Sedimentation Processes, River Morphology and Reservoir Modelling

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Abstract:
This study concerns Tarbela dam reservoir which is a major resource of Pakistan in terms of electricity generation and irrigation supplies. Rapid filling of reservoir due to sediment transported and deposited by Indus River is described and analysed in this article. Causes of sediment deposition, and their impact on dam's function and life are studied. The main characteristic parameters of the site are presented. The morphological evolution induced by dam construction is examined between the original River bed in 1974 and the situation in 2006. Finally, five potential remedial solutions are thoroughly discussed.

Résumé :
Cette étude concerne le barrage de Tarbela et son réservoir. Ce barrage représente pour le Pakistan une très importante source d'énergie électrique et d'irrigation des zones agricoles. Un rapide comblement du réservoir dû aux apports en suspension par le fleuve Indus est décrit et analysé dans cet article. Les causes expliquant le dépôt des sédiments et les conséquences du comblement sur le fonctionnement du barrage sont étudiées. Les principaux paramètres caractéristiques du site sont présentés. L'évolution morphologique des fonds induite par la construction du barrage est examinée entre la situation observée en 1974 au moment de la mise en fonctionnement du barrage et celle de 2006. Enfin, cinq possibles solutions pour pallier au problème du comblement sont discutées.

Keywords:
Sediment transport – River morphology – Reservoir sedimentation – Flushing – Tarbela dam – River Indus – Pakistan

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1. Introduction

The study of the morphology of rivers is one of the most complex problems related to fluid dynamics. This is because the river flow changes over time and space. Therefore, knowledge based on experience and good understanding of physical phenomenon involved in sediment transport, are two crucial aspects.

The sediment transport is an important process that occurs in the rivers, estuaries and coastal regions. In many situations, this process and the morphological changes that result may have an adverse impact on the hydraulic structures and the environment. Thus, the reservoirs of dams, navigation canals and ports could be rendered unusable by the accumulation of sediment. The maintenance of these structures in operational state may require dredging, which may represent a significant cost for the authorities. Furthermore, the structural integrity of the structures could be compromised by excessive washouts of the bed around them.

Two major transport modes can be distinguished: the bed load travelling immediately above the bed supported by intergranular collisions (WILSON, 1966), and the suspension load dominated by turbulence and performing on the entire water column (FREDSOE & DEIGARD, 1994).

Tarbela Dam was impounded in 1974 and now the sediment deposition has reached a stage where major problems have occurred which have to be dealt early. The map of upper Indus basin is shown in Figure 1 that flows through Himalaya and Karakoram mountain ranges.

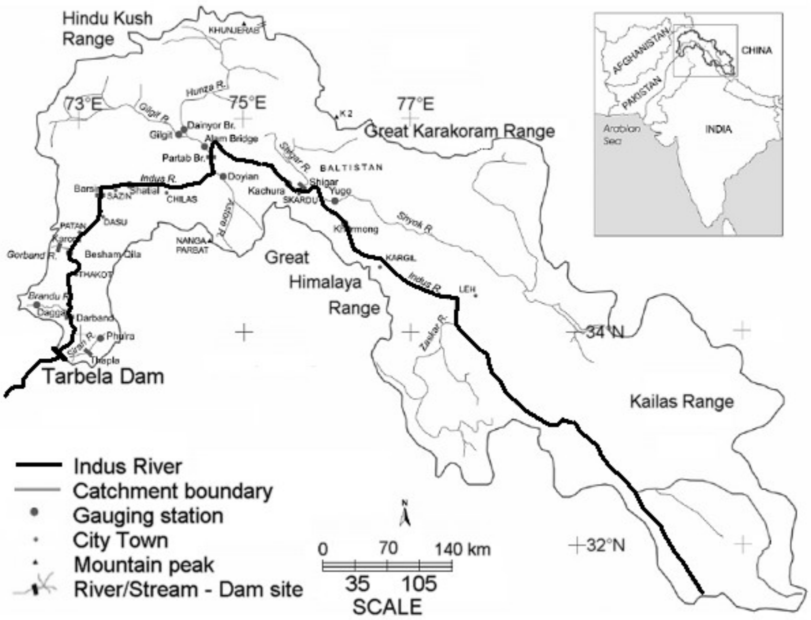

Figure 1. Upper Indus River basin flowing through Himalaya and Karakoram ranges.

Loss of storage capacity, abrasion of equipment and concrete surfaces by sand, probability of blockage of intakes and tunnels, and degradation at downstream are the major threats for the useful life of Tarbela dam project.

The objective of this study is to find out the causes of sediment deposition and highlight the remedial measures that could be taken in account. In fact, a continuous power generation is unavoidable for local economy, because Tarbela dam produces more than 50% of the total electrical energy of Pakistan.

2. Study of Tarbela Dam

Tarbela Dam (figure 2) on the Indus River is the main resource of producing electricity and irrigation water requirements of Pakistan. Issues related to the sediment transport are highlighted here through the presentation of the problems posed by the rapid filling of Tarbela reservoir. The reservoir impounds the water of the Indus which carries a heavy sediment load. The source of Indus River is situated in the Tibetan Plateau, at an elevation of 5500 meters above sea level.

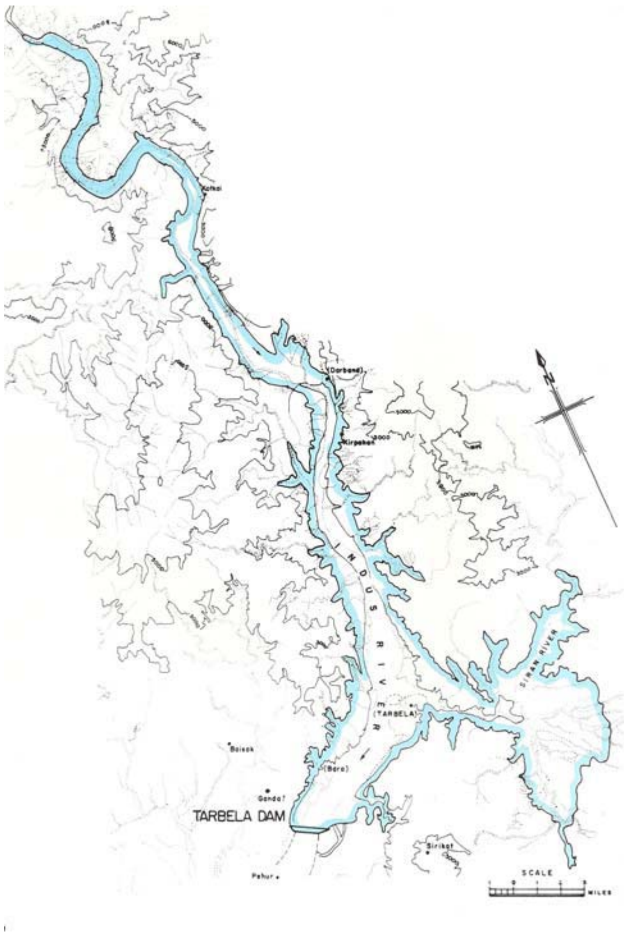

Figure 2. Schematic view of Tarbela reservoir.

Out of 1127 km long with an area of 169650 km^2 of the upstream river basin, almost 10%, about 10400 km^2 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. Glaciers in the upper Indus basin are the largest outside the polar region and serve as natural storage reservoirs that provide perennial supplies to river Indus and some of its tributaries. The meltwaters from seasonal and permanent snow fields and glaciers from these mountains contribute a major part of the annual flow that reaches Tarbela.
Figure 3 shows the average monthly inflow in Tarbela reservoir (TAMS & HR WALLINGFORD, 1998). It is shown that snowmelt contribution is greater than rainfall. Nevertheless, rainfall is directly linked with peak values. The flow regime of the Indus, by world standards, is very consistent from year to year, with a major peak in the annual hydrograph during the months of June to September in response to regular inflows of snowmelt from the upper catchment and rainfall on the lower catchment. An understanding of the hydrological regimes of the mountains is critical. The coefficient of variation of annual runoff is only 15% which is very low by the world standards. Mean annual inflow calculated by TAMS & HR WALLINGFORD (1998) is 80920 million m^3 which varies from year to year due to different temperature ranges and rainfall each year.

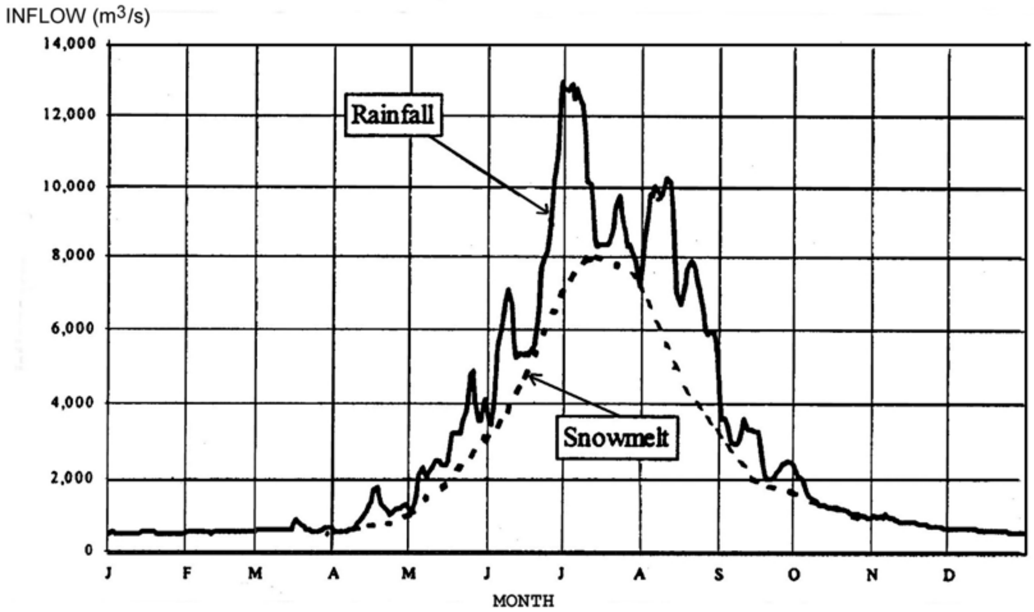

Figure 3. Average monthly inflow in Tarbela reservoir.

The sediment load from the glaciers and the eroded sediment from the river banks thus travel with river and reach the Tarbela 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 (SLOFF, 1997). More than up to 80% of the sediment load is transported in the reservoir during the months of July and August.
The average composition of the deposits determined from samples collected from Tarbela reservoir is 28% of sand, 55% of silt and 17% of clay (TAMS & HR WALLINGFORD, 1998). Gradual sediment deposition could be seen in figure 4 which shows the longitudinal profiles of bed. The location of the sediment delta front which has reached almost 10.6 km from the main dam imposes the danger of clogging of the five low-level tunnels of the dam.

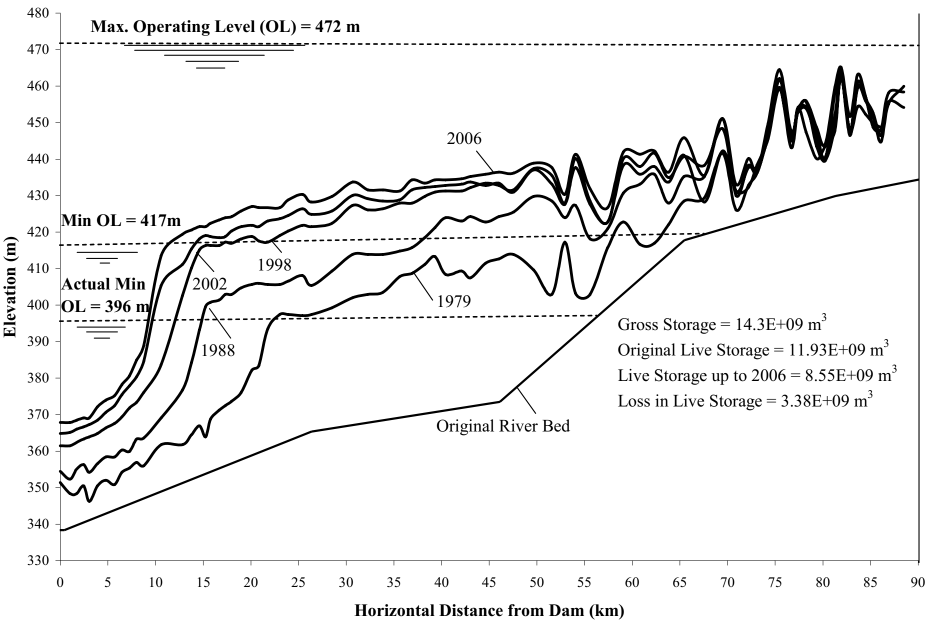

Figure 4. Annual longitudinal profiles of deposited sediment in Tarbela reservoir.

Table 1 shows some major characteristics of the Tarbela Dam. The predicted rate of sediment inflow was 0.294 billion m^3 annually 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). However the trap efficiency of the sediment is quite higher than predicted. But one aspect of the sediment deposition which was however not expected so early is the rapid advancement of the sediment delta front which is 10.6 km from the dam in 2006. This 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 minimum reservoir drawdown level was raised from initial 396 m to 417 m until 2006. Raising the minimum reservoir level will make the effect of sediment deposition in the upstream and thus reduce the delta advancement. Consequently, it reduces the live storage and the water availability in the dry season.

Table 1. Characteristics of Tarbela Dam. Data from TAMS CONSULTANTS INC & HR WALLINGFORD LTD. (1998) and WCD (2000).

Characteristics	***Values***
Completion year	*1974*
Dam height	*148 m*
Length of main dam	*2744 m*
Reservoir length	*97 km*
Reservoir area	*260 km^2*
Gross storage (volume)	*14.3 x 10^9 m^3*
Original live storage	*11.93 x 10^9 m^3*
Live storage up to 2006	*8.55 x 10^9 m^3*
Maximum gross capacity level	*472 m*
Actual minimum operating level	*396 m*
Minimum reservoir level in 2006	*417 m*
Capacity below min. reservoir level	*1.55 x 10^9 m^3*
Average annual sediment deposit	*0.134 x 10^9 m^3*
Sediment volume up to 2006	*4.23 x 10^9 m^3*
Total loss up to 2006	*29.48 %*
Hydro power capacity	*3478 MW*
Electrical energy generation	*14.8 GWh yr^{-1}*
Number of tunnels for electricity	*3*
Number of tunnels for irrigation	*2*
Tunnels' diameter (constant)	*13.7 m*

3. Methods

In order to estimate the annual sediment transport, an attempt has been carried out by using Meyer-Peter and others formulas for bed load and suspended transport. The sediment delta induced by the dam is explained by deposition of suspended sediment resulting from low current velocities in the reservoir.

A simulation of average monthly variations in Tarbela reservoir has been realised. Calculation of inflows and outflows permits to evaluate the water level variations.

Inflow is linked with snowmelt and rainfall upstream from the reservoir. Outflow depends on evacuations by spillways and tunnels for electricity and irrigation.
In this study, five potential remedial measures are considered. The interest and viability of these measures are evaluated on the basis of the possible sediment evacuation and economical cost. The studied solutions are:

- Solution 1: Establishment of a fluvial regime in the reservoir.
- Solution 2: Flushing through a low level tunnel.
- Solution 3: Mechanical dredging and transport of the sediment.
- Solution 4: Heightening of the dam.
- Solution 5: Replacement of existing dam by another.

4. Results

From the estimations of the annual sediment transport with the theoretical formulas, we have concluded that the actual sediment transport is controlled by catchment area production and not by River transport capacity. In fact, the transport capacity calculated is a lot more than that evaluated from the observed deposition in the reservoir. On the other hand, there is no granulometric continuity between rocks observed upstream of the reservoir and the incoming fine sediment. The sediment forming the delta in the reservoir is rather fine, so, it is possible to affirm that this sediment has been transported as suspended load.
The mean erosion rate of the catchment producing the fine sediment filling Tarbela reservoir is evaluated to be 0.8 x 10^{-4} m yr^{-1}. Rock erosion is explained by physical and chemical agents. In order to understand this topic, some characteristics of rocks are presented as follows.
Indus basin contains the bed rock which is composed largely of igneous and metamorphic rocks that have undergone wide deformation due to very high degree of tectonic activities. There is a large variety of surficial materials which is commonly exists as glacial deposits, alluvial fans, and recently deposited alluvium (MONENCO, 1984). The bedrock in the region is subjected to high weathering rates (FERGUSON, 1984) and extreme variations in climate. Frequent avalanches, rock slides and other mass movements in the basin play an important role in generating large sediment fluxes (HEWITT, 1998). Figures 5 and 6 illustrate the variability and sizes of the rocks in this region. Figure 5 shows the Indus passing through the Sandstone Canyons in Tibet region and figure 6 gives an idea of the sediment that are eroded by the Indus water in Mansehra near Besham, about 60 kilometres upstream of the top end of Tarbela reservoir.
An analysis of the five considered solutions is presented as follows.

4.1. Solution 1: Establishment of a fluvial regime in the reservoir

As the sediment deposits in the reservoir due to inactive pool behind the dam, one solution is to establish a fluvial regime in the reservoir and let the river flows naturally for significant period of time during the season when the inflow is at its peak. The resulting shear velocity of the river will make the deposited sediment to erode and flushed out of the reservoir.

A flushing operation has been simulated with hydrographic conditions characterized by a River inflow of 4000 $m^3\ s^{-1}$ that corresponds to the month of June. If a complementary opening is built in order to drain completely the water at 8000 $m^3\ s^{-1}$, five days are necessary to make the reservoir empty. The effective flushing operation takes six days as minimum and finally to fill the reservoir again, five more days will be needed.

To carry out flushing, very important civil engineering structures must be built and a non electricity production period of 16 days must be programmed for each operation.

Figure 5. Sandstone canyons in Tibet region.

Figure 6. Indus at Mansehra, 60 km upstream of the top end of the reservoir.

4.2. Solution 2: Flushing through a low level tunnel

It will provide an essential long term live storage with only a small annual reduction. The site of the tunnel, its length and level will be a crucial decision to make. To evacuate a quantity of sediment equivalent to the inputs through a low level tunnel permanently open, the tunnel diameter must be equal to 2 m if the suspended sediment volumetric concentration is 6%. Over a year, almost 1% of the reservoir water would be evacuated by this tunnel.

4.3. Solution 3: Mechanical dredging and transport of the sediment

Dredging is useful but a very costly option to manage the sediment in the reservoirs. Even a large dredging operation could only remove a small quantity of sediment as compared to the annual inflow. However, dredging could be very useful in maintaining the sediment near the tunnel intakes which is very harmful for the turbines.

4.4. Solution 4: Heightening of the dam

Heightening the dam can also be considered but it will only increase in the live storage equal to few years of sediment inflow. Moreover, the gates of the service and auxiliary spillways would then also be modified. The stability of the dam must also be studied.

4.5. Solution 5: Replacement of existing dam by another

To abandon the reservoir is the last option and will only be considered when the production and benefits from the dam will become less than the management cost of the project.

5. Conclusions

As discussed earlier that the predicted rate of sediment inflow in the reservoir was 0.294 billion m^3 annually which envisages that the sediment load will fill up the capacity of Tarbela reservoir up to 90% in 50 years. After that, the dam will continue to provide only about 1.2 billion m^3 of live storage. The usable life of the dam is considered to be 85 years now but the usable storage will gradually decline over this time.

The conclusions concerning the five examined remedial measures for silting problem of Tarbela reservoir are discussed below:

After consultation with the authorities at Tarbela, solution 1 is considered impossible as any interruption in the production of electricity from Tarbela will affect severely the economy of Pakistan.

In this research, solution 2 has been studied in detail and it seems to be a very interesting possibility to prolong the live storage. Continuous flushing will be accomplished through a 2 m diameter low level tunnel. To extend the eroded region upstream from this tunnel, the utilization of a flexible mobile pipe is proposed for the suction of sediment over a region 2-3 kilometres near the upper end of the tunnel. So, the hydraulic potential energy would be utilised to maintain the reservoir depths.
Solution 3 is also discarded due to excessive cost and non utilization of the material in Pakistan that will be evacuated by the dredging operation. We are currently studying solution 4 because heightening of the dam will lead to the modifications in the whole structure and the stability of the dam could be affected. Solution 5 could not be discarded but it will not be considered as a viable option due to the cost of constructing a new dam and the time required to make the feasibility and to find an appropriate location.

6. References

FERGUSON R.I. (1984). *Sediment load of Hunza River. The international Karakoram project*. Cambridge University Press, Cambridge, pp 580-598.
FREDSOE J., DEIGARD R. (1994). *Mechanics of coastal sediment transport*. Advanced Series on Ocean Engineering, vol. 3. World Scientific Publication, Singapore, 369 p.
HEWITT K. (1998). Catastrophic landslides and their effects on the upper Indus streams, Karakoram Himalaya, northern Pakistan. *Geomorphology*, n° 26, pp 47-80.
MONENCO (Montreal Engineering Company) (1984). *Hydroelectric inventory ranking and feasibility studies for Pakistan*. CIDA Project 714/00603. Commissioned by WAPDA, Lahore.
SLOFF C.J. (1997). *Modelling reservoir sedimentation processes for sediment management studies*. Proc. Conf. "Hydropower into the next century". Portoroz, Slovenia, pp 513-524.
TAMS CONSULTANTS INC., HR WALLINGFORD LTD. (1998). *Tarbela dam sediment management study - final report*. Commissioned by WAPDA, Lahore.
WAPDA (Pakistan's Water and Power Development Authority) (2005). *Tarbela Dam Project, Reservoir Sedimentation Report*. Lahore, 40 p.
WCD (WORLD COMMISSION ON DAMS) (2000). *Tarbela dam and related aspects of Indus River basin of Pakistan - final report*. Asianics Agro-Dev. International (Pvt) Ltd., Islamabad, 181 p.
WILSON K. (1996). Bed load transport at high shear stress. *Journal of Hydraulic Engineering (Hydraulics Division)*, n° 92(11), pp 49-59.