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Advancement of the Pivot Point of Underwater Delta: A Study of Tarbela Reservoir, Haripur, Pakistan

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Abstract

Tarbela dam, with the main functions of hydropower (3,750 MW installed capacity) and irrigation, is being threatened by the menace of sedimentation. The underwater delta is advancing at a rapid pace towards the main embankment dam, being at 5.25 miles from Main Embankment Dam (MED) in 2012. This study is aimed at monitoring Tarbela reservoir's underwater delta pivot point advancement and its forecast mapping. Secondary data regarding pivot point elevation and its distance from the MED was obtained from the reservoir's library. Base map of delta direction was obtained from the surveying department at Tarbela dam. The data was processed in Arc GIS and Microsoft Excel to perform meaningful analysis. The study concludes that the average sediments deposited in the reservoir for the period of 1980-2012 were 0.1 MAF. Delta pivot point was at a distance of 5.45 miles from the MED in 2012 and according to our study, it will be only at a distance of 0.45 miles from MED in 2032. The In order to enhance the efficiency and life of Tarbela dam, this study suggests that immediate sediment management, either active or passive methods e.g. dredging, hydro suction and flushing must be adopted.

Keywords: Underwater delta, Pivot point, Main Embankment Dam, sedimentation, Tarbela dam, sediment management, dredging, hydro suction.

1. Introduction

River basin erosion naturally leads to the silting up of reservoirs (Vincenzo et al., 2017). Building a dam usually alters the balance of the sediment inflow and outflow. Rehman et al., (2018), state that annually on a global scale, reservoirs loose annual storage of about 1%, and this loss varies between 0.1 to 2.3%. Chinese rivers carry 80 to 90% of the annual sediment load accompanied by 50-60% of its annual runoff, during its flood season which leads to a loss of 66% of its reservoir capacity (Wang and Hu, 2009).

Sedimentation leads to loss of storage capacity which in turn causes a reduction in the efficiency of the dam to generate power, control the flood intensity, supply of water, navigation, environmental benefits and recreation (Vincenzo et al., 2017; Hosseinjanzadeh, Hosseini, Kaveh, and Mousavi, 2015; Wang and Hu, 2009). It can also lead to abrasion of the hydraulic machinery and blocking off the intake tunnels. Navigation and ecology of the region can get badly affected due to sediment accumulation in the delta region (Wang and Hu, 2009). Various sediment-related problems take birth upstream and downstream of dams, thus the detailed study about this phenomenon and the movement of its resultant underwater delta is extremely significant.

Tarbela the only main reservoir on Indus, the largest river of Pakistan, is the world's largest earth and rock filled dam. The dam has a height of 145m above the bed level (Khan and Tingsanchali, 2009). At the time of closure in 1974, it had a total capacity of 14.3 billion cubic meters and this capacity, due to high sedimentation rate, drastically reduced by 17.4% in 1992 (Lowe and Fox, 1995). It has five main tunnels, amongst them tunnel 1, 2 and 3 are equipped with power houses, with a generation capacity of 3470 MW. Rest of the two tunnels are kept reserved for irrigation flows and low-level flushing (Khan and Tingsanchali, 2009).

The mega reservoir Tarbela is being threatened by the menace of sedimentation since 90% of its inflow comes from snow and glacial melt. River Indus, in an average year, is capable of bringing along 200 million tons of sediments and deposit it in Tarbela reservoir (WAPDA, 1996). Since 1974, Tarbela reservoir has lost some 20% of its gross capacity and almost 40% of its original dead storage (Tate and Farquharson, 2000). The reservoir has an 89% trapping efficiency (Ali and Boer, 2007). Another dam of the world with such high trap efficiency is Burdekin Falls Dam, Australia. According to the calculations of Lewis et al., 2013, the measured trap efficiency of the reservoir Burdekin Falls Dam, Australia ranges between 50-85%.

A huge underwater delta has been created in Tarbela reservoir due to the heavy sedimentation, whose pivot point was 10 km from the dam toe in 2009 (Khan and Tingsanchali, 2009). Tarbela Dam Project 2009, recorded a 917m advance of delta per year that led to 80% of the live storage to become unavailable (Tate and Farquharson, 2000). Khwaja and Sanchez (2008) postulated that the delta will reach the main dam around 2030. H.R Wallingford's (2011) study also indicates that at the current rate of sedimentation the reservoir's dead and live storages will be largely filled up by 2030, while the intake tunnels will be blocked much before. Average inflow of sediment at Tarbela is 0.55 MST per day, while 0.11 MAF storage of the reservoir is lost per year. While at Mangla, the second largest reservoir of Pakistan, the average inflow of sediment is 0.164 MST per day with a storage loss of 0.034 MAF per year (Haq and Abbas, 2007). According to Rahman (2005), the gross capacity of the reservoir has been reduced from 11.620 MAF to 8.782 MAF in the year 2004 i.e. (24.42%) and the usable capacity from 9.679 to 7.973 MAF i.e. (17.63%).

The total inflow of sediments is estimated to be 208 million tons per year, which is composed of 59% of fine sand, 34% silt, and 7% clay. Lowe and Fox (1995), state that according to an estimated 99% of the sediment that comes into Tarbela reservoir gets trapped and settles mainly in the shape of a delta deposit, which continues its advancement towards the Main Embankment Dam. This delta "top-set beds have a slope of about s= 0.0006 to 0.0008". According to Mazhar et al., 2021, among the factors affecting the sedimentation of Tarbela reservoir, temperature and rainfall in the catchment area of Indus river and inflow coming into Tarbela reservoir, most significant one is inflow.

Agha, (2011) indicates that as the quantity of sediments increases, the front of the underwater delta advances towards the main embankment dam. The underwater delta is approaching the main dam at a fast rate and may cause the problem of clogging the intakes that feed the turbines. Furthermore, the downstream facing slope of the delta may cause landslides (Lowe and Fox, 1982). Larger landslides can be caused due to earthquakes (TAMS, 1998).

Ahmed and Sanchez (2011) postulated that the major threats to Tarbela Dam Project (TDP) due to rapid sedimentation were storage loss, clogging of power intakes, abrasion of equipment and concrete surfaces by sand and degradation downstream. The study of the bed level of the dams is essential for the assessment of the risk of clogging of the intakes. The bed levels of Tarbela continue to rise each year, showing an increasing tendency in the last 5 years, Roca (2012). The aim of the present study is to monitor the changes in the shifting of the pivot point of the underwater delta in Tarbela reservoir from 1981-2012 and forecast its advancement till 2032.

2. Materials and methods

2.1. Study site

Tarbela reservoir in district Haripur, Pakistan, is chosen as the study site of the present study. The region is one of the wettest parts of Pakistan, with maximum rainfall being received in early spring and in the summer season. This study area receives less intense rainfall events, but the highest number of rainfall days (Hussain and Lee, 2016). The region around the Tarbela reservoir experiences significant decadal precipitation variability of -17.45 to -13.63mm (Mazhar et al., 2016). The study area lies in the region experiencing a 0.4-degree centigrade rising trend of mean temperature, which might lead to increased snowmelt and the resultant rise in sediments being carried to the reservoir downstream. (Mazhar et al., 2015). The monitoring of the pivot point of the underwater delta has been performed through mapping of the underwater delta advancement which has been a neglected part of literature till present. Fig. 1 presents the study area map.

2.2. Delta pivot point advancement map

Delta pivot point advancement map was prepared using delta direction map obtained from Tarbela Dam library as a base map. The data of elevation of pivot points and their distance from Main Embankment Dam was obtained from official reports in Tarbela Dam Library and was entered in the attribute Tab. of Arc GIS, and yearly pivot points were plotted on the flow line, while their elevation was shown using proportional symbols in Arc GIS.

2.3. Forecast of delta pivot point advancement

The average advancement of the pivot point for the 32 years was calculated to be 8.16 miles. The per-year delta pivot point advancement was calculated by dividing the average advancement of 32 years by the total number of years, the result was 0.25 miles advancement per year. Later the per year advancement rate was multiplied by 5 to get five-year advancement Fig. i.e. 1.25 miles advancement per five years. Lastly, 5, 10, 15 and 20-year advancement was calculated by simply subtracting 1.25 from 2012 Fig., then subtracting 1.25 from the 2017's forecasted Fig. and so on. The calculations are shown in Table 1.

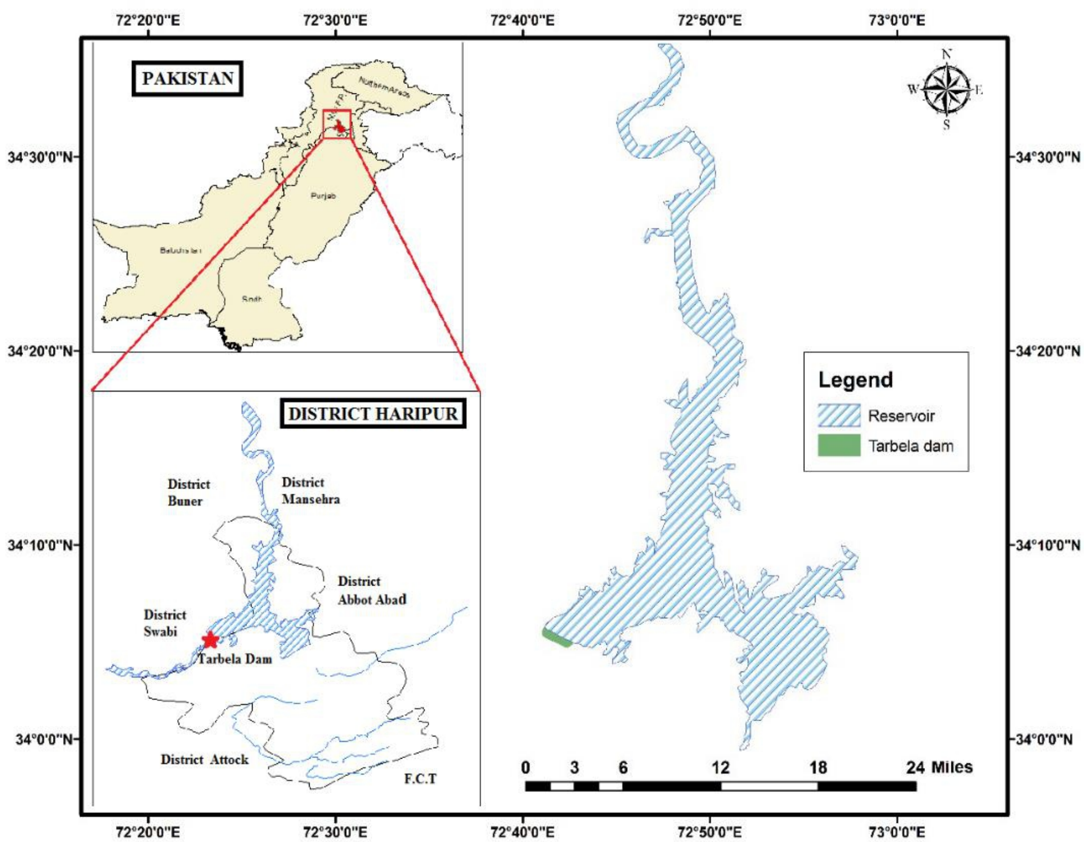

Fig. 1. Study area map, Tarbela reservoir, district Haripur, Pakistan

3. Results and discussion

3.1. Main reservoir sedimentation

The mean sedimentation coming in the reservoir from 1980 to 2012 was 0.100 MAF. From Fig. 2 it is obvious that 2012 was the year that experienced abnormally high sediment inflow. 1984, 1994, and 2010 presented a considerably higher amounts of sediments being deposited in the reservoir, i.e., 0.159, 0.199 and 0.197 MAF respectively.

3.2 Trap efficiency

Table 2 presents trap efficiency for the years 1980-1996, which can be supported with Fig. 3, where drastic fluctuation in 1997 and 1998 was due to very low inflow. The trapping efficiency went through slight fluctuations from 1999-2004.

3.3. Delta Pivot Point Advancement

The pivot point of the delta of Tarbela reservoir was at a distance of 11.11 miles away from MED in 1981 and was only 5.45 miles away from MED in 2012. Its elevation has also varied a lot over the years, being 1296 ft. high in 1981 and 1382 ft. in 2012.

The map shown in Fig. 5 shows the location of the delta pivot point of the Tarbela reservoir for the period 1981-2012. The volume of the proportional symbols in pink color shows the elevation of the pivot point in feet, the higher the elevation of a point the thicker the deposit is from the bed. The pivot point was at a distance of 11.11 miles from the MED in 1981, it advanced towards the MED and was only at a distance of 8.56 miles from the MED in 1996.

Fig. 4 presents a clear declining trend of the distance from the main embankment dam line. On the contrary, the obvious ascending trend of the delta pivot point is also identifiable. However, these both lines coincide with the years 2000-2003 when the distance from MED decreased sharply from 8.93 in 1999 to 6.59 in 2002. In the same years, delta pivot point elevation decreased from 1373 ft. in 1999 to 1330 ft. in 2002.

Table. 1 Calculations of Delta Pivot Point advancement forecast.

Number of Advancement Years	**Year**	**Calculations**	**Forecasted distance from M.E.D in miles**
5 years	2017	5.45-1.25	4.2
10 years	2022	4.2-1.25	2.95
15 years	2027	2.95-1.25	1.7
20 years	2032	1.7-1.25	0.45

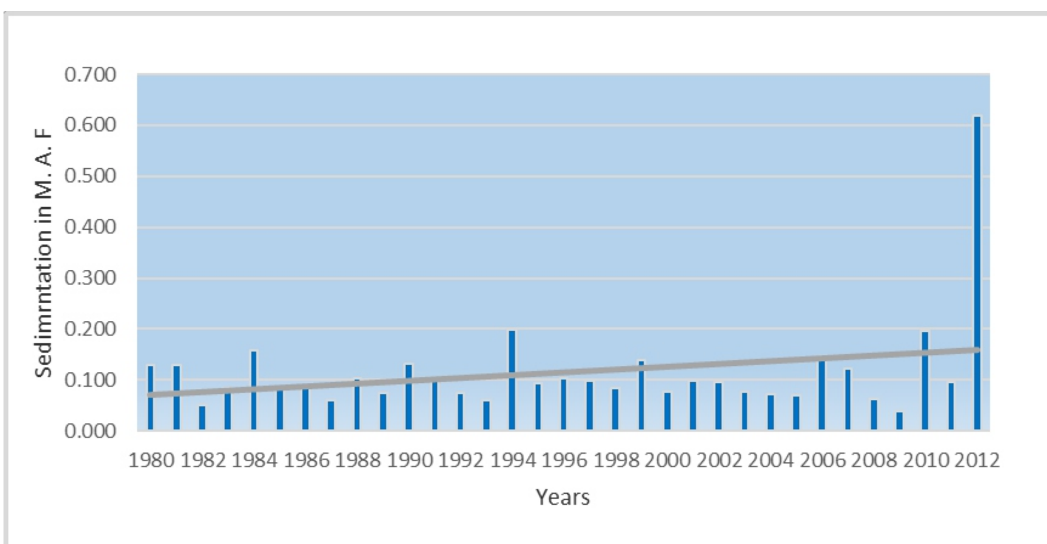

Fig. 2. Tarbela Main Reservoir Sedimentation in MAF, 1980-2012, Hydrographic Survey

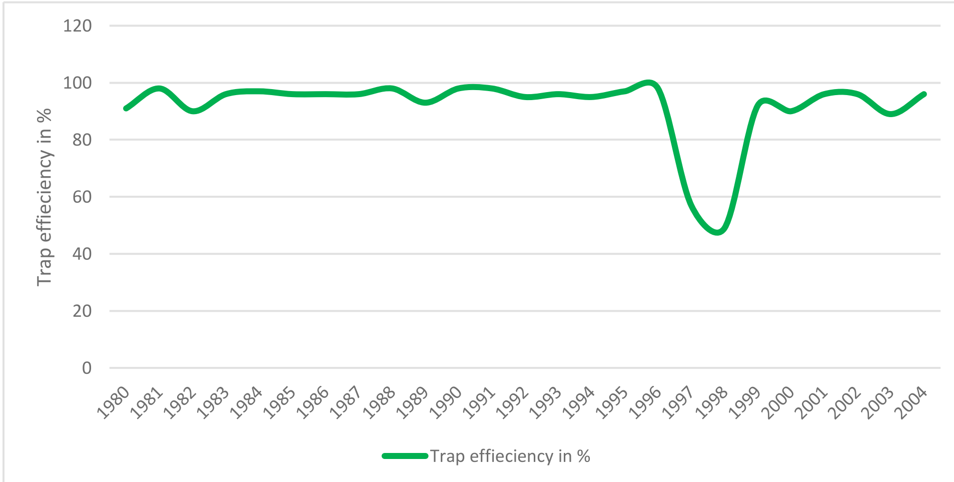

Fig. 3. Tarbela Reservoir Trap Efficiency, 1980-2004.

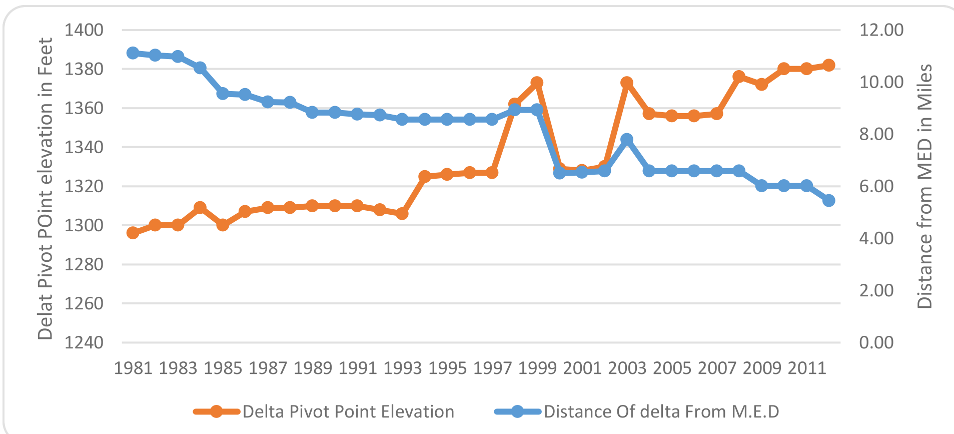

Fig. 4. Tarbela Reservoir Pivot Point Advancement, 1981-2012.

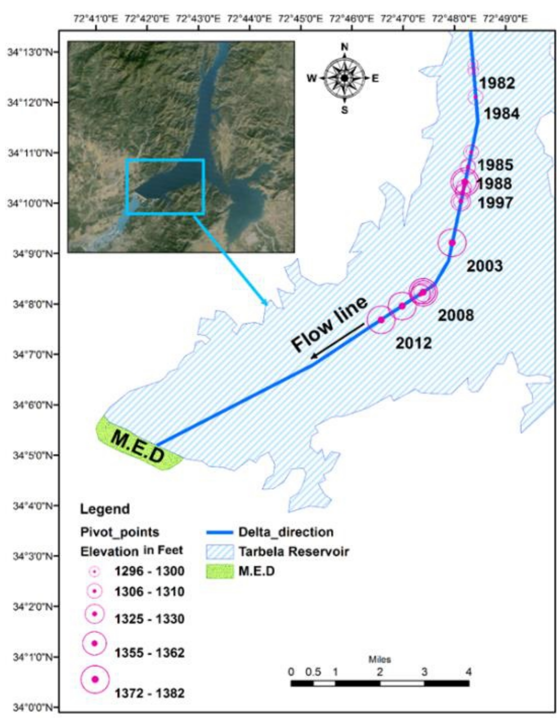

Fig. 5. Delta Pivot Point Advancement towards M.E.D, 1981-2012.

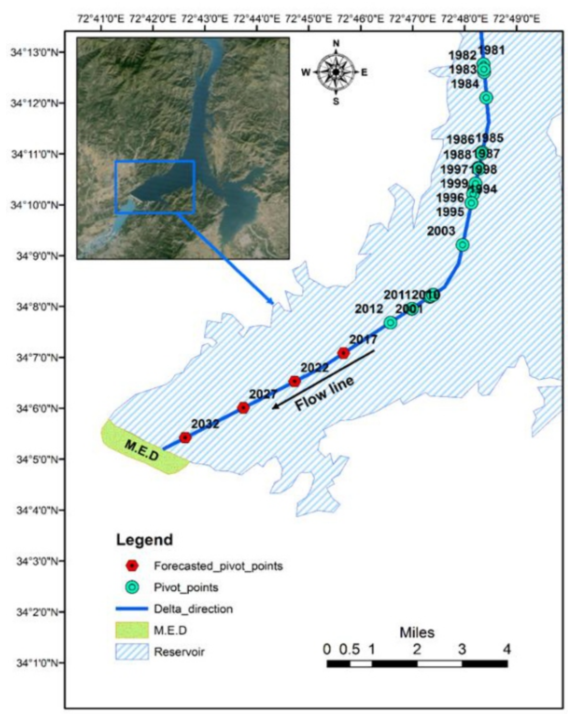

Fig. 6. Forecasted Delta Pivot Point Advancement till 2032.

However, the pivot point retreated in 1997 and was 8.93 miles away from MED. In the year 2000, the pivot point rapidly plunged forward to remain only 6.50 miles away from the MED. A major retreat was experienced by the pivot point again in the year 2003 when the pivot point was at a distance of 7.79 miles away from MED. Fig. 4 proves that the delta pivot point abnormally retreated because of very low inflow in the reservoir in 2003. Later, from 2004 to 2011 the pivot point steadily advanced towards MED and moved from 6.59 to 6.02 miles.

In 2012, however, the pivot point advanced further and was only 5.45 miles away from the MED. Elevation of the pivot point was only 1296 ft. in 1981 and rose to 1382 ft. in 2012. The elevation of pivot point dropped drastically from 2000 to 2003, the same years when the delta pivot point retreated away from the MED. The most appropriate explanation could be that the lower inflows lead to lower sediments coming into the reservoir and thus lesser elevation of delta pivot point. These were the same years when UIB received lower rainfall than normal. Fig. 4 explains the relationship between pivot point advancement and its elevation. Various efforts have been made by experts to forecast the rate of delta pivot point advancement. The findings of this study can be supported by the results of a recent study, where the greatest bed elevation of the Tarbela reservoir was indicated to be between range lines 7-12, which lies near the MED (Mazhar et al., 2021). The pivot point advancement map (Fig. 6) presents the drastic picture of the intake tunnels of the reservoir becoming unable to operate perhaps by 2032 when the pivot point would be only 0.45 miles away from the MED.

4. Conclusion

The average sediments deposited in the reservoir from 1980 to 2012 was 0.100 MAF. Drastic fluctuation in the trap efficiency of the reservoir in 1997 and 1998 was due to very low inflow. Delta pivot point was at a distance of 5.45 miles from the MED in 2012 and according to the forecast of this study, it will be only at a distance of 0.45 miles from MED in 2032, with an advancement rate of 1.25 miles/year. The results of this study are consistent with Wallingford's (2011) study that concluded that at the current rate of sedimentation the Tarbela reservoir's dead and live storage capacity will largely be filled up by 2030. This can lead to catastrophic impacts on the irrigation and energy sector of the country. The study provides the policymakers with a practical mapping method to continuously monitor the advancement of the underwater pivot point of delta in the reservoirs across the globe so that timely measures can be taken to avoid complete clogging of intake tunnels.

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Authors' Contribution

Nausheen Mazhar proposed the main concept, collected the data from the field, performed the mapping analysis and was involved in write up. Ali Iqtadar Mirza finalized the methodology and did the proof reading and supervision of the paper writing process. Zaynah Sohail Butt assisted in performing the mapping analysis and conducting review. Muhammad Nawaz did technical review before submission and helped raise the standard of paper before submitting to the journal. Muhammad Ameer Nawaz Khan provided assistance in the statistical analysis and helped in addressing the reviews.

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