changes and deposition of the sediment in the reservoir over different
time periods. RESSASS, another 1-D model made by (TAMS & HR WALLINGFORD,
1998) is different from this model as we used the Krone model to calculate the
concentration at the downstream of each section which gives more accurate results. A
number $N=37$ of sections of the reservoir all along the length of 96 km have been taken
into account. Figure 2 shows the schematic discretization of the transversal sections of
the reservoir. Average widths of each section were known from the bed of the river $\eta_0$,
at the interval of 5 m vertically till 472 m, $\eta_{max}$, which is the maximum operating level
of the reservoir. The values estimated by interpolation of the local width $L_1$ were then
used to calculate the horizontal surface area $S_i$ of each section as a function of the level $\eta$.
The reason of these calculations is to get the local flow $Q_i$ of water in each particular
section at any interval of time. The flow $Q_i$ depends on the level $\eta$, $Q_{output}$ and $Q_{input}$,
which are respectively the reservoir output and input water flow. We used $\eta$ as the
average level of the reservoir each month to calculate the total horizontal surface area
$S_T$. The input water flow $Q_{input}$ is given by natural river flow. Average values of river
flow vary from $420$ m$^3$ s$^{-1}$ in winter to $6220$ m$^3$ s$^{-1}$ in summer due to monsoon rains and
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Himalaya and Karakoram glaciers melt. Output water $Q_{output}$ also varies each month due to the water usage for electricity generation and water evacuation for irrigation supplies.

![Figure 1. Tarbela Dam and reservoir (schematic diagram).](image)

Figure 1. Tarbela Dam and reservoir (schematic diagram).

Some of the equations that govern in this whole model are:

$$Q_i = Q_{input} + \frac{1}{S_T(\eta)} \sum_{j=1}^{N} S_j(\eta)(Q_{output} - Q_{input})$$  \hspace{1cm} (1)

$$S_T(\eta) = S_L + \sum_{i=1}^{N} S_i(\eta) = S_L + \sum_{i=1}^{N} (L_i(\eta) \times \Delta x_i)$$  \hspace{1cm} (2)

where: $S_L$ is lateral surface area of the river, which is calculated in terms of $\eta$.

Krone model is used to calculate the concentration at the downstream of each section resulting from deposition. The reduction of the concentration $\Delta C_i$ in a section between upstream and downstream is given by:

$$\Delta C_i = -\frac{W_o C_o}{d} \left( \frac{\tau - \tau_c}{\tau_c} \right) \Delta M_i$$  \hspace{1cm} (3)

where: $C_o$ is concentration near river bed, $W_o$ is the settling velocity near the river bed, which is calculated as a function of $C_o$ through an Owen power law; $\tau$ is the shear stress, which is calculated as function of the square of local velocity, $\tau_c$ is critical shear stress above which the sediment do not deposit and $d$ is mean depth.
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The main equation to calculate the reduction by deposition of the transversal section is:

$$\Delta S_{i+1} = \Delta S_i - \frac{1}{(1-n)\rho} Q_i \frac{\Delta C_i}{\Delta x_i} \Delta t_i$$  \hspace{1cm} (4)

where: $n$ is the porosity, $t$ is time and $\Delta t_i$ is the time step.
Erosion is considered as a function of $Q_{input}$, but only in the downstream region when reservoir level is low enough that a fluvial regime is observed.

3. Results

Figure 3 shows the evolution of sediment deposition according to the actual data received from Tarbela authorities calculated by the field surveys. Original river bed level and the initial survey data of the year 1979 has been kept constant in the model and in the following figures as well and four different years are being selected to compare the evolution of sediment deposition from the observed data and calculated by the model. We did sensibility study and changed the parameters of law describing the settling velocity $W$, the critical shear stress for deposition $\tau_c$, to obtain the best results. Subsequently, to carry out the sensibility study, we kept changing the values of one parameter keeping others constant as initial values. Final result is presented in figure 4.

Figure 3. Observed annual longitudinal profiles of deposits in the reservoir.

Figure 4. Annual profiles obtained from the model.

4. References


