Evaluation Of Sediment Management Strategies For Large Reservoirs

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Abstract

Multipurpose large dams play a key role in the development of world by providing water for irrigation, flood control and hydropower. Tarbela is one of the world's largest earth and rock fill dam. Being multipurpose dam, it provides vital role for economic stability and social development of Pakistan. Tarbela Reservoir has lost its significant capacity due to sediment deposition. The objective of the study was to evaluate different options for evacuation of deposited sediments and reducing sediment inflows to Tarbela Reservoir through sediment modeling by HEC-RAS. Sediment flushing from existing power tunnels was evaluated in first option and found not feasible due to the downstream constraints and loss of 7848 MW hydropower from Tarbela and Ghazi Barotha. New sediment bypass tunnels were proposed on right bank of the dam to overcome the constraints in second option. Sediment modeling was performed by HEC-RAS to evaluate each scenario of sediment flushing with different parameters. The sediment balance ratio and long term capacity ratio was also checked for each scenario for technical evaluation and also economic analysis was performed. Most technical viable scenario was flushing for 90 days at reservoir drawdown level of 390 m with discharge of 5000m³ /s. However, this scenario was not economically feasible as net present value was negative, internal rate of return was 3-4 %, and benefit cost ratio was found less than one. The 3rd option, with under construction multipurpose Diamer Basha Dam on upstream of Tarbela Reservoir, was also evaluated on HEC-RAS. Results depicted that large amount of sediments were trapped in the upstream reservoir which ultimately reduced significantly the inflow of sediments and delta movement in Tarbela Reservoir. This option is recommended because it will enhance the life of Tarbela Reservoir and it will keep on providing multiple benefits for longer time.

1. Introduction

Storage depletion of large reservoirs around the world due to sediment deposition has not only affected the availability of water for irrigation, drinking and hydropower but also a key factor for retarding global economy. World Commission on Dams (2000) reported that most of the water resources projects are not providing the optimized benefits. White (2010) emphasized that the focus of water resources development and management should be towards conservation of existing reservoirs in addition to construction of new dams

Schleiss et al. (2010a) estimated that \$13-20 billions were required for storage replacement and to mitigate the decrease of the reservoirs' storage due to sedimentation. Significant reduction of existing reservoirs' capacity around the world was found due to sediment deposition (Jacobsen,1999). Mavima et al. (2011) highlighted that the causes for the silting up of the reservoirs were attributed to deforestation, population growth, and lack of proper education of the communities in catchment management. High sediment concentration in the reservoir can be reduced by progressively increasing the sluicing discharge (Hug et al. 2000).

Rashid et al. (2018) asserted that by optimized operation of existing reservoirs, a lot of benefits can be capitalized. The optimized rule curves developed using the RESOOSE model reduced more than 16%

irrigation shortages for Tarbela and Basha Dam. Moreover, the reservoir's sustainability could be enhanced through increased sediment evacuation. Another optimization study on Tarbela Reservoir concluded that the optimized rule curves maximized net economic benefits up to 250% over the existing rule curves (Khan and Tingsanchali, 2009).

Schleiss et al. (2010b) summarized that worldwide loss of capacity in reservoirs due to sedimentation is greater than the increase of capacity due to construction of new reservoirs. Sedimentation in large reservoirs can be managed by storing clear water and releasing the turbid water. This strategy gave sediment releasing efficiency up to 100% (WANG and Hu, 2009; Schleiss et al. 2014).

Podolak et al. (2015) highlighted that maintaining reservoir storage capacity has been valuable for a variety of national purposes. The study pointed out the fact that reservoir sedimentation can be reversed through active sediment management options of flushing, dredging, reducing sediment inflow. White (2010) presented the factors which affect the viability and efficiency of sediment flushing through reservoirs. It was concluded that flushing was more effective in hydrologically small reservoirs with storage capacity <30 % of mean annual flow.

Sedimentation can affect hydropower production due to loss of reservoir storage and damage to the facility's mechanical components. Sediments deposited in reservoirs may affect the safety of dams and it has negative impact on environment. In developing regions, sustainable hydropower development must involve consideration of sediment management techniques during design, construction, and operation (Obialor et al. 2019). The utility of the reservoirs start reducing after 40 years and after 200 years it would be nothing but a collection of sand and sediment with no water in it (Garg, 2009).

Morris et al. (2008) assessed that global per capita reservoir storage has decreased since its peak in 1980s. Current storage was found equivalent to the level of year 1960. Chang et al. (2005) discussed that good operating rules of reservoirs enhance the system performance for water supply, energy production and conserve storage capacity. Peter and John (2005) concluded that the dredging cost is highly variable and depends on characteristics of bottom sediments, pipeline distance to dewatering sites, the land cost for dewatering sites, weather, and topography.

Some large reservoirs could store huge worth of incoming sediment before filling up completely. Interruption of sediment continuity through the river system can also damage ecological systems and human infrastructure downstream of the dam. From the perspective of sediment management in reservoirs, sustainable reservoirs were suggested. Moreover, the characteristics of sustainable reservoirs defined were (a) maintaining reservoir capacity and life indefinitely, (b) positive economic value for full life cycle method considering decommissioning and sediment management (c) without adverse impact on the social, environmental, and economical aspects of the affected area. All the characteristics (Palmieri et al., 2003; International Commission on Large Dams (ICOLD), 1999)

Reservoir sedimentation management is an essential task worldwide. In Switzerland, most dams are dedicated to electricity production mainly by storage plants, the dead storage designed to accumulate the

sediment deposit is generally completely filled. This is a source of problems regarding the safe operation of turbines and bottom outlet devices. The economic and societal importance of water storage makes sedimentation in reservoirs an active and expanding field of research (Meile et al., 2014).

Rashid et. al (2014) conducted evaluation of sediment management options of dredging, trucking, flushing and hydrosuction for Tarbela Reservoir. Dredging and trucking was found technical feasible but economically non feasible. Hydrosuction was found technically non-viable. Flushing through existing tunnels was found technically and financially feasible but not recommended due to constraints at downstream of the dam.

The excess of sedimentation in a reservoir leads to sediment entrainment in waterway systems and hydraulic schemes (Faghihirad, Lin, & Falconer, 2015). Depending on the degree of sediment accumulation, outlet structures may be clogged. Blockage or damage of intakes and outlets, not designed for sediment passage, may generate security problems. Guangqian et al. (2005) discussed the sedimentation problem in the Sanmenxia Reservoir which caused loss of storage capacity. Sediments increased the flood risk due to the decrease in the discharge capacity. Moreover, it threatened the industrial and agricultural economic productivity in Xi'an, the capital city of Shanxi province in the lower reaches of the Wei River. Reconstruction of outlet structures in the dam had significantly increased the discharge capacity and provided the dam with the necessary facility to allow flood flows along with deposited sediments to pass out from reservoir. A balance of sediment deposition and evacuation was maintained in the reservoir by flushing the sediment out of the reservoir, eventually minimizing the adverse effect of reservoir sedimentation.

Kondolf et al. (2014) presented the summary of managing sediments of reservoirs of five continents. The successful options found were sluicing, flushing and bypass sediment around the reservoirs depending on the geometry of the reservoir along with technical feasibility. Asahi Dam on the Shingu River (Japan), built in 1978, had severe sediment deposition issues which lead to loss of reservoir capacity. The construction of a sediment bypass with a 13.5 m high diversion weir and 2350 m long tunnel in 1998 was completed in order to avoid the loss of storage capacity of Asahi dam. The deposited sediments in the Ashai Reservoir were flushed through this bypass flushing tunnel and channel. The results of this evacuation by 2006 depicted that sediment bypassing through the tunnel had avoided a cumulative 750,000 m³ of sediment deposition (Mitsuzumi et al., 2009).

The sediment deposition in Keswick Reservoir and construction of other dams interrupted the continuity of the river system for transporting the sediments to downstream and coastal regions. These huge sediments play an important role in global geological cycle, global geochemical cycle, costal ecosystems and the evolution of deltas (Kondolf, 1997). One of the main impacts of reservoir sedimentation on hydropower generation was the loss of storage. Globally, the total volume of water stored in reservoirs used for hydropower and other purposes around the world currently exceeds 6,800 km³ (White, 2000).

Dams inevitably alter the natural environment and affect the existing users of natural resources, including wild capture fisheries. The loss of storage endanger the sustainability of aquatic life of Mekong Basin (Mekong River Commission (MRC), 2017). Hurtle (2009) highlighted the adverse impact of reducing storage capacity by sediment deposition on aquatic life. The total catch of fish and other aquatic animals from the Lower Mekong Basin (LMB) has been estimated to 2.3 million tons per year. The aquatic life dependent on reservoirs' water supports millions of people's livelihoods and provides a significant part of the food supply across the entire basin.

Basson (2008) estimated that 64% of the total capacity of reservoirs of the world will be lost by 2050 due to sediment deposition. The storage reduction has enhanced the probability of flood damages. Therefore, reduction in sediment loads by incorporation of different strategies was the way forward found as it will result in restoration and improvement of water quality, aquatic habitats, navigation, hydropower, irrigation and reduction of flood damages.

The objectives of the study were to evaluate different options for evacuation of deposited sediments from large reservoirs along with the possibility of reducing sediment inflows. Tarbela Reservoir in Pakistan was selected as a case study and sediment modeling was carried out by HEC-RAS.

2. Case Study Reservoir

Tarbela is one of the World's largest earth and rock filled dam which was started in 1968 and completed in 1974 on Indus River having annual average flows of 180 Billion m^3 . The main dam is 2743.2 m long, 143.2 m high with an inclined impervious earth core. There are two spillways, service and auxiliary spillways which have discharge capacities of 18400 m^3/s and 24000 m^3/s respectively. Initially, five tunnels were constructed as part of Tarbela Dam's outlet works. Originally Tarbela Dam Project has a maximum power generation capacity of 4,888 MW from turbines installed on tunnels 1, 2, and 3, which were originally designed as power tunnels. Tunnels 4 and 5 were initially intended for irrigation supplies. However, Tunnel 4 is already converted to provide 1410 MW hydropower in 2018 and a new project of converting Tunnel 5 to generate hydropower is also being commissioned. The conversion of 5th irrigation tunnel to hydropower will enhance the total capacity of Tarbela to 6398 MW. The layout and components of Tarbela are shown as Figure 1 (WAPDA, 1984; WAPDA, 1991; WAPDA, 2017).

3. Data Used

The geometric, hydrologic and sediment data of Tarbela Reservoir was collected from Tarbela Dam Project – Water and Power Development Authority (WAPDA) and used in the study. The geometry of the reservoir was described through layout and cross-sections. The hydrological and sediment data comprised of water flow series, sediment concentrations and levels of the Tarbela Reservoir. The flow and sediment data was collected from Besham Station for the period 1979 to 2017. The Tarbela Reservoir inflows and levels are shown in Figure 2 and Figure 3 respectively. In the hydrological years from 1992-93 to 1997-98, the inflow was gauged generally less than the outflows, while in later years the gauged inflow

has been always higher. On average the total inflows and the outflows of Tarbela Reservoir were 73 Billion m³ (WAPDA, 2010; WAPDA, 2015; WAPDA, 2017).

The sediment rating curve was developed from double mass plot of flow versus daily sediment load of data collected at Besham station and is presented as Figure 4.

The hydrographic survey of Tarbela reservoir of different years revealed that the average sediment inflow at Tarbela was of the order of 200 million tons per year, the greatest proportion being transported during the flood season between May and September. The total sediment inflow from Besham Qila estimated by the 2017 was 147 Million Tons, 63 Million Tons of fine material, silt and clay (smaller than 0.063 mm), and 84 Million Tons of sand (defined as coarser material than 0.063 mm). Annual sediment inflow in Tarbela Reservoir from 1975 to 2017 is shown in Figure 5. Figure 6 indicates the sediment bed gradation curve of Tarbela Reservoir.

4. Hec-ras Model

There are various softwares used for performing reservoir operations and sediment modeling. HEC-RAS is the most commonly used software for computing water surface profiles of system of channels for evaluation of structures performance under various hydraulics conditions. It can perform steady and unsteady flow simulations, movable boundary sediment transport computations, water quality analysis, etc. HEC-RAS 5.0.7 has been used in the present study because of its enhanced robust capabilities to simulate reservoir sedimentation. It is freely available model and its results are considered reliable all over the world.

The layout and river cross-sections of 1974 covering the Tarbela Reservoir were provided as geometric input to HEC-RAS. The upstream boundary condition was inflows series 1979-2017 and downstream boundary condition was actual reservoir levels 1979-2017. The upstream and downstream boundary conditions were added as quasi unsteady flow input in the model. Sediment rating curve, curves were also added sediment characteristics in the HEC-RAS. The geometric, quasi unsteady flow and sediment data are prerequisite to run sediment modeling computations.

5. Calibration And Validation Of Hec-ras Model

The model has been calibrated as per the suggested guidelines of Hydrologic Engineering Center (HEC) (2016). HEC-RAS is a 1-D model and adopts a single profile of water across each cross-section. Flow in Indus River at Tarbela usually ranges from low and high values (370-10,000 m³/s) and roughness normally decreases with an increase in flow and depth. Manning's roughness coefficient value was adjusted for the calibration of the model. The variation of calibrated values of Mannings' n with discharge used in the model is shown in Figure. 7

The sediment bed profile, volume of sediments deposited, volume of sediment outflow, and remaining capacity of the reservoir were the parameters used for calibration and validation of model. These

parameters of Tarbela reservoir were calibrated for the year 2008 in HEC-RAS. Settling velocity of clay and diameters of silt and sand fractions were allowed to vary during the calibration process. The simulated and actual bed profiles for calibration year 2008 is shown in Figure 8. The actual capacity of the reservoir was 8.8 BCM whereas the simulated capacity was 8.5 BCM for the calibrated year 2008, there was a difference of 4% between actual and simulated values.

The HEC-RAS model developed for Tarbela Reservoir was validated for the year 2013. The validation results are shown in Figure 9. The actual capacity of the reservoir was 8 BCM and the simulated capacity of the reservoir was 7.6 BCM for the validated year, there was a difference of 5% between actual and simulated value. Thus, model accuracy of 4-5% can be considered reliable to run future simulations for Tarbela Reservoir's capacity under various operational scenarios.

6. Results And Discussion

The comparison of hydrographic surveys of Tarbela Reservoir of different years revealed that the delta pivot point has advanced towards the main dam from 23.5 km in 1979 to 6.46 km in 2017. The storage capacity of the reservoir has reduced every year by the deposition of huge amount of sediment. In 44 years period the gross storage of reservoir has reduced from 14.3 BCM to 8.4 BCM (41% storage reduction). The longitudinal bed profiles of the Tarbela Reservoir for different years are shown in the Figure 10. The Figure revealed the patten of sediment deposition in the reservoir from its commissioning to 2018.

The options of reducing sediment inflow and sediment evacuation from Tarbela Reservoir envisaged for the study for evaluation are as follows:

1. Sediment flushing from existing power tunnels
2. Sediment flushing through new sediment bypass tunnels
3. Reducing sediment inflow by constructing reservoir upstream

6.1 Sediment Flushing from Existing Power Tunnels

Availability of flushing tunnels of suitable numbers and capacity play a key role in successful flushing of deposited sediments from large reservoirs. Tarbela Dam has five tunnels, four of which are already equipped with power generation facilities and project of hydro power turbine installation is also underway on tunnel 5. The existing tunnels were not found suitable for flushing of sediments at high discharges and low reservoir levels due to two restraints. One aspect was the historical review of performance of sediment outflows at low levels on hydropower facilities of Tarbela and other aspect was the physical infrastructure available at downstream of the dam. In 1997, the outflow discharge from tunnels with reservoir level of 402m for very short time resulted in chocking of system of power turbines and abrupt movement of delta movement towards the power intakes. As a result, the shutdown of power facilities was observed for many weeks. It required huge effort of Engineers to start the hydropower production after removing the faults. Based on this actual event of sediment outflows for short duration, it can be

concluded that the flushing from existing power intakes will have severe repercussion on cheap hydropower of 6398 MW of Tarbela. The physical infrastructures available at 7 km downstream of the Dam are mega hydraulic structure Ghazi Barotha Hydropower Project of 1450 MW with pond. The studies confirmed that the evacuated sediments from Tarbela Reservoir will deposit in the form of big mountains in the pond of Ghazi Barotha and it will choke its intake. Moreover, the downstream of Tarbela Dam river regime will be disturbed and it will constitute environmental problem. Therefore, the sediment flushing with existing power tunnels was not recommended (WAPDA, 2010; WAPDA, 2015).

6.2 Sediment flushing through new Sediment Bypass Tunnels

The negative impacts of sediment flushing on existing power tunnels of Tarbela, Ghazi Barotha, downstream river and environment were the constraints which needed to be addressed. The constraints could be removed only if flushing were executed through new bypass tunnels. Therefore, new sediment bypass tunnels of 4.2 km were proposed on right bank at 900m upstream of the Tarbela dam near the existing power tunnels connected with 5.9 km bypass flushing channel of 90m wide and 9 m deep. The flushing channel shall also bypass the downstream Ghazi Barotha Hydropower intake structure and pond. These tunnels will also not interfere with existing power tunnels and minimize any risk to the turbines as a result of the flushing. The intakes of flushing tunnels will be below the normal level, as the reservoir needs to be drawn down to that extent to enable effective flushing. Therefore, the sediment modeling was carried out by considering flushing outlets on the right embankment near the existing power tunnels of Tarbela Dam in the study. The location of flushing tunnels and flushing channels is shown in Figure 11.

Different scenarios were formulated by adjusting different invert levels of the sediment bypass tunnels. The technical viability of sediment flushing from reservoirs was checked by computing the two factors, Sediment Balance Ratio (SBR) and Long Term Capacity Ratio (LTCR). SBR is the ratio of sediment inflow and sediment outflow from the reservoirs. Whereas, LTCR is the ratio of long term capacity retained to the original capacity of the reservoir. For flushing to be technical viable the values of $SBR > 1$ and $LTCR > 0.35$ (Palmieri et al., 2003). The technical viability of flushing for Tarbela was checked for each scenario of Tarbela Reservoir. The scenarios evaluated are as follows:

- Scenario 1: Normal Operation with existing minimum operating level of 426m (No flushing).
- Scenario 2: Invert level 390 m.
- Scenario 3: Invert level 400 m.
- Scenario 4: Invert level 411.5 m.
- Scenario 5: Invert level 420.5 m.
- Scenario 6: Invert level 425.5 m.

It was observed through sediment modelling using HEC-RAS that flushing operations with a lower water level resulted in removal of higher percentages of coarse sediment from the reservoir. The time and water level to start flushing was very important as it had impact on fulfilment of water demands and on future

filling of the reservoir. It had been analysed for Tarbela Reservoir that if flushing started at the end of the flood season, it will have a greater impact on the necessary releases for irrigation. Moreover, it would imply emptying the reservoir from its highest level and losing the capacity to release water in the following months. Accordingly, the filling of the reservoir at the start of the low season would also be difficult. If the flushing is performed too early in the season, the target water discharge may not be achieved because of unavailability of sufficient water for flushing in the reservoir. If flushing started too late, inflows in the reservoir increase, and due to the limitation of the capacity of the outlets, the water level during flushing will start to rise making the flushing operation less efficient. The optimum starting date was assessed to be 30th of May and optimum duration of the flushing was established as 90 days starting the drawdown from level 425.5 m down to the target level of 390 m or other selected invert level to be maintained during the flushing. It was analysed by sediment modelling that by enhancing the flushing period, more sediment would be removed from the reservoir and more volume will be recovered.

The simulations have been run from the year 2018. For each scenario of flushing; the time, duration and minimum invert level had been maintained. In scenario 1, the model was simulated for 20 years from 2018-2038. Under normal operation of the Tarbela reservoir at minimum operation level of 426 m and without flushing, the increase in deposition of sediments resulted in a decrease in storage capacity from 7.4 BCM to 4.5 BCM. A comparison of bed profiles of 2018 and 2038 is shown in Figure 12.

The results of flushing for scenario 2 in which the invert level of the tunnels was adjusted at 390 m, with the target discharge of 5000 m³/s for a period of 3 months (May, June, July) preserved a large storage capacity. The SBR was 1.08 and LTCR was 0.35 for this scenario. The values of SBR and LTCR described technical viability of sediment flushing for this scenario. The sediment modelling by HEC-RAS depicted that the position of the delta pivot point receded and the removal of 20 million tons of sediment was observed. The impact of sediment removal through flushing tunnels was 15 km upstream from the main dam body, and the delta pivot point shifted 6 km backward from its original point. A comparison of bed profiles is shown below in Figure 13.

The scenario 3 with invert level of 400 m and discharge of 5000 m³/s for 3 months from May to July resulted in restoration of storage capacity. The SBR and LTCR were found 0.92 and 0.29 respectively. The position of the delta pivot point receded and the removal of 10 million tones was noticed. The impact of sediment removal through flushing tunnels was 1.75 km upstream from the main dam body, delta pivot point shifted 3 km upstream from its original point and preserved a less storage and also less decrease in the height of the delta pivot point compared to scenario 2. A comparison of bed profiles is shown below in Figure 14.

The results of Scenario 4 in which the invert level of the tunnels were adjusted at 411.5 m and other parameters kept same including flushing start time and its duration revealed preservation storage capacity. The SBR and LTCR were found 0.75 and 0.24 respectively. The position of the delta pivot point receded to some extent and the removal of 5 million tones was noticed. The impact of sediment removal

through flushing tunnels was 500 m upstream from the main dam body, delta pivot point shifted 500 m upstream from its original point .A comparison of bed profiles is shown below in Figure 15.

Similar conditions of flushing start time and duration were kept for scenarios 5 and 6 with invert levels of 420.5 m and 425.5 m respectively. The SBR was 0.62 and 0.55 for scenarios 5 and 6. Whereas, the LTCR was found less than 0.21 for both scenarios. No noticeable impact was observed in sediment removal and delta movement was observed for scenario 5 as shown in the Figure 16. Similarly no visible storage preservation, delta movement and sediment removal was observed for scenario 6.

The technical viability of sediment flushing alone is not sufficient for its execution. The economic viability of sediment flushing is also very important and pre-requisite for execution. The economic analysis of scenario 2 has also been carried out to endorse the financial viability of the sediment flushing from the Tarbela Reservoir. The cost of flushing tunnels and channel has also been included in the analysis which comprised of the cost of intakes, excavation, concrete, steel, earthwork, civil and electromechanical etc. The total cost of flushing tunnels and channel used in the analysis was \$986 Million. The Value of flushing water used for analysis was \$67 per acre feet, discount rate was taken 9% and it was assumed that 25% of flushing water will be wasted. The basis of input parameters were taken from the Tarbela Reservoir Sediment Management Study (WAPDA, 2015). The results of economic analysis depicted Internal Rate of Return 3%, Net Present Value was negative at 9% discount rate and benefit cost ratio <1. The economic analysis results indicated that sediment flushing through bypass flushing tunnel was not financially feasible.

6.3 Reducing Sediment Inflow by Constructing Reservoir Upstream

This is the scenario of considering an upstream Reservoir Diamer Basha to reduce sediment inflow in Tarbela Reservoir. Diamer Basha is a roller compacted concrete dam with 272m height, storage capacity of 10 Billion m³, hydropower generation capacity of 4500 MW, located 315 km upstream of Tarbela Dam. Diamer Basha is multipurpose dam currently under the construction stage. This scenario was also run on HEC-RAS for sediment modelling. Large amount of sediments were trapped in the upstream reservoir which ultimately reduced the inflow of sediments in to the Tarbela Reservoir. The results showed no further advancement of delta movement. This scenario resulted in halting loss of reservoir capacity and had least impact of sediment evacuation. Moreover, no advancement of delta was observed for this scenario. A comparison of bed profiles is shown in Figure 17. The decrease in sediment inflow will enhance the life of the Tarbela Reservoir and it will keep on providing benefits of hydropower, irrigation and will also reduce flood damages.

7. Conclusions And Recommendations

The study analyzed the sediment flushing options of large Reservoir Tarbela through HEC-RAS and ended up with some useful conclusions and recommendations as given below

1. Reservoir flushing from bypass tunnels was a technically viable solution for the Tarbela Reservoir. The most viable scenario was flushing for 90 days at reservoir drawdown level of 390 m with discharge of 5000m³/s. The impact of sediment removal through flushing tunnels was observed 6 km upstream from the main dam body.
2. The sediment flushing from the bypass tunnels was not economically viable option as net present value was negative, internal rate of return was 3-4 %, and benefit cost ratio was found less than one. The cost of new bypass tunnels and channel was found key factor for making the sediment flushing economically not viable.
3. For reducing the advancement of delta and sediment deposition in Tarbela Reservoir, the best option found was the commissioning of multipurpose Upstream Diemer Basha Dam which is in the construction phase. Sediment modeling through HEC-RAS depicted that large amount of sediments were trapped in the upstream reservoir which ultimately reduced the inflow of sediments and delta movement in to the Tarbela Reservoir.
4. The sediment flushing from new bypass tunnels was technically viable and economically non-viable option. Therefore, it was not recommended for Tarbela Reservoir. The sediment flushing from existing tunnels were not found suitable because it will halt the hydropower production of both Tarbela Dam (6398 MW) and Ghazi Barotha (1450 MW). Moreover, the flushed sediments will deposit in the downstream pond of Ghazi Barotha and environmental issues may arise.

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Figures

Figure 1

Layout of Tarbela Dam

Figure 2

Inflows of Tarbela Reservoir

Figure 3

Water levels of Tarbela Dam

Figure 4

Sediment rating curve of Besham Station (1979-2017)

Figure 5

Annual Sediment Inflows of Tarbela Reservoir (1975-2018)The grading shown in

Figure 6

Sediment Bed Gradation Curve of Tarbela Reservoir

Figure 7

Variation of Manning's n with flow

Figure 8

Simulated and actual bed profiles of year 2008 for model calibration

Figure 9

Simulated and actual bed profiles of year 2013 for model validation

Figure 10

Observed bed profiles/sediment deposits in Tarbela Reservoir

Figure 11

Location of Flushing Tunnel in Tarbela reservoir.

Figure 12

Simulated Bed Profile at Normal Operation Scenario for the Year 2038

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Sediment bed profile for Scenario 2

Figure 14

Sediment bed profiles for Scenario 3

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Sediment bed profiles for Scenario 4

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Sediment bed profiles for Scenario 5

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Sediment bed profiles for Scenario with Upstream Reservoir.