Tarbela Dam in Pakistan. Case study of reservoir sedimentation

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Abstract

Reservoir sedimentation is a main concern in the Tarbela reservoir in Pakistan. This major storage reservoir on the Indus River, constructed between 1968 and 1974, plays a key role in the provision of water for irrigation, power generation and flood control. Sediments have reduced 30% the initial capacity of the reservoir (11,600Mm^3). The advance of the foreset slope towards the dam also increases the risk of blocking the low level outlets that provide flows downstream to the irrigation system and to the power station.

The paper presents historical data of the evolution of the sediment deposits in the reservoir and how this data has been used to validate a numerical model, RESSASS, that predicts the future development of the delta. The advance of the delta is clear when analysing the surveyed longitudinal profiles and the numerical model is able to predict very accurately this behaviour. Several aspects of the analysis of the future evolution of sediment deposits are discussed including the influence of upstream reservoirs that could reduce the incoming sediment towards Tarbela and the need to estimate the likely amounts of sediment passing through the turbines.

1. Introduction

Tarbela Dam was constructed in the 1970's on the Indus river in north central Pakistan. It was conceived to help to regulate the seasonal flows both for irrigation of the Indus plains downstream and for generation of hydropower. Tarbela is a strategic national resource providing 50% of the total irrigation releases and 30% of the total power and energy needs of Pakistan.

Tarbela Project comprises three dams, the main embankment with a length of 2,750m and a height of 143m. The reservoir had an initial capacity of 11,600Mm^3 and a reservoir length extending approximately 70km upstream the dam.

The Indus River carries a very high sediment load. This is largely due to the erosive effect of the glaciers that supply much of the flow. It is estimated that over 200 million tonnes of suspended sand, silt and washload (Lowe and Fox, 1982) are deposited entirely in the reservoir accumulating in the form of a delta that grows toward the dam. When the project was conceived it was considered that Tarbela Reservoir would have been filled with sediment within 30 years but sediment rates have been lower than expected.

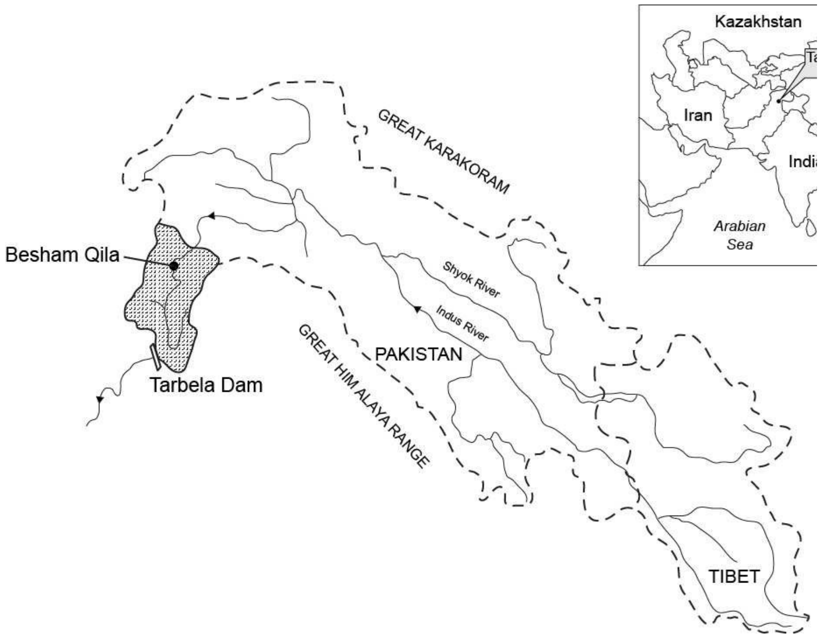

Figure 1: Catchment of the Indus River at Tarbela Dam. Catchment area subject to monsoon rainfall shadowed.

However, sedimentation at Tarbela Reservoir has been a concern for a number of years. The trap efficiency of the reservoir is high because its shape leads to deposition of almost all the incoming sediment. The reduction in live storage since 1974 has been estimated in 2009 as 30%. The decrease in live storage is a concern as it may result in reduction of irrigation releases and power supply. The impact of the delta created by the sediment deposits approaching the main dam may also cause problems clogging the intakes feeding the turbines. The instability of the downstream sloping face of the delta may result in sloughing or landslides (Lowe and Fox, 1982). The occurrence of an earthquake may give raise to larger landslides (TAMS, 1998).

This paper presents historical data of the evolution of the sediment deposits in the reservoir. Chapter 2 discusses the existing available information about water and sediment discharges, longitudinal profiles and cross-sections at the reservoir. The characteristics, validation and application of a specific reservoir numerical model, RESSASS, is described in chapter 3. The model predicts the future development of the delta and estimates the amount of sediment passing through the intakes at the dam. The capabilities and limitations of the numerical simulations are also discussed.

2. Existing data

2.1. Water discharge

The Indus basin upstream of Tarbela Dam has an area of 169,650 km^2. Over 90% lies between the Great Karakoram and the Himalayan ranges and meltwaters from this region contribute to the major part of the annual flow reaching Tarbela. The remainder of the basin, lying immediately upstream of the dam (Figure 1), is subject to monsoon rainfall primarily during the months of July, August and September. The monsoon rains runoff causes sharp floods of short duration which are superimposed on the slower responding snowmelt runoff.

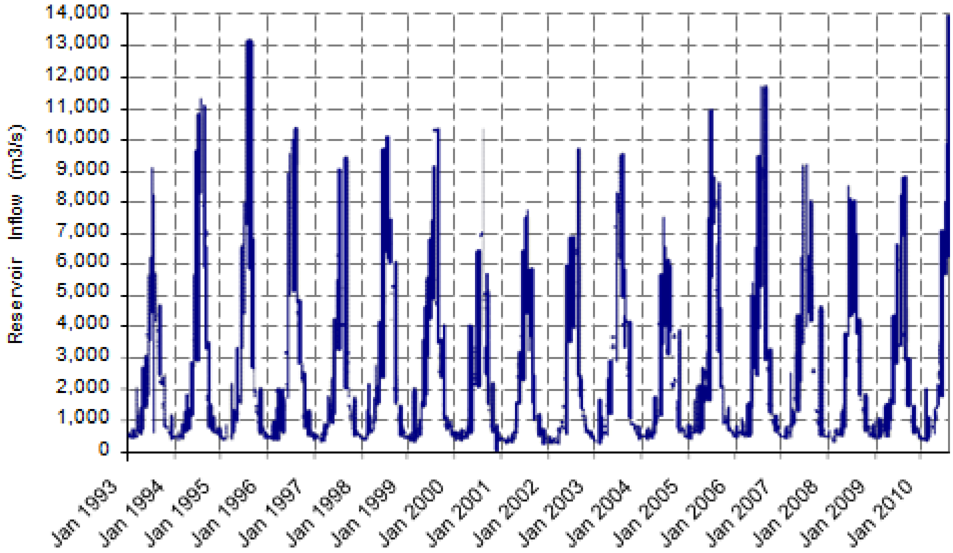

Figure 2: Water inflows to Tarbela Dam at different years.

The average annual inflow to Tarbela is 81,000 Mcm (TAMS 1998). As the Indus has a high proportion of snowmelt runoff the variability of the annual runoff is relatively modest. Peak flows due to snowmelt can be as high as 5,660 to 11,300 m^3/s with an additional rainfall contribution typically reaching a maximum of 5,660 m^3/s (Figure 2).

Water discharges are measured at Besham Qila (Figure 1), a gauging station located on the Indus river some 60 km upstream of the top end of the reservoir. It provides valuable information on water discharges and sediment concentrations. About 93% of the inflows to Tarbela dam originate upstream of Besham Qila. The existing information consists on a set of water discharges and levels at the dam every 10 days from 1968 to 2009. A more detailed data set, with daily records, is available from the period 1993 to 2010.

2.2. Sediment load

Information on sediment inflows into Tarbela reservoir has been collected from several sources. TAMS (1998) shows that annual sediment inflows vary between 100 and 300 MT with an average just below 200 MT for the period 1967-1996. Lowe and Fox (1984) also state that the average sediment inflow in Tarbela is 200 MT, 97% or more carried during the large flows in summer, between May and September with a peak in July and August, primarily caused by snowmelt. White (2001) states a value of 240 MT, with 40MT of very fine sediment passing down- stream the dam. Tarbela Dam Project (2009) provides two estimations of the average annual sediment yield for the period 1975-2009. The first estimation is obtained by using a comprehensive set of sediment rating curves based on data at Besham Qila and gives a value of 160 MT. A second estimatation is based on information from the hydrographic survey showing an annual average of 168 MT, excluding the Siran and Brandu loads (tributaries into the Tarbela Reservoir).

These differences show the difficulties in providing accurate sediment yield estimations that originate from high spatial and temporal variability of quantities related to the physical processes.

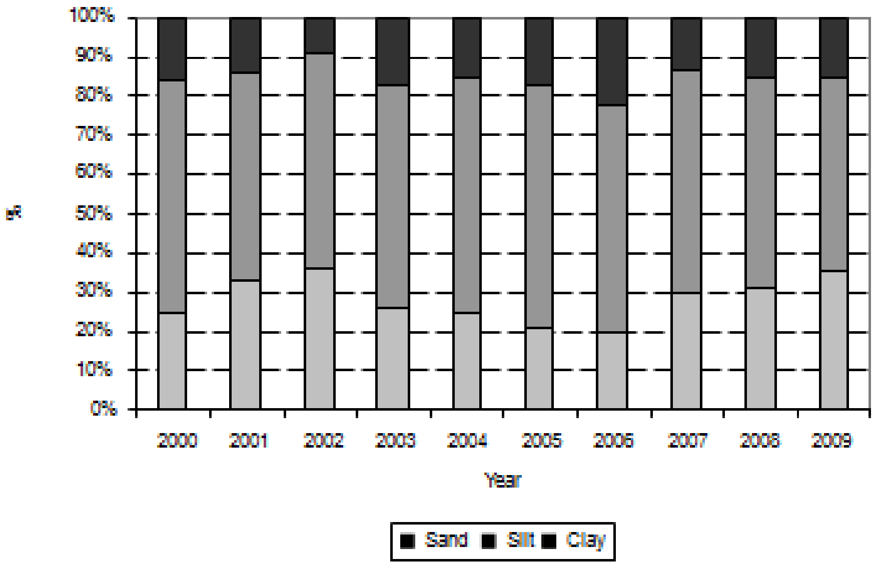

Figure 3: Annual average percentage of sand, silt and clay at Besham Qila for the period 2000-2009.

One third of the inflowing sediment at Tarbela Reservoir is sand, and the remaining two thirds is silt and clay (TAMS, 1998). Individual samples of suspended concentrations at Besham Qila (the gauging station upstream the reservoir) show high variation for the sand proportion, from less than 10 % to 75 %. Annual average values for the 2000-2009 period (extracted from Tarbela Dam Project, 2009) show a variation of proportion of sand between 20 and 35% (Figure 3).

2.3. Operation levels

Seasonal fluctuations in river discharge together with requirements for irrigation, hydroelectric power generation and considerations for safe operation of the reservoir during flood season combine to establish the operating levels for filling and emptying the reservoir.

The operating levels at the dam follow a drawdown and fill cycle: water levels drop after September, reaching a minimum around the months of March, April, May, and rising again during the summer.

Operating levels have a great influence in determining the advance of the delta towards the dam. When the water levels at the dam are low, the sediments deposited in the upper reaches are reworked and transported downstream within the reservoir. This influence is represented in Figure 4 that shows the advance of the delta towards the dam as a function of the differences between minimum water operating levels and topset bed elevations. Two sets of data are presented in that figure: TAMS (1998) and Tarbela Dam Project (2009).

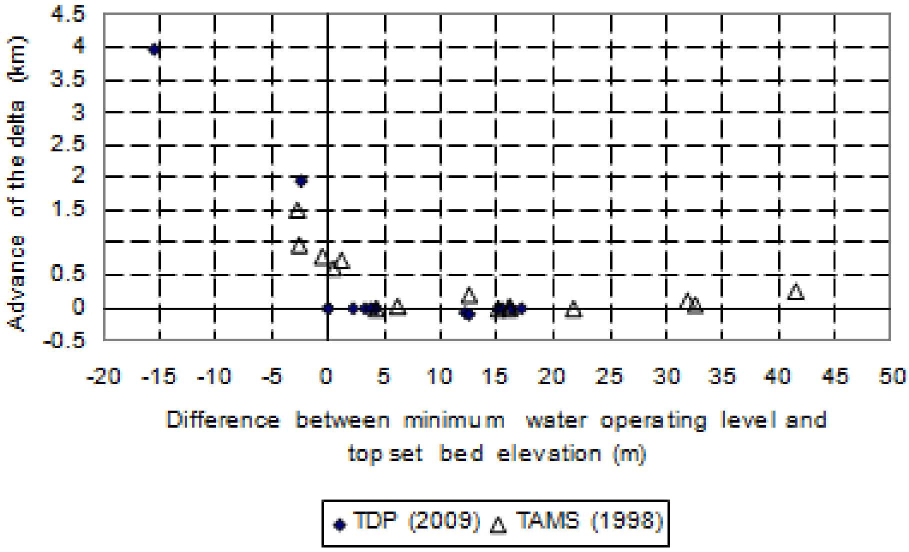

Figure 4: Advance of the delta towards the dam

2.4. Bathymetry of the reservoir

Cross-section lines across the reservoir are surveyed every year to compute the volume changes. Some of this information has been digitized and analyzed to provide a description of the evolution of bed levels in the reservoir (Figure 5). The longitudinal profile in the reservoir presents a clear delta that has been advancing every year. In 2009 the position of the delta point was located 10 km upstream of the dam.

Tarbela Dam Project (2009) records 917 m of advance of the delta in one year (2009). It has to be noted that some inaccuracies are possible in those estimates because of the difficulties in determining the exact position of the topset delta point. The density of points in the profile also influences the accuracy of the results. Due to these difficulties a point at half of the downstream sloping face of the delta, at elevation 396.2 m, is used to illustrate the rate of advance of the delta towards the dam (Figure 6). The advance of the delta slope towards the dam has always been increasing, although at different rates.

Bed levels at the dam are important to assess the risk of clogging the intakes. Figure 7 shows bed levels at the dam at different years. The accuracy of the data varies as some values are obtained from surveys (2008 and 2009), from plots included in other reports (1979-1994) or have been extrapolated from survey information at a range line located about 700 m upstream the dam (1998-2006).

Bed levels near the dam are higher every year showing an increasing tendency in the last 5 years (Figure 7).

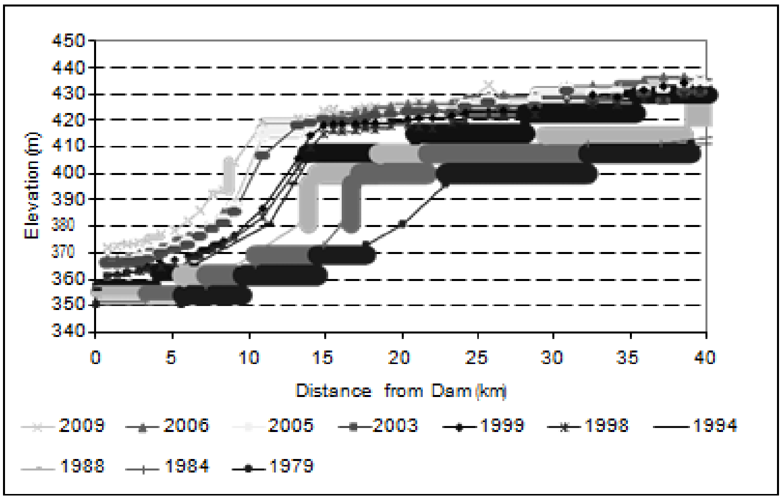

Figure 5: Longitudinal bed profile

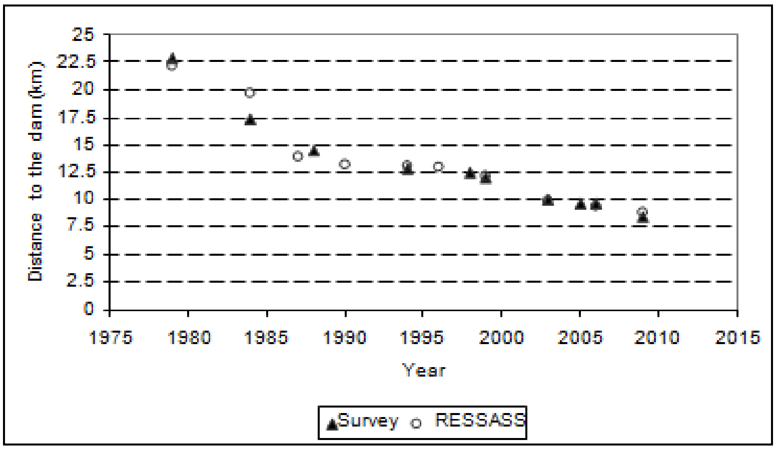

Figure 6: Advance of the delta towards the dam

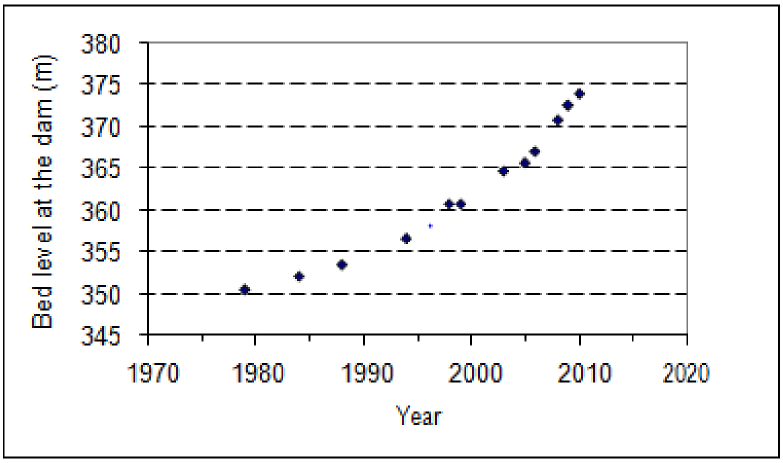

Figure 7: Bed levels at the dam

2.5. Influence of upstream reservoirs

A proposal exists to construct a dam at Basha, upstream of Besham Qila, with an approximate catchment area of 152,100 km^2. It is expected that the dam will be commissioned in 2020. Basha Dam is going to trap sediments of the upper catchments of the Indus, therefore reducing the incoming sediment to Tarbela.

Diamer Basha Consultants (2007) reports a trapping efficiency of Basha reservoir around 94% for the first years. This amount is expected to reduce to 80%. This efficiency is translated into a reduction of 69% of the incoming sediment to Tarbela.

Once Basha is commissioned a new large capacity storage will become available upstream of Tarbela and the flow sequences through Tarbela will change. The dams will operate in series and the scenarios for water levels variations through the year will undoubtedly change.

3. Numerical simulation of sedimentation processes

3.1. Description of RESSASS

The numerical model RESSASS is used to predict the future sedimentation patterns at the reservoir.

The RESSASS model is based upon physically based equations that describe flow and sediment movement in open channels based on steady state backwater computations, and sediment transport calculations for a range of sediment sizes. A time stepping model is used in which initial conditions are input to equations which predict water levels and bed levels a short time later. These predictions provide the input conditions for the next time step. The cycle is repeated many times to make predictions over the simulation time period that can extend over periods of several years with a time step of one day. The flow and sediment transport simulations are one-dimensional, that is only variations along the length of the reservoir are considered, and all the quantities calculated are averaged over a cross-section.

The model requires a time series of the discharges entering the reservoir as input. If the water level variations at the dam are not specified they are calculated using a storage routing method. Velocities and depths through the reservoir are calculated using a backwater computation. The effects of the shape of the reservoir in generating turbulence and mixing are accounted for by adding a term to the shear velocity calculated from a friction relationship derived from 3-D turbulence modeling.

Sediments are divided into different size ranges. The transporting capacities for the sand and larger sizes are calculated separately from finer sediments, silts and clays, in the cohesive size range. Corrections are applied to both sand and silt concentrations to allow for non equilibrium transport conditions.

The sediment masses deposited or eroded at each section are converted to volumes taking consolidation effects into account. The distribution of sediment deposits across the reservoir sections is varied according to user-defined functions. An important aspect of the model is that it calculates the composition of the sediments on the bed of the reservoir from the deposition that has taken place during the simulation. Thus the sediment sizes of the deposited sediment are predicted, rather than being specified initially, as is the case when most "river" models are applied to reservoirs.

3.2. Application of RESSASS to Tarbela dam

TAMS (1998) calibrates the numerical model RESSASS at Tarbela reservoir comparing measured and estimated loss of storage in the reservoir, observed changes in the longitudinal bed levels and in cross-section geometry for the period 1974-1997. Among the different parameters considered in the calibration, sediment sizes of sand and silt were fixed to provide the better estimation of the observed values. The model was validated with the new available information from the period 1997 to 2009 (HR Wallingford 2011). The numerical results of variables such as deposited material and transport rates, show that RESSASS describes the physical processes in the reservoir reasonably well. The comparison between numerical results and real data shows very good agreement as in the estimation of the rate of advance of the delta shown in Figure 6.

3.3. Results of the numerical model

Water inflows and reservoir operation (water level and outflow) both influence the sediment dynamics in the reservoir. As the future water inflows and levels at the dam are not known, several scenarios need to be simulated to establish the uncertainties of the predictions of the future behavior.

It has been observed that the future operation levels have a bigger impact than the water discharge time series. In this paper two possible scenarios are analyzed: in Scenario 1 the water level rises to maximum as the river inflow starts to rise. In Scenario 2 it remains low almost till the peak flow (Figure 8).

In Scenario 1, the delta arrives near the dam around 2040 which causes less sediment inflow to pass the dam section as well as into the intakes. However, the trapping efficiency is high which decreases the storage of the reservoir. Scenario 2 shows the opposite result. The numerical model predicts a quick advance of the sediment delta between 2010 and 2020 with bed levels at the dam rising rapidly. This indicates that sediment will pass through the intakes in increasing quantities but preserving the storage capacity. Under this scenario it is likely to be a maintenance commitment of increasing severity in the long term. TAMS (1998) already stated the need to adopt a suitable reservoir operation policy to avoid sediment ingress to the irrigation and power station intakes.

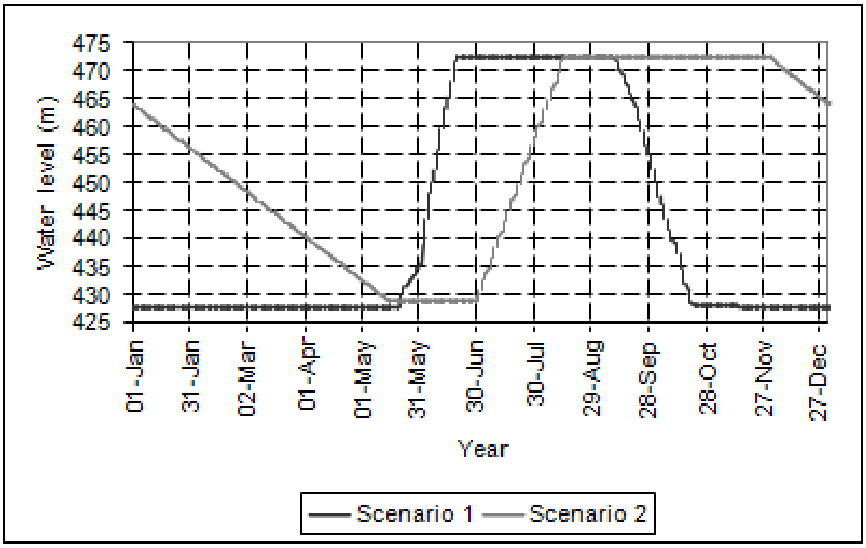

Figure 8: Comparison of future operation levels

Some parameters are not well simulated by the numerical model such as bed levels at the dam. In the period 2005-2009 bed levels calculated with RESSASS do not follow the increase showed in surveys (Figure 7). One possible explanation could be related to the fact that in 2005 a major earth-quake, of 7.6, affected the north area of Pakistan, including the Tarbela reservoir. It could have been possible that sediment inflow entering the reservoir had increased due to mobilization of material in upstream catchments, especially fine material. Some kind of movement or landslides of the sloping faces may also have happened. The RESSASS model is unable to predict the slumping of material that may happen during an earthquake. It has not been possible to review the sediment loads at Besham Qila in that period to study the possible impact of the earthquake.

When predicting the future storage capacities and bed levels along the reservoir there is the assumption that the power station and irrigation intakes can continue to function when the bed levels adjacent to the dam exceeds the level of the intakes by quite a large margin.

RESSASS also estimates the daily concentrations of sediment arriving at the dam. Combining these values with water discharges through the different intakes, the amount of sediment flowing into each intake and thus, through the turbines can be calculated. This is a useful result to estimate the life span of the turbines. Due to the number of assumptions about the different parameters such as the incoming flows, the results should be regarded as an indication of the likely order of magnitude rather than an absolute value.

Taking into account that the average annual inflow of sediment into the reservoir considered in the numerical model is about 195 MT, the total outflow downstream the dam is calculated as 60 MT per year before the arrival of the delta and about double (or slightly more) after the arrival of the delta, especially of sand material.

After 2020, when Basha Dam upstream Tarbela is expected to be commissioned, the amount of sediment inflow decreases and therefore lowest deposition rates, lowest amounts of silt arriving to the dam and larger storage volumes are observed. Very low or no proportion of sand material is expected to pass through the intakes after the commissioning of Basha Dam.

The numerical simulations taking into account the influence of Basha Dam must be regarded as only indicative because residual flows to Tarbela and level sequences within Tarbela are as yet undefined and both these affect sedimentation quantities and patterns.

4. Conclusions

The information provided by Besham Qila, a gauging station upstream the reservoir, about water discharges and sediment concentrations and the information obtained from the annual surveys is fundamental to understand the sedimentation processes in the Tarbela Reservoir. Field data is also extremely useful to validate numerical models. It should be noted that monitoring of sediment related processes is a demanding task, often associated with a certain degree of uncertainty due to high spatial and temporal variability. For example, different estimations of the same variable can be found based on different real observations.

The application of a numerical model to simulate sedimentation in the future needs to consider of a series of water discharges and operation levels representative of the future scenario. The results will depend on the assumptions made about the temporal series. Short term predictions will depend in part on how close the real sequences are to the one used as input in the numerical model. It is assumed that predictions for dates 10 years or more into the future are representative provided that there is no change in the long term average inflows of water and sediment and the reservoir is operated in the same manner as the model assumes.

However uncertainties in the predictions increase with time due to the numerous assumptions made during the study not materializing in the future.

The longitudinal profile in the reservoir presents a clear delta that has been advancing every year. RESSASS, a 1D reservoir model, has proved to describe well the behavior of the reservoir. The modeled results match with the estimations based on observations within the expected tolerances. Some limitations are observed when estimating bed levels near the dam.

The sediment deposition in the reservoir and the amounts of material flowing through the intakes are significantly influenced by the water level operation, which is given to the model as input data.

5. References

Diamer Basha Consultants. 2007. Review of feasibility report, engineering design, tender drawings/documents of Diamer Basha Dam Project. Reservoir Operation and Sediment Transport. Main report. Volume 1

HR Wallingford. 2011. Tarbela 4th extension. Sedimentation study. HR Wallingford report EX6486

Lowe, J. & Fox, I.H.R. 1982. Sedimentation in Tarbela reservoir. In Commission Internationale des Grandes Barrages. Quatorzieme Congres des Grands Barrages, Rio de Janeiro

TAMS and HR Wallingford. 1998. Tarbela Dam Sediment Management Study". Main report. Volume 2

Tarbela Dam Project. 2009. Annual Survey and Hydrology Tarbela Dam. WAPDA

White, R. 2001. Evacuation of sediments from reservoir. Thomas Teldford Publishing