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MITIGATING WATER SHORTAGE BY MAKING TARBELA, A SUSTAINABLE RESERVOIR

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1. INTRODUCTION

Tarbela reservoir had all the features required to make it a sustainable source of water for irrigation. TAMS, the designers of the dam, had planned to prolong its life by flushing as much sediments as possible, out of their maximum estimated 294 million cubic meter (Mcm) or 390 million tons (Mt) annual sediments inflow. However, for various reasons the flushing or sluicing of large quantities of sediments was not followed in actual practice. The World Commission on Dams, in its November 2000 report on Tarbela dam, stated that the actual inflow of sediments into the reservoir averaged only 106 Mcm or 141 Mt per year, less than 36 percent of the maximum quantity forecast by TAMS, and the sediments also showed a slightly decreasing trend. According to a December 1997 report of TAMS, on sediment management, the annual sediments inflows at Tarbela varied from 62 Mcm (83Mt) to 196 Mcm (264Mt), with an average of 125 Mcm (167Mt) from the year 1979 to 1995. The flushing of the relatively smaller quantity of the actual sediments posed a far less formidable problem than what the designers had apprehended. The abandoning of the planned flushing of the sediments trapped several billion cubic meter of sediments in the reservoir, causing a very rapid loss of the storage capacity, and aggravating the water shortage in the dry years. Some loss of the storage capacity was expected even if the flushing of sediments had continued, however, an equilibrium between the inflows and the outflows of the sediment would have been achieved by now, making the remaining storage perpetual and sustainable.

Tarbela was constructed as a part of the Indus Basin Project together with link canals, barrages and Mangla dam. The primary objective of Tarbela dam was :

- To provide Pakistan with replacement of irrigation water ceded to India from the Ravi, Beas and Sutlej rivers,

- To provide an 11,600 Mcm or 9.4 million acre foot(Maf) of live or usable water storage for ensuring a substantial degree of integration and regulation of Pakistan's irrigation system which was required for increasing the production of food and other crops.

The generation of cheap hydropower, through a staged development of 2100 mega watt (MW) capacity, was envisaged as a secondary benefit of the dam. In the planning stage of the dam 75 percent and 25 percent benefits were assumed from the irrigated agriculture and the hydropower respectively, however, as per November 1997 report by TAMS, the revenue from the irrigated agriculture reduced to 32 percent where as the revenue from the hydropower increased to 68 percent.

Tarbela dam project comprised a reservoir formed by 143m high earth-fill dam, four tunnels (Tunnels No.1 to 4) on the right bank, one tunnel (Tunnel No. 5) on the left bank, a 700 MW power station on the right bank (comprising Generating Units No. 1 to 4, each of 175 MW capacity, on Tunnel No. 1), one service spillway and one auxiliary spillway, both the spillways are on the left bank of the dam. The live storage of 11,600 Mcm (9.4 Maf) comprised water stored between the minimum

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**Former Executive Vice President, NESPAK operating level of 396 m (1300 ft) and the maximum level of 472 m (1550 ft). Tarbela dam was the largest earth-fill dam of the day, and its design and construction presented a number of challenges. At the time of its initial impounding in 1974, one of the intake gates jammed, the intake structures of Tunnels No. 1 and 2 and the outlet control structures of Tunnels No. 3 and 4 were severely damaged, the control of the reservoir was completely lost. To avert the impending danger to the safety of the dam, and the life and property further downstream, the reservoir was depleted. The problems were resolved after extensive repairs and the dam was finally commissioned in 1976, but many new problems continued to interfere with the operation of the reservoir.

1. HISTORY OF OPERATION

Soon after the final commissioning of the dam new problems occurred which included the appearance of sinkholes in the reservoir, damage to the stilling basin of Tunnels No. 3 and 4 and the erosion of the plunge pool of the service spillway. The new problems were resolved by 1982, when preliminary results of the latest dynamic analyses of the major structures of the reservoir raised new apprehensions. The original design of the project was based on a pseudo static analysis, assuming a horizontal ground acceleration of 0.1g, due to an earthquake. During the construction of the dam, it was realized that the Tarbela site was susceptible to a much higher intensity of the earthquake than that assumed at the design stage. A maximum credible earthquake causing a ground acceleration of 0.5g was considered probable during the life of the dam. New computer software was also then available in the market for carrying out dynamic analyses of complex soil-structure-water interaction. By the end of 1983 TAMS had completed the dynamic analysis of the major structures forming the rim of the reservoir under the maximum credible earthquake. This analysis showed that the intake towers of Tunnels No. 1 and 2 and the spillways would fail under the maximum credible earthquake. The remedial measures were identified by the consultants which were implemented for the intake towers. The cost and the impact of the remedial measures proposed for the spillways seemed prohibitive and could not be implemented. Furthermore, the dynamic analysis had shown that the spillways were safe under the maximum credible earthquake as long as the water level was below 468 m (1535ft). The probability of the occurrence of the maximum credible earthquake, when the water level was above 468 m, was considered as very low. However, this low risk of the vulnerability of the spillways to the maximum credible earthquake should be a stark reminder that :

- The level of water above 468 m be raised very slowly, the maximum level of 472.4 m (1550 ft) should be kept for a minimum duration, and must never be exceeded, in any event.

- Several billion cubic meter of sediments in the reservoir pose a threat to the life and property along the Indus, downstream of the dam, for which situation the only remedy is the regular flushing of the sediments.

The first extension of the power house comprising Generating Units No. 5 to 8, each of 175 MW capacity on Tunnel No. 2, was completed in 1982 while the second extension comprising Generating Units No. 9 and 10 of 175 MW capacity each, also on Tunnel No. 2, was completed three years later. In the year 1985 the Generating Units No. 5 to 8 started vibrating violently and could not operate satisfactorily when the reservoir was near the minimum operating level of 396 m. The bolts holding the head covers of turbines were broken, releasing water into the power house. Subsequent investigations indicated that by adopting certain remedial measures the violent vibrations could be reduced but could not be eliminated. In order to avoid this problem and for protecting the Generating Units 5 to 8, WAPDA recommended (in November 1985) to the Ministry of Water and Power that the minimum operating level should be raised to 408 m (1339 ft) for all the future operations.

The question of raising the minimum operating level of the reservoir arose at an interesting time, when the design of another large reservoir, Kalabagh dam, on the Indus river had been finalized, its tender documents were under preparation, and its construction schedule, targeting its commissioning in 1992, was ready. At the same time the preliminary studies had confirmed the economic and technical viability of Bhasha dam. The planners were confident that Kalabagh dam would be constructed by 1992 and Bhasha dam would be ready by the end of the century, therefore, the loss of storage capacity of Tarbela dam due to raising of its minimum operating level as well as sedimentation was not considered as a serious matter. In anticipation of the new dams, the policy makers and the planners had commenced the conversion of Tarbela dam to a power oriented project, rather than a storage of water for irrigation. This shift in policy was apparent from the decision (in the mid eighties) of replacing the malfunctioning stilling basin of only Tunnel No. 4, and not Tunnel No.3, into a flip bucket. The shift was further confirmed by disconnecting the outlet control structure of Tunnel No. 3 from the reservoir in the late eighties which reduced the discharge capacity for depleting the reservoir in an emergency.

By the year 1992 third extension of the power house was completed which comprised installation of Generating Unit No. 11 to 14, each of 432 MW capacity, raising the installed capacity of Tarbela power station to 3478 MW, against the originally planned capacity of 2100 MW. A fourth extension was also planned in 1992, comprising 960 MW on Tunnel No. 4.

From early 1990 to mid 1996 the nature was very kind to Pakistan, there were good rains and more than normal water flows in the rivers. Therefore, the demand for the release of the irrigation water from Tarbela, during this period, was relatively less than the normal demand. These transient weather conditions also favored the optimization of the generation of electricity from Tarbela, by abandoning the original operating rule for lowering the reservoir to 396 m level. Except for a short period (in 1993-94) the minimum reservoir level remained between 419 m (1375 ft) and 440 m (1445 ft) during this period. In this way several billion cubic meter of sediments were trapped in the reservoir, encroaching upon its live storage capacity.

A panel of expert visited Tarbela in 1995 to study the movement of the sediment. The panel observed that there was a relationship between the minimum operating level and the rate of advancement of the sediment delta toward the dam. When the water level was drawn down, the sediment delta that was formed at the upstream end of the reservoir was exposed and susceptible to erosion from forthcoming flows which resulted in the reworking of the delta, moving it downstream towards the dam. This movement of the delta had the following two conflicting consequences:

(1) It increased the volume of sediments in the dead (non usable) storage zone and decreased the sediments in the live storage zone, thus increasing the live storage and the ability of the reservoir to regulate the Indus river.

(2) The sediments moved closer to the intakes and the dam, threatening the blockage of the intakes and the erosion of turbines of the power plant.

The first consequence favored the preservation of the live storage at the cost of increased wear and tear of the power plant plus the increased risk of blockage of the intakes. The second one favored protection of the power plant as well as the intakes by sacrificing the storage capacity. The panel advised WAPDA to raise the minimum operating level to 412 m (1350 ft) to slow the downstream movement of the delta.

A dry cycle commenced in 1997 and the demand for water rose, forcing WAPDA to lower the reservoir level to 402 m (1318 ft). The Generating Units No. 11 to 14 of Tunnel No. 3 stopped operation due to the choking of their cooling water system. The result was shortage of power and considerable loss to WAPDA. Subsequent efforts to start these units when the reservoir level rose to about 412 m (1345 ft) also failed because the choking of the cooling water system persisted. Tunnel No.4, which had not been operated for a long time, was opened to flush out the sediments sitting in the vicinity of intakes of the right bank tunnels. Initially the discharge from Tunnel No. 4 contained about 580,000 parts per million (ppm) of sediments but ultimately intakes area was cleared of all sediments and Generating Units 11 to 14 started their normal operation. After that event, WAPDA informed the Ministry of Water and Power (in May 1997) that lowering of the reservoir below 412 m (1350 ft) level had transported high concentration of silt and sand into the tunnels and the power plant, posing a potential danger of damaging the power plant and therefore, in the future the minimum operating level must not fall below 412 m level. The construction of 1450 MW Ghazi Barotha Hydropower Project (GBHP) also commenced in 1997 which further increased the stakes against flushing the sediments from Tarbela reservoir.

In the year 2000, again WAPDA was forced to lower the minimum operating level below 403 m (1322 ft). However, this time the entire power plant, including the generating units on Tunnel No. 3, continued to operate satisfactorily. This successful operation was a result of the modification of the operating procedures in the light of the experience gained in the year 1997. The chief engineer in-charge of this operation was so confident after this experience that in his report he jubilantly declared:

Quote

Tarbela Units 11 to 14 are capable to run at low reservoir level if the modified procedure is followed. The turbine parts are designed to withstand the prevailing situation of sedimentation for next 5 -10 years, where after the repair facilities would be available in Pakistan, to cope with the abrasion/erosion of hydraulic surfaces.

Unquote

3. IMPACT OF ABANDONING ORIGINAL OPERATING RULE

Under the original operating rule, stipulated by TAMS, it was mandatory to lower the reservoir level, every year, to 396 m (1300 ft) by May 20 and be held there until June 20, before being raised to 472 m (1550 ft) level. This important rule was stipulated by the designers to ensure the optimum condition for effectively flushing out the sediments from the reservoir using Tunnels No. 3 and 4, because their intakes were at the lowest level. As long as this rule was diligently followed the delta formed by the sediments continued to move toward the dam at an average rate of 1.6 kilometer (one mile) per year. The most important evidence of the usefulness of this rule and the flushing efficiency of the tunnel was noticed in the year 1997 when Tunnel No. 4 discharged water containing 580,000 ppm sediments which amounted to discharging mud, not water. As mentioned earlier, this important operating rule was abandoned in the year 1990 because of the following two apprehensions:

(1) The removal of very large quantity of sediments from the reservoir, through the tunnels, would erode the turbines and other appurtenances installed in the tunnels, necessitating very large expenditures on subsequent maintenance and repair.

(2) If the sediments were allowed to accumulate in the dead storage, near the dam, the possible forward slumping and movement of the sediments delta might block the intakes.

Since the year 1990 the movement of the sediments delta toward the dam had slowed, thus preventing the flushing of sediments. The abandoning of this rule did not prove worthwhile because construction of the new reservoirs was delayed. It only deferred the problems of the erosion at the cost of the storage capacity which is the most important resource. It did not diminish the risk of the blockage of the intakes, that risk, if it is a real risk, still exists. Theoretically, the slumping or liquefaction of the delta can take place any time, and its devastation increases with the accumulation of more sediments in the reservoir. No remedy has been planned to mitigate this possible devastation.

4. IMPORTANCE OF SEDIMENT FLUSHING

The Indus river is one of the largest sediment producing rivers in the world. The main source of sediment is from the glacial landscape and erosion from steep sided barren slopes. Although the actual sediment inflow into the reservoir has been far less than the predicted inflow, the sediment flushing is still a problem without any precedent. The raising of the minimum operating level tended to render Tarbela dam unsuitable for a sustainable operation, threatening to deprive the country of its irrigation as well as power benefits. In fact in spite of this practice the so called 'limit line' has already moved dangerously close to the intakes. The limit line for Tarbela dam is defined by the experts, as a line having its origin at the dam at 341 m(1120 ft) level and sloping upwards, away from the dam at a slope of 5.3 m per kilometer or 28 ft per mile. It was predicted by TAMS in the year 1997 that without additional remedial measures for the management of sediments the delta will cross the limit line by the year 2006, preventing the operation of Tunnels No. 3, and 4 and a few years later Tunnels No. 1 and 2 will also be similarly affected.

A detailed sediment management study was carried out by TAMS in 1997. In their final report TAMS recommended the following measures for the sustainable operation of Tarbela dam (albeit with a reduced but perpetual live storage capacity of 7400 Mcm or 6 Maf which is 64 percent of the original capacity) :

(1) The sediment profile being within 3.2 kilometer of the limit line poses a threat of overwhelming the intakes of Tunnels No. 3 and 4, therefore it is necessary to raise the minimum operating level by 1.2m every year and this level should not last for more than 15 days in any year.

(2) By the year 2008, an under water dike should be constructed to protect the intakes of the right bank tunnels, the crest of the dike should be at 421 m level.

(3) By the year 2015 a bypass should be constructed for flushing out the sediments. The bypass should comprise four new tunnels to be built between the service and auxiliary spillways.

(4) Dredgers having an annual dredging capacity of 0.5 Mcm should be procured for dredging the intake channel required for carrying the silt laden water to the new tunnels.

The estimated cost of the measures proposed by TAMS was indicated as US$ 663 million, which cost and the prospects of a 7400 Mcm or 6 Maf perpetual storage seem very attractive. However, TAMS proposal has the following drawbacks :

(a) The long term effectiveness of the underwater dike in stopping the sediments from entering into the right bank tunnels is questionable. At Warsak dam a similar dike did not prevent inflow of sediments into the powerhouse. The dike at Warsak was overtopped by the sediments within a few years of its construction and over 60 percent of all sediments entering into the reservoir continue to pass through the power intake.

(b) On the average 18,000 Mcm (14.5 Maf) or 22 percent of the annual water inflows will be required to flush out the sediments from the reservoir. This huge quantity of water will not be available for power generation in the critical months of May and June, resulting in a substantial loss of cheap hydropower.

(c) The bypass will dump the large quantity of sediments along the left bank of Ghazi Barotha barrage which will seriously affect the GBHP.

(d) The geological conditions at the proposed location of the bypass are not favorable for its construction.

Tarbela dam is a strategic national resource whose sustainable and efficient operation is of paramount interest for Pakistan. Unless action is taken to flush out the sediments on a regular and sustainable basis, the reservoir will continue to lose its storage capacity and will be ultimately filled up. Agriculture contributes about 25 percent of Pakistan's GDP, employs over 50 percent of our labor force and is the largest source of foreign exchange earnings. Irrigation is the life blood of our agriculture and Tarbela dam plays the most important role in meeting the demand of irrigation by supplying about 60,000 Mcm (48.6 Maf) of regulated flow in an average year. Pakistan is facing an acute shortage of water and at the same time, as rightly pointed out by the Dawn newspaper in an editorial dated August 17, 2002, the construction of new water storages on the Indus river, without a consensus among the four provinces, has become very uncertain, because it involves the complex social, environmental, political and seismic issues. In these circumstances Pakistan cannot afford to lose any more storage capacity of Tarbela.

In view of the investment already made in Tarbela dam, and of its critical national importance, a policy of inactivity must be replaced with immediate action to change the operating rule so that Tarbela can serve its primary and secondary objectives in a sustainable way. By enforcing the original operating rule it is still possible to preserve the remaining storage of Tarbela and to ensure sustainable operation of this vital reservoir, without the construction of new bypass tunnel and under water dyke. The following precautionary measures would be required for this purpose :

- Intakes of Tunnels No. 3 and 4 have an invert level of 353 m (1160 ft) which is 20 m (65 ft) lower than Tunnels No 1 and 2. Therefore, Tunnels No.3 and 4 can be very effective in flushing out the sediments. It is therefore, advisable to operate the power plant of Tunnel No 3 on the base load so that maximum quantity of sediment is carried through this tunnel. The satisfactory performance of Tunnel No. 3 and Generating Units No. 11 to 14 in the months of March and April 2000 demonstrated that it is possible to discharge water with silt contents over 5000 ppm through the power plant. Assuming an average discharge of 1,000 cubic meter per second, 2500 ppm sediments and 250 days of operation per year, Tunnel No. 3 would flush over 50 Mcm (72 Mt) sediments annually. The feasibility of reconnecting Tunnel No. 3 to the reservoir should also be investigated for using it for drawing down the reservoir in an emergency.

- Tunnel No. 4 should be converted to power without disconnecting its outlet works from the reservoir. After converting it to power, Tunnel No. 4 should also be used for base load. There are a number of factors which influence the movement of the sediments in the reservoir, making it rather difficult to predict flushing capacity of the tunnels, however, on April 24, 1997 the discharge of Tunnel No. 4 contained 580,000 ppm sediments, and if one assumed a discharge of 1000 cubic meter per second at that time, the tunnel flushed an unbelievable 2 Mcm (2.8 Mt) sediments per hour, without suffering any major damage. This rate of flushing is not sustainable but it shows that the existing tunnels would be able to flush the bulk of the annual sediments inflow, and eventually, would create an equilibrium between annual sediment inflows and outflows.

- Operation of power plants of Tunnels No. 3 and 4 on the base load will require a detailed study of its impact on WAPDA's power system, particularly with respect to the requirements for the spinning reserve and the frequency control. In this respect GBHP could play a useful role because its each generating unit has 290 MW capacity and a very reasonable response to the transient conditions due to the short length of its penstock.

- If the water demand is more than the capacity of Tunnel No 3 and 4, then Tunnel No. 1, followed by Tunnel No 2, should be operated.

- When the reservoir level falls below 347 m (1139 ft) Generating Units No. 5 to 8 should be shut down to avoid any damage due to excessive vibrations. Any short fall in the water demand, above the combined capacity of Tunnels No. 1 to 4 should then be met by opening Tunnel No. 5. If the short fall still persists the outlet control gates of Tunnels No. 3 and 4 should be opened.

- Operation of power plant and tunnels at low reservoir level, with a very high concentration of sediments will necessitate provision of cleaner water for the cooling systems. A number of alternative sources of clean water are available, like Tunnels No. 1 and 2, tube wells, seepage from dam, closed cycle cooling or a combination thereof. Arrangement for this purpose should be made after a detailed evaluation of available alternative water sources and selecting the most advantageous alternative.

- In the long run, say after 5 to 10 years, repair facilities would be required to cope with the erosion of hydraulic surfaces due to silt laden water. Such facilities should be planned now, in the light of experience gained at Warsak about the similar erosion problem. It may be pointed out that the turbine runners and wicket gates of Generating Units 11 to 14 are made from stainless steel castings conforming to ASTM A 743 CA-6NM, which has a very good resistance to abrasion. This material also has good welding properties and therefore, it is easy to repair its erosion by welding. The use of similar stainless steel at Warsak had been found reasonably durable, although sediments of the Kabul river are far more abrasive than the sediments of the Indus river.

- To avoid the risk of blockage of intakes either due to liquefaction during an earthquake or slumping of the delta due to any other cause, deep water suction dredging system of a reasonable capacity should be arranged to clear the blockage as quickly as possible. With the collaboration between the local industry and the foreign manufactures, very large barge mounted dredging systems, operating on the available hydropower, can be fabricated and assembled at the site. (Very large dredgers are being built worldwide. Suez Canal Authority purchased a dredger of 24,000 cubic meter per hour dredging capacity in 1984). The provision of the dredger is necessary to guard against the prolong blockage of the intakes due to the liquefaction or the slumping of the sediments delta, which provision should be made immediately, even if the reservoir operating practice is not changed.

- As stipulated in the original operating rule, minimum water level of 396 m (1300 ft) should be maintained from May 20 to June 20 every year, irrespective of demand for the irrigation or the power. This step will ultimately create a condition of equilibrium between the sediment inflows and outflows, and will also help in establishing a stable delta.

Finally it is suggested that a team of engineers, experienced in the design and the operation of large water resources and hydropower projects handling the sediments, should thoroughly deliberate on the impact of the above measures and advise the Government of Pakistan in implementing the measures, as appropriate. The impact on the GBHP needs very careful consideration. Although, GBHP is designed to handle the sediments released from the right bank tunnels of Tarbela, special procedures would be required for operating GBHP to handle very large quantities of sediments. Similarly the rate at which the minimum operating level of Tarbela should be lowered, needs to be determined after a very careful examination of the movements of the sediments every year.