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TARBELA RESERVOIR: TOWARDS A SUSTAINABLE FUTURE

Amjad Agha

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1. ABSTRACT

Tarbela reservoir, commissioned in 1976, is a key component of the Indus Basin Project. It was built primarily to regulate flows in the Indus River and support downstream irrigation abstractions, but with power generation as an important adjunct which has increased in value with the staged introduction of additional generating units.

Sedimentation in the reservoir during the first 30 years of operation has occurred broadly in accordance with the original expectations of the designers. The point has now been reached when decisions need to be reached on the most appropriate scheme of sediment management – together with possible capital works – which should now be adopted to ensure a sustainable future for the reservoir and for the economic and social benefits it contributes to Pakistan.

Several studies on sedimentation in the reservoir have been carried out over the years, starting well before construction, and numerous opinions have been offered in technical papers and correspondence, so there is clearly already a considerable body of understanding. This paper has been prepared in order to draw together the threads of opinion, and if possible suggesting a way forward. It is proposed that a dedicated conference of international experts on the subject of reservoir sedimentation be organized in order to obtain their advice on the most appropriate course of action. On the basis of expert advice Government may then take an informed decision about the feasibility and the risk assessment of sluicing or otherwise managing the sediments.

2. INTRODUCTION

Tarbela reservoir is located on the Indus River in the foothills of the Himalayas, approximately 100km northwest of Islamabad. It had an original live storage capacity of 11.6km^3 (9.4M acre-ft), between the conservation level of 472m (1550ft) and the minimum operating level of 396m (1300ft). The main components of the scheme are:

- the main embankment dam, 2750m long and 143m high, the largest in the world at the time of construction, founded on deep alluvial deposits;
- two auxiliary dams;
- two gated chute spillways, with a combined discharge capacity of 40 000 m^3/s (1415000 ft^3/sec.) ;

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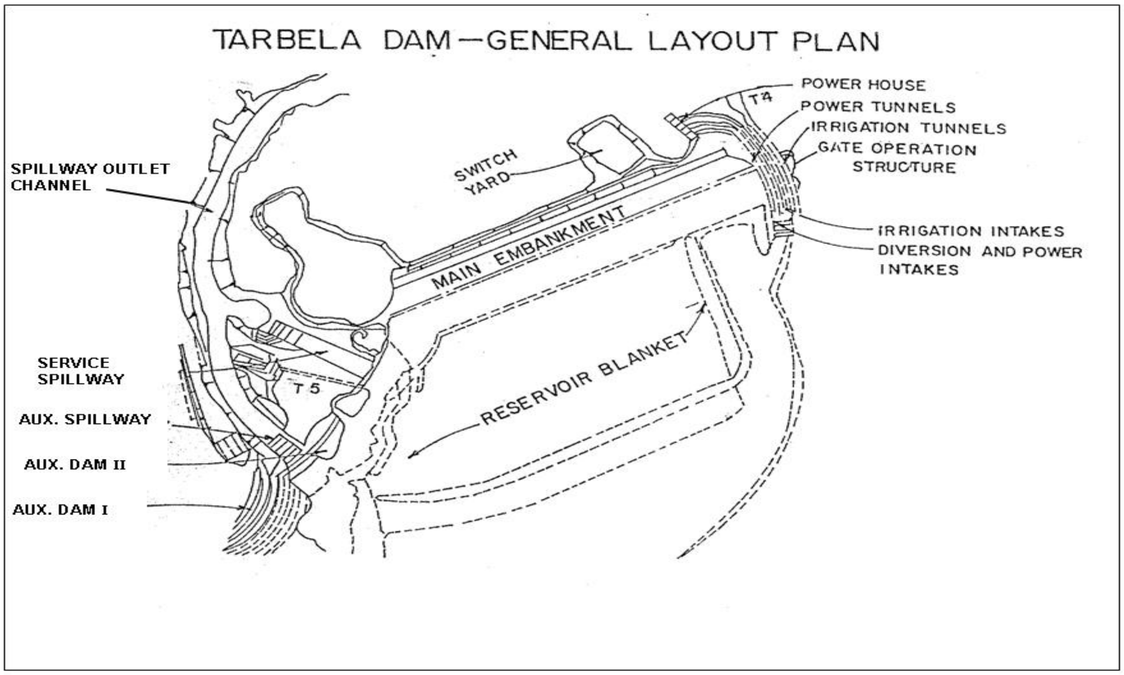
- four tunnels at the right abutment and one at the left abutment of the main dam; and
- Fourteen hydropower units served by Tunnels 1 to 3, built in four stages.

The initial generation capacity was 700MW, through four 175MW units on Tunnel 1. Units 5–8 were completed in 1982 on Tunnel 2, and Units 9 and 10 added in 1985, also on Tunnel 2, bringing the total generation capacity to 1750MW. The total generating capacity was subsequently almost doubled to 3478MW in 1992, by the addition of Units 11–14, each 432MW, on Tunnel 3.



3. HYDROLOGY

From its source in the Tibetan plateau, the Indus River drains some of the highest mountain ranges in the world. Its total catchment area of about 170 000 km^2 at Tarbela can be considered as two distinct regions, with over 90% lying between the Himalayan and Karakoram mountain ranges from which snowmelt and glacial water contribute the majority of the annual discharge entering the reservoir. Less than 10% of the catchment, near to the reservoir, is subject to monsoon rains, which mostly fall in July to September.

Because of its hydrological setting, Tarbela reservoir has a regular pattern of inflow, with the annual hydrograph dominated by snow meltwater, which normally starts to build up at the beginning May, peaks in July and has virtually finished by the end of September. The mean annual inflow is about 80km^3(64.8MAF), representing about seven times the initial live storage capacity, and the coefficient of variation is only 15%.

4. SEDIMENT BEHAVIOUR IN THE RESERVOIR

Sediment influx to the reservoir broadly follows the annual flow hydrograph. Estimates made from a limited amount of sediment sampling at Darband prior to construction of the reservoir (Drisko, 1962) indicated a mean annual load of the order 360M tons. A rather greater figure of 390 Mt/yr was anticipated at the time of construction, but it was realised by the time of the completion report in 1984 that the true sediment inflows would be much less. Subsequent measurements have indicated the mean annual sediment load to be about 200Mt, excluding a washload of very fine material non-settleable material which passes through the reservoir. The mean sediment inflow (excluding washload) is equivalent to a continuous flux of over 6 tonnes per second about 200 M ton per annum, or a mean concentration of 2.5 g/l (2500 ppm by mass), most of which is silt and sand.

The general behaviour of sediment in the reservoir is as follows:

- The majority of the incoming sediment, entering when reservoir levels are high during the summer months, is deposited in a delta commencing at the head of the reservoir.
- When reservoir levels are low at the beginning of the high-flow season, incoming flows pass over the exposed delta (the 'topset' slope), reworking the deposits and bringing them forward to the front of the delta (the 'foreset slope').
- As the volume of sediment trapped in the reservoir increases, the front of the delta advances towards the dam and outlet works.

The profile of the delta is influenced by the way in which the reservoir is operated, with the 'pivot point' (the intersection of the topset and foreset slopes) advancing towards the dam fastest in years when the minimum operating level at the start of the high-flow season is low, but rising (along with the topset slope) in years when the minimum operating level is high. The trap efficiency is about 90%.Table-1 gives the inflow and outflow of sediment and the trap efficiency.

Table –1: Sediment Inflow, Outflow & Trapped (MST) Trap Efficiency (%)

Water Year (Oct-Sep)	Inflow	Outflow	Trapped	Trap%
1980-81	40.6081	3.7659	36.842	91
1981-82	214.77	3.831	210.939	98
1982-83	81.6663	8.2165	73.450	90
1983-84	96.6063	3.7711	92.836	96
1984-85	186.564	5.03	181.534	97
1985-86	189.039	7.503	181.536	96
1986-87	220.759	8.629	212.130	96

1987-88	158.978	6.934	152.044	96
1988-89	272.094	4.924	267.170	98
1989-90	148.26	10.522	137.738	93
1990-91	271.831	6.47	265.361	98
1991-92	187.129	4.243	182.886	98
1992-93	153.2598	7.2821	145.978	95
1993-94	78.164	3.021	75.143	96
1994-95	278.649	12.767	265.882	95
1995-96	158.349	4.764	153.585	97
1996-97	140.066	14.255	125.811	90
1997-98	213.273	5.048	208.25	97
1998-99	185.823	7.016	178.807	96
1999-2000	139.738	11.094	128.644	92
2000-01	170.607	16.536	154.071	90
2001-02	101.649	4.214	97.435	96
2002-03	136.251	5.83	130.421	96
2003-04	99.614	10.91	88.704	89
2004-05	128.108	4.483	123.629	96
Total	4051.8555	181.0596	3870.826	95

The reservoir fills quickly, usually in less than a month, as downstream irrigation demand decrease due to rains and high inflows continue. The reservoir has been filled to its maximum El. 472 m. in almost all the years. Ideally the reservoir should reach its max level by 20th August and remain full till mid-September. It is the period when reservoir is well above the level of the delta and deposit of new sediments is formed in the upstream of reservoir on top of the existing delta surface.

The reservoir is lowered as irrigation releases are made. The draw down of the reservoir continues until minimum water level is reached usually in April or early May of the next year when the inflows are low. The process then repeats itself with the start of snowmelt runoff & high flows in late May to end July.

Each year after impounding of the reservoir hydrographic (sonar) survey is carried out with the help of 75 range lines.

The original rule curve for Tarbela reservoir required the water level to be lowered to 396m (1300ft) by 20 May and held at that level until 20 June, to keep the lowest tunnel intakes (at Tunnels 3 and 4) clear of sediment.

Through the early and mid 1990s, river flows in Pakistan were generally greater than normal, resulting in less severe demands on the irrigation water stored in Tarbela reservoir. This, together with the adverse effects of low operating heads on the optimisation of power generation, led to the *de-facto* abandonment of the original rule curve, or indeed the raised minimum operating level of 408m. In the period 1990–96, with the exception of 1994, the minimum operating level in the early meltwater season was between 419m and 440m, with a mean of 427m.

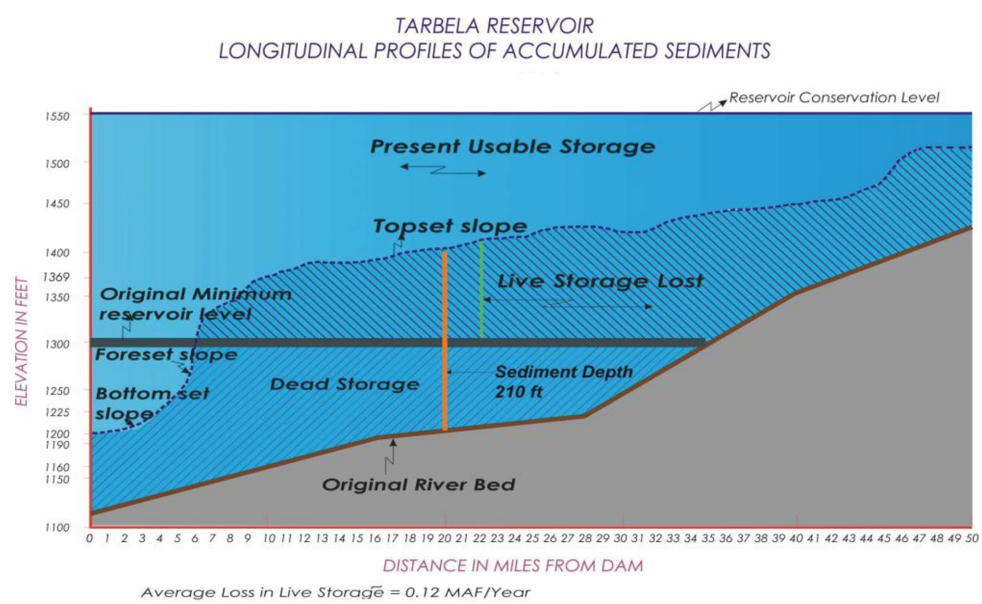
5. CURRENT STATUS

With the yearly cycle of reservoir operation, the delta formation if continuously reworked and moved downstream closer and closer to the dam. The Pivot Point of delta has been advancing at about one Km per year and is presently located at about 10.6 Km upstream of the dam at an elevation of 413.3 m. The yearly hydrographic surveys reveal that about 61 m deep sediment deposits have accumulated at about 12 Km upstream of the dam. The capacity of reservoir is decreasing due to this heavy sediment load. The remaining storage capacity calculated from hydrographic survey 2006 is as under:

Table – 2:

Reservoir Capacity	Initial (1974) BCM	Year 2006 BCM	Reduction %
Gross Storage	14,344	10.110	29.50
Live Storage (El. 472 m)	11.948	8.550	28.38
Dead Storage (El. 417 m)	2.395	1.560	34.86

The average sedimentation rate in Tarbela reservoir is 0.132 BCM (0.12 MAF) per year. See Fig. 1



Various problems, which arise as a result of heavy sedimentation of the reservoir, are as follows:

a. A loss of live storage, which is causing gradual reduction in the regulated yield of reservoir. This in turn would result in reduction in water availability for the agriculture for Rabi (winter crop season) and early Kharif seasons and also reduction in the firm energy available from the project.

b. The physical effect of sediment, which includes the risk of clogging of low level tunnel outlet particularly in a seismic activity, the erosive action of sediment-laden water on outlet concrete structures and Power turbines will result in exorbitant maintenance costs.

6. SEDIMENT MANAGEMENT STUDIES CARRIED OUT

A number of studies have been carried out to tackle the sediments and their management.

6.1 1st Periodic Inspection

The first periodic inspection report for Tarbela, submitted by TAMS in 1988, put forward four scenarios for sediment management in the reservoir:

- Continued operation according to original rule curve, with a minimum operational level of 396m (1300ft) and the expectation of occasional shutdowns due to clogging of the intake;
- As above, but with the addition of an underwater dyke to protect the intakes;
- As above, but with a sediment bypass channel on the left bank to evacuate sediments dredged from upstream of the tunnels; and
- Progressive raising of the minimum pool level by about 4ft per year to delay the advance of the delta towards the intakes.

6.2 2nd Period Inspection

The second periodic inspection report, by Nespak in 1992, recommended the following sediment management measures:

- Soil conservation measures, especially in the monsoon-affected part of the catchment;
- Sediment sluicing in the early part of the flood season, using a proposed 5000 $m^3/3$ bypass; and
- Raising the intakes of Tunnels 1-4 and adapting the tunnels for sluicing;
- Dredging and density current venting were not considered feasible.

6.3 World Bank Mission 1995

An expert review mission for the World Bank was undertaken in November 1995. Amongst the terms of reference were considered of the practicability of proposals for increasing the effective life of the reservoir through sediment management measures, the possibility of liquefaction of the sediment delta during an earthquake and means of overcoming clogging of the tunnels if this resulted from a liquefaction failure. The experts recommended:

- as a short-term measure, progressive raising of the minimum operating level from 402m (1320ft) to 455m (1492ft);
- as a medium-term measure, constructing the underwater dyke;
- For long term protection, consideration of a low-level outlet tunnel for flushing of sediments, or the construction of a new dam upstream.

They considered liquefaction of the foreset slope of the delta during an earthquake of 0.15g recommended to protect the intakes by keeping the pivot point upstream of a limit line drawn at a gradient of 1:210 (25 ft/mile). If the pivot point moves forward of the limit line, then the underwater dike would be required. It was stated that the delta must not be allowed to reach the spillway crests, as the sand would cause severe abrasion damage. Earthquakes upto 0.25g have been recorded at the crest of the dam but there has been no liquefaction of delta so far.

6.4 Tams in Association with HR Wallingford 1997-98

A detailed sediment management study was undertaken by TAMS in association with HR Wallingford, in 1997-98, making use of a new mathematical model RECESS to simulate historic and future sediment movement in the reservoir. An 'action plan' in three phases was proposed as follows:

Phase-I Implement interium operating rules, with minimum operating level of 1365ft (416m) in 1998 and then raising 4ft in stages each year from 1369ft to 1390ft.

Phase-II Design and construct underwater dyke.

Phase-III Design and construct bypass comprising four 11 m diameter tunnels situated between the two spillways in the left bank.

Upon the full implementation of the scheme, the minimum operating level (sustained for the 30 days of June each year) would be lowered to 411m (1350ft). The combined discharge capacity of Tunnel 5 plus the four new tunnels in this scheme would be 7500 m^3/s at the minimum operating level. TAMS envisaged that a live storage capacity of over 7.4km^3 (6 MAF) would be retained until 2055, decreasing at a low rate thereafter.

6.5 Fifth Periodic Inspection 2007

Fifth Periodic Inspection of Tarbela Dam was carried out in April 2007. One of the TORs of the Inspection was to review sedimentation and provide recommendations as to an optimal approach for managing reservoir sedimentation Dr. Annandle Sediment Specialist was associated.

Dr. Annandle concluded that the technically feasible and economical means of removing deposited sediment from the reservoir was only through drawdown flushing. Drawdown flushing requires the presence of low-level outlets at the downstream end of the reservoir, and drawing down the water level as low as possible for an extended period of time. The objective is to create river-like flow conditions in the reservoir to erode the deposited sediment and discharge it through the low-level outlet to the river reach downstream of the dam.

The analysis indicates that periodic implementation of the drawndown flushing can preserve about 50% of the original gross reservoir capacity in the long term, using a flushing discharge of about 6,000 m^3/s for a period of 30 days and drawing down the reservoir water level to 1,300ft.

It was suggested that an additional tunnel on the right bank close to the Power Intakes be constructed through the hill for discharging sediment laden water into the Nala across the hill and back to Indus River downstream of Ghazi Pond.

7. AVAILABLE OPTIONS AND THEIR ANALYSIS

(i) Reduction of sediment influx either by watershed management or by construction of check dams in the upper catchment is impractical as about 90% of total runoff is dominated by snow / glacier melt. Nothing can be done at this altitude on the steep mountains. Most of the catchment area is out of the monsoon zone. Water shed Management is being implemented by the Forest Department upto Besham and it has very little effect.

(ii) Construction of upstream Diamer Basha Dam shall have positive impact as it would stop most of the sediment flowing into Tarbela for about 35 years and enhance its life. However no definite schedule for the construction of dam is yet finalized.

(iii) The sediment deposition within the reservoir can be managed by means of reservoir operation. Raising the minimum reservoir level every year by 1.2 m would result in deposition of sediments in the upper reaches of reservoir and thus delay the advancement of sediment delta. Though this option entails no capital cost but would progressively result in increased loss of live storage. Minimum reservoir level of 417 m fixed in 1998 is being maintained in order to use optimally the available storage.

A period of relatively dry years commenced in 1997 and put increasing demands on irrigation releases, with the result that a minimum operating level of 402m (1318ft) occurred in 1997. Operation of Units 11–14, fed from Tunnel 3, had to be suspended because of choking of their cooling water system with sediment, which persisted when the water level rose. In order to clear the sediment, Tunnel 4, which had not been opened for some years, was opened. The initial sediment concentration in that flow was estimated as 580 g/l (or 580 000 ppm by mass). After clearing sediment from the intake area in this manner, Units 11–14 were started normally.

As a result of the 1997 incident, WAPDA recommended a minimum operating level of 412m (1350ft). Notwithstanding that recommendation, in 2000 the operating level fell to 403m (1322ft). On this occasion, however, it was possible to continue operating Units 11–14, because of a change in operating procedures for the cooling system which had been made in the light of the 1997 experience (WAPDA, 2000). The present minimum operating level is 417.3m (1369 ft.)

The construction of the underwater dike could bring permanent protection to the intakes, but would lead to a much smaller sustainable live storage and the passage of sediment – laden flows over the spillways. Without the underwater dike the best method of prolonging security of tunnel intakes would be to raise the minimum operating level by 1.8m (6 feet) every year.

Agha and Khan, in an unpublished paper prepared in 2002, supported the TAMS conclusion that flushing is the key to the sustainability of the reservoir, but pointed out the following main problems for the implementation of TAMS 'action plan' -

- the expected requirement to use over 20% of the average annual flow for flushing; the loss of generation capacity at Tarbela during the period of flushing;
- the potential effects of the sediment passed into the Ghazi barrage pond on the operation of GBHP; and
- the poor geological conditions at the site on the left abutment proposed for the four new tunnels.

They considered that primary attention should be given to the feasibility of reversion to the original operating policy – maintaining a minimum operating level of 396m (1300ft) between 20 May and 20 June every year – and that this would allow sustainable operation without the construction of either the underwater dike or a bypass, subject to the following measures:

- preferential use of Tunnels 3 and 4, which have intakes about 20m lower than Tunnels 1 and 2;
- use of Units 11–14 (on Tunnel 3) for baseload generation;
- if possible re-establishing a direct outlet from Tunnel 3, so that it can be used for emergency drawdown of the reservoir if needed;
- conversion of Tunnel 4 to power, but without removing the possibility of direct discharges to the river downstream, and its subsequent use for baseload generation;
- the establishment of alternative clean sources of cooling water for the turbines, with the alternative of closed systems;

- the establishment of arrangements for upgrading the turbines as necessary to cope with high sediment loads and for periodic repair and renewal if that is more economic; and
- the establishment of facilities for deepwater suction dredging, on standby to clear any blockage of the intakes (and also presumably available for controlling any potentially dangerous development of the foreset slope).

They acknowledged that this would not necessarily be a risk-free option and would also present a number of issues to be resolved, such as whether to vary the minimum operating level each year in response to fluctuations in the sedimentation behaviour in the reservoir.

8. THE WAY FORWARD

From the foregoing comments it can be seen that the general situation and characteristics of Tarbela reservoir and its catchment are the key to its sedimentation problems and also to their solution. The high annual sediment load – equivalent, if it were all trapped, to the loss of over 1% of the storage capacity per annum – means that continuing to trap nearly all the sediment would have severe consequences for the remaining operational life of the reservoir. On the other hand, the large annual discharge of several times the storage capacity, together with the strong seasonal pattern and consistency of the annual hydrograph, mean that the reservoir is potentially suitable for sustainable operation through flushing at low water levels prior to annual filling commencing at the start of the high-flow season.

The key issues which will need to be addressed and resolved in order to move forward to a solution which avoids the need for the full 'action plan' put forward by TAMS in 1998, including an underwater dike and massive new flushing tunnels, are as follows:

- Whether the discharges which can be passed through the available low-level outlets (including some of the turbines) are sufficient to maintain the requisite water level in the reservoir and also achieve an adequate rate of sediment evacuation from the reservoir.
- Whether the effects of high concentrations of silt and sand passing through the existing tunnels and turbines will be acceptable in terms of the resulting maintenance, repair and periodic replacement required (including a study of which of the 14 turbines should be subject to those discharges).
- Whether the optimum solution for passing sediment-laden flows through the hydro machinery includes the use of specialist coatings, such as ceramics and polyurethane.
- Whether suitable changes can be made to the cooling water systems of the turbines to avoid them clogging at times of high sediment load.
- How to manage huge quantity of sediments coming out and their disposal in the river downstream.

These are very difficult questions and there are no ready made answers available. Tarbela Reservoir is the backbone of Pakistan economy, and the experimentation cannot be afforded. The final solution should place great stress on experience of similar problems and their solutions both in Pakistan (particularly Warsak) and internationally, including special attention to reservoirs in China, Nepal, India and Alpine countries of Europe where the sediment characteristics may resemble those in the Indus River.

In this regard, it is suggested that a dedicated conference be organized by WAPDA and the GOP on the sedimentation issues of Tarbela reservoir. In this Conference top international experts should be gathered in order to get their opinion on the appropriate course of action. Their review will also include a risk assessment of generation and choking of low level outlets based on probability of sediment foreset slope collapse under earthquake and how it might change with time, with and without flushing. In other words an attempt to try to bracket the changing financial and economic risk associated with leaving the status quo and with the flushing option. In the recent ICID Conference held in Lahore the idea of such expert consultation was also endorsed. WAPDA with the support of World Bank is now planning to engage consultants to study various options for evacuation of sediment from Tarbela reservoir. I hope this exercise will also include the high level conference of experts being suggested in this paper.

The findings of such a high level conference when available can be presented to the Government so that an informed decision about sediment flushing may be taken. In case it is concluded that sluicing through the tunnels and turbines is not recommended, then the future action plan will be to raise the minimum reservoir by 4 – 6 feet every year and keep the delta away from the tunnels for as long as possible. At the same time building of Basha Dam would need to be expedited so that further inflow of sediment entering Tarbela reservoir is stopped for the next many years.

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