SEDIMENT FLUSHING STRATEGY FOR RESERVOIR OF PROPOSED BHASHA DAM, PAKISTAN

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ABSTRACT

Reservoir sedimentation is a major problem world wide. Large reservoirs in Pakistan have lost 33% of their design capacities due to sedimentation. Diamer Bhasha Dam having storage capacity of 10 BCM is proposed in northern areas of Pakistan on Indus River having average annual sediment inflow of 196.91 million tons/year at dam site. Evaluation of sediment management measures is necessary before the start of such mega project. Various methods are in use to maintain storages of reservoir but sediment flushing has been opted in this study as compared because of economy and prevailing site conditions. The HEC-6KC model, an extended version of the original HEC-6 model, has been used for sediment simulation and flushing.The life of the reservoir without any sediment management measure is estimated 70 years, with annual capacity reduction of 1.16%. Different flushing scenarios have been evaluated and it is found that the life of reservoir could be extended to more that 140 years through sediment flushing. The sediment balancing ratio (SBR) nearly equal to 1 and long term capacity ratio (LTCR) of nearly 0.5 can be achieved through annual sediment flushing at drawdown level below 1010m amsl with the reservoir release above 5,300 m^3/s for 30 days.

Keywords: Sedimentation, Diamer Bhasha Dam, Sediment Flushing, Indus River Pakistan, Sediment Balancing Ratio, Long Term Capacity Ratio.

1. INTRODUCTION

Sedimentation is one of the major problems for the reservoirs and it is reducing the capacities of the reservoirs at rate of 1% annually worldwide (Mahmood, 1987). The reduction in the storage will effect hydropower production, irrigation, water supply, ecosystem, recreation and navigation. As only few sites are available in the world for construction of dams. Dam managers need to use the techniques and operations to reduce the sedimentation of reservoirs in order to increase their lives.

About 70% population of Pakistan is linked to agriculture, which engages about 45% of the labour force of the country. According to the economic survey, contribution of agriculture in GDP is 21% (Agriculture in Pakistan, 2014). Most of the agriculture land in Pakistan is fed by two Major reservoirs Tarbela and Mangla, both of which have lost about 1/3 of their capacities due to sedimentation.

DiamerBhasha dam is proposed on Indus river 315 Km upstream of Tarbela Dam in Northern Areas of Pakistan. The rate of sedimentation in rivers of Pakistan is very alarming so it is necessary to put some efforts toward the optimum reservoir operation and sediment management for long term management and sustainable use of reservoirs.HEC-6KC mathematical model has been used for simulation of sedimentation and flushing in the present study. The purpose of this research is to

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find the expected life of DiamerBhashareservoir without sediment flushing and with varioussediment flushing scenarios to find outthe most effective flushing scenario in term of discharge release with time and duration of releases.

Table 1. Loss in reservoir storages of Pakistan due to sedimentation (Javed, 2012)

Reservoir	Original Storage Capacity (BCM)	Storage Capacity Loss upto 2005 (BCM)	Storage Loss upto 2010(BCM)
Tarbela	14.33 (1976)	4.01 (28%)	4.87 (34%)
Mangla	7.25 (1967)	1.49 (21%)	1.97 (27%)
Chashma	1.07 (1971)	0.53 (49%)	0.59 (55%)
Total	22.65	6.03 (27%)	7.43 (33%) Equal toMangla Dam

2. METHODS

2.1 Case study: Diamer Bhasha Dam, Pakistan

DiamerBhasha Dam is located on Indus River 40 km downstream of Chilas, the district headquarters of Diamer in Northern Areas (NA) as shown in Figure 1. The Indus River at Bhasha has a total catchment of about 153,200 km² draining Karakorum, Himalayas and Hindukush.Diamer Bhasha Dam will be also amongst the largest water storages of Pakistan and would have a gross storage capacity of about 10 billion cubic meters (BCM). Other benefits, including electricity, flood control, fish production and esthetic values, can be attributed to the project. A roller compacted concrete (RCC) dam with crest elevation of 1,170.0 m asl is envisaged with a maximum height of about 272 m, the highest in the world so far.

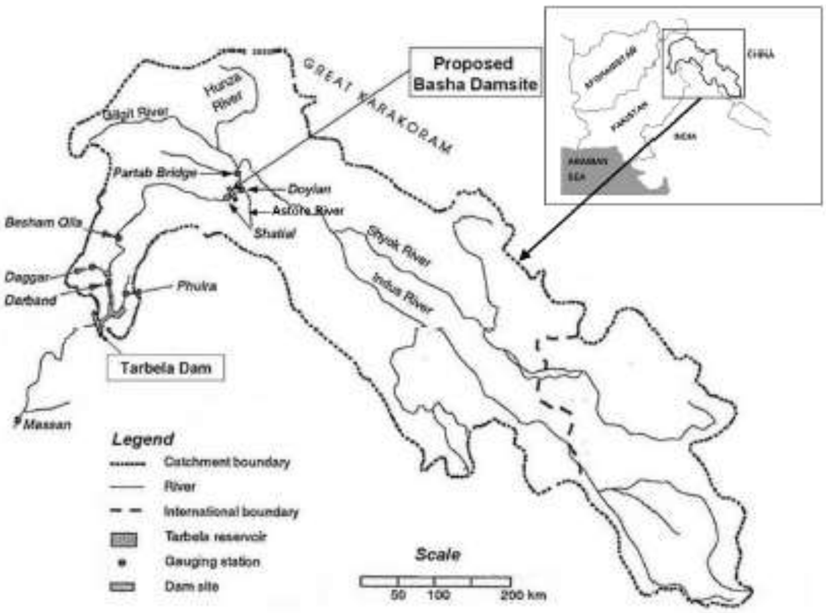

Figure 1. Location of Bhasha Dam (Ali &Sterk, 2010)

2.2 Use of flushing process than other methods for sediment evacuation

Various methods applied globally to conserve already existing storages of reservoir are soil conservation, bypassing incoming sediments, venting density current, lateral erosion, dredging by dredgers, sediment diverting, siphon dredging, joint reservoir operation and sediment flushing through reservoirs.

The terrain of the area is hilly with steep slope and hills are consisting of sedimentary rocks. The Tarbela Watershed Management Project began in 1971 with the commencement of construction of Tarbela Dam Project. This project has increased the life of Tarbela reservoir by 27 years (Khan, 2008). Despite of watershed management still a lot of sediments are coming in river Indus. Watershed management for Bhasha dam can reduce the sediment inflow upto 50% but it requires serious investment (Ali and Sterk, 2010). Dredging is another popular method of sediment removal but it is useful in shallow reservoirs or at habours. Infrastructure of roads and other transport system e.g. railway and roads are not well developed in the area to carry out such a huge dredging works. The site for disposal of evacuated material is also an issue. So, as far as the facilities available at the site, dredging will not be a viable option in case of Diamer Bhasha Dam. Siphoning dredging is also not possible in case of this reservoir because it is very deep. As there are very high mountains on both sides of the reservoirs, constructing a diversion channel for sediment diversion is also not possible. Therefore, keeping in view this preliminary analysis, flushing is the best option considering the site conditions as it also satisfies the criteria mentioned by Atinkson-(1996) for sediment flushing.

2.3 Use of 1-D HEC-6KC mathematical model for the study

The equations governing flows of fluids in reservoirs are as same as those governing in rivers and other water bodies. In those equations necessary approximations are often made, based upon the principal process at play in the reservoir. Two dimensional and one-dimensional models are commonly used for engineering applications. 1-D models are usually suitable for run-of-the-river reservoirs, wherever the flows are very much channelized and follow closely the thalweg, and transverse mixing is accomplished well. Whereas, when the pool of reservoir is wide and there is no single clear direction of flow, multi-dimensional models should be used. Two different reservoir types where this phenomenon might occur are shown in figure 2. Tarbela Reservoir in northern Pakistan is a long and narrow reservoir on Indus river, the region consist of mountains, where the behavior of flow is virtually like a one-dimensional river. San Luis Dam has a shallow reservoir and a wide lake that is typical of flat and low regions, where the circulation of flow is two-dimensional (Simoes& Yang, 2006).

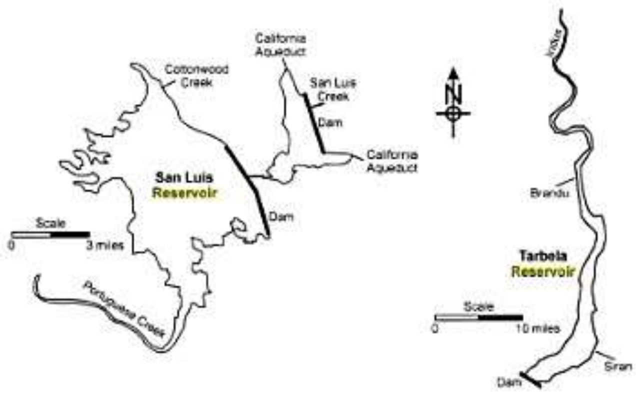

Figure 2. Pool contours for San Luis reservoir and Tarbela reservoir

Diamer Bhasha Dam reservoir is located 315 Km upstream of Tarbela Dam on the same river and it is more narrow in cross-section than Tarbela reservoir. Therefore, the flow is considered as one-dimensional, hence one-dimensional model has been used for sediment simulation.

There are many 1-D, 2-D and 3-D sediment simulation models like HEC-RAS, HEC-6, G-Star-3, RESSASS, ISIS Sediment transport, MIKE-11 and many more. HEC-6KC one dimensional mathematical model which has been used in this study due to long and narrow shape of reservoir as discussed above and the limitation of original HEC-6 like reworking of silt deposit in reservoir delta, complex geometry and reservoir configurations which cannot be adequately simulated.HEC-6KC has also been used very successfully in sediment studies of various dams in Pakistan by different consultants. Various sediment studies have been done using this model i.e. Mangla Dam Raising project, Dasu Dam, Bara Dam and many more.

2.4 Sediment transport and effectiveness of sediment flushing

Ackers and White equation developed in 1973 is used for estimating total load sediment transport of coarse materials whereas equation for transport of clay and silt (Krone, 1962) in the original HEC-6 model has been used in the present study.The density of the deposited sediments is required to convert the mass of deposited sediments into the volume change. Initial weight of clay, silt and sand in a reservoir depends upon manner by which reservoir is to be operated, texture and size of sediment particles entering the reservoir and compaction or consolidation rate of the deposited sediment. Initial weight of the deposited sediment is determined from method given by Lara and Pemberton1965(equation 1), and Miller equation (2) is used to predict the consolidation.

$$W_1 = W_C P_C + W_M P_M + W_S P_S \quad (1)$$

$$W_T = W_1 + 0.4343K\left\{\left(\frac{T}{T-1} lnT\right) - 1\right\} \quad (2)$$

Where W_1, W_C, W_M, and W_S are initial weight of the deposit, and initial weights of clay, silt and sand, respectively, and P_C, P_M and P_S are percentages of clay, silt and sand, respectively.W_T is the weight after T years of operation and K is compaction factor.

SBR (Sediment Balancing Ratio) and LTCR (Long term capacity ratio) has been preferred by Atkinson (1996) and White (2001) for estimation of flushing efficiency are used in present study as flushing efficiency indicators. SBR is ratio of sediment flushed to sediment deposited in between two successive flushing. SBR should be greater or equal to 1 for efficient flushing SBR can be calculated as:

$$SBR = \frac{Q_s n}{N Q_i TE} \quad (3)$$

Where Q_s = sediment flushed (ton/Sec), n is duration of flushing (Sec), N isfrequency of Flushing (Years), Q_i is annual sediment inflow (Tons),TE is trap efficiency of the reservoir.

LTCR can be calculated as;

$$LTCR = \frac{Sustainable\ Capacity}{Original\ Capacity} \quad (4)$$

If the value of LTCR is greater than 0.5, it means that the capacity criteria is partially satisfied and if this value approaches 1 then one can say that it is fully satisfying the capacity criteria but usually value of 0.35 is acceptable (Noor, 2012).

2.5 Hydrological, topographic and sediment data

Historical discharge and sediment data of Indus river from 1969 to 2003 has been used in present research. Average annual inflow volume at Dam site is computed as 61.62 Bm^3. In total 58 cross sections have been used to represent reservoir configuration. Sediment rating curve developed by Diamer Bhasha consultants is used to estimate annual inflow of sediments at dam site. From the curve, annual inflow of sediment at the dam site is estimated to be 196.91 million tons (MT) per year. Sediment inflow comprises of 14% clay, 40% silt and 46% sand.

2.6 Model calibration and verification

The HEC-6KC model is calibrated and verified firstly for water surface profile and secondly for sediment transport rates. Water surface levels at three stations near dam site were available for different flows. The model is calibrated with available stage-discharge at two stations (station 1 & station 2) for different discharges and then model generated water surface profiles for different discharges is verified with the water surface elevation at station 3. After calibration of water surface profile, HEC-6KC model is calibrated with sediment data of 25 years i.e. 1969-1993 and then verified with 10 years sediment data i.e. 1994-2003. The calibration and verification results are shown in figure 3. (Javed, 2016)

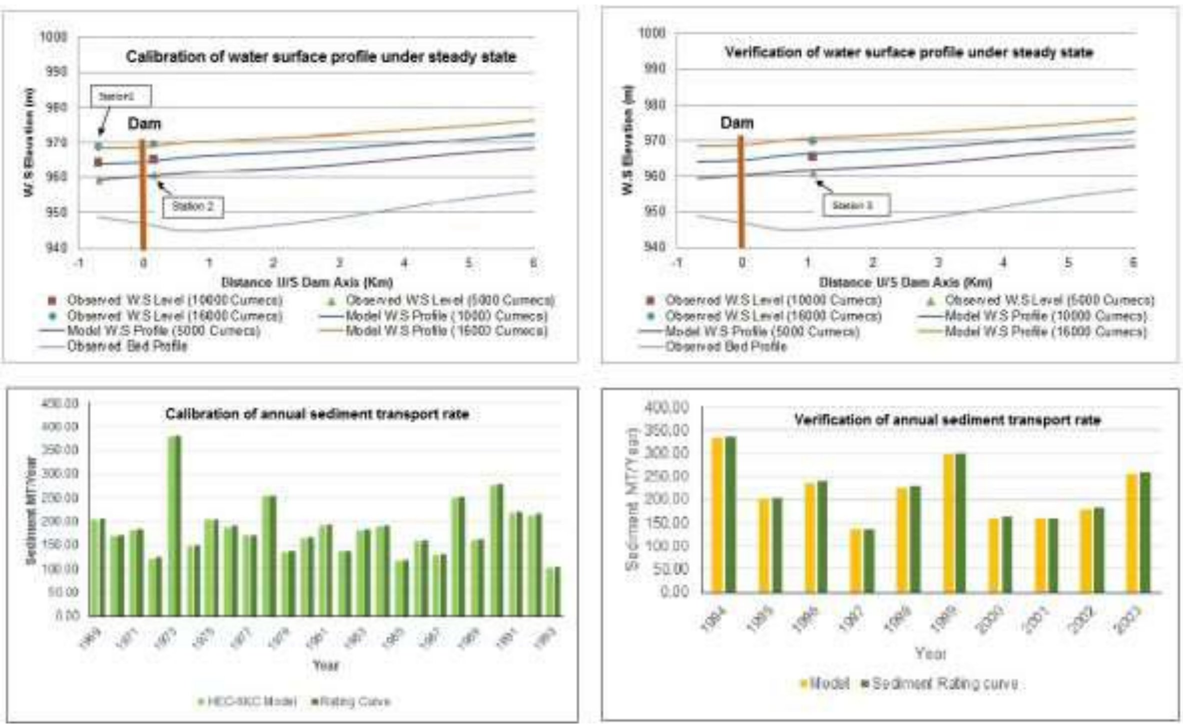

Figure 3. Water Surface Profile And Sediment Transport Rate Calibration and Verification.

3. RESULTS

3.1 Loss in reservoir capacity without sediment management

Useful life of the reservoir starts from its construction till the time it fills with the sediment ureand it became unable to serve the intended purpose (UNESCO, 1985). Generally, the useful life of reservoir can be taken till its capacity is reduced to about 20% of its designed capacity (WAPDA, 2004 & NWDA India, 2016). The computation of the model shows that dam will loss 80% of its designed capacity nearly in about 70 years of operation which means its useful storage will finish after 70 years of operation if any necessary sediment management measures are not adopted. The original capacity at the beginning of reservoir operation is computed as 9.99 BCM that will deplete to 1.92 BCM after 70 years of operation due to sedimentation. This means that the annual reduction in the reservoir capacity of Bhasha Dam due to sedimentation is 1.16%. This value of annual reservoir sedimentation rate is slightly higher than the figure of 1% given by Mahmood (1987) for Tarbela Dam and the reservoirs all over the World and slightly lower than 1.23% as predicted by Ali andSterk (2010) for Bhasha Dam using RESSASS Model. Confidence limit analysis has also been carried out for 95% confidence to check the accuracy of life of the dam computed by HEC-6KC. Confidence interval for sediment data of 35 year (1969-2003) has been determined with a mean value of sediment inflow of 196.91 MT/year and lower limit and upper limit of sediment inflow is 176.41 MT/year and 217.42 MT/year, respectively. The life of reservoir for 95% of confidence for lower limit of sediment inflow come out to be 84 year whereas for high limit of sediment inflow is roughly estimated to be 63 years. From the literature and confidence limit analysis one can say that HEC-6KC performance in sediment simulation is quite satisfactory.

Figure 4 shows that how the capacity of Diamer Bhasha Dam will diminish over the passage of time. It can be seen that there is a consistent decrease in the capacity of the reservoir till 80 years of operation after that the reservoir will attain equilibrium that is the incoming sediment become equal to outgoing sediment, there has been no further loss in storage over the time.

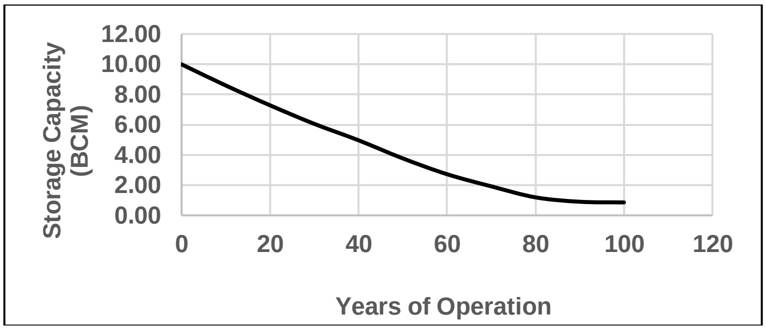

Figure 4. Predicted capacity depletion curve for Bhasha Dam Reservoir without sediment management

3.2 Effective scheme of sediment flushing in term of discharge releases with time and duration of releases:

In present study different scenarios for sediment flushing in term of discharge, time, duration and frequency/interval have been developed to find out the most effective flushing scheme for the proposed Bhasha Dam so that maximum long term benefits can be achieved. It is proposed to carry out flushing after atleast 30 years of reservoirs operation due to following reasons:

- If sediment flushing is carried out early the sediment delta form in the tail portion of the reservoir will move faster to the dam site which may chokeup low level outlets and flushing facilities.
- Negative impact of sediment flushing on the storage capacity of Tarbela dam reservoir which is located at 315 Km downstream Bhasha Dam.

Two major indicators, sediment balancing ratio and long term capacity ratio as mentioned by Atinkson (1996) for evaluating the effectiveness of sediment flushing have been used in the present study. Different scenarios considered to evaluate the effectiveness of sediment flushing are as following:

Scenario 1: Flushing after 30 years of commencement of reservoir operation with flushing after every 10th year for 31 days (11 May-10 June) by using currently designed low level outlet and flushing outlets in conjunction for flushing purpose with discharge, 1,453 m^3/sec at level of 1000m from 11 May-20 May, 2,066 m^3/sec at the level of 1001 m from 21 May to 31 May and 3,071 m^3/sec at level of 1010m from 1 June to 10 June. Level of flushing is kept below 1010m amsl, according to the recommendation by Atinkson (1996), if the reservoir depth is less than 1/3 of full depth of reservoir the flushing may then only be classified as full drawdown flushing.

Scenario 2: Flushing after 35 years of commencement of reservoir operation with flushing after every 5th year for 31 days (11 May-10 June) by using currently designed low level outlet and flushing outlets in conjunction for flushing purpose with discharge, 1,453 m^3/sec at level of 1003 m from 11 May-20 May, 2,066 m^3/sec at the level of 1005 m from 21 May to 31 May and 3,071 m^3/sec at level of 1010 m from 1 June to 10 June.

Scenario 3: Flushing after 35 years of commencement of reservoir operation with flushing after every year for 31 days (11 May-10 June) by using currently designed low level outlet and flushing outlets in conjunction for flushing purpose with discharge, 1,453 m^3/sec at level of 1003 m from 11 May-20 May, 2,066 m^3/sec at the level of 1005 m from 21 May to 31 May and 3,071 m^3/sec at level of 1010 m from 1 June to 10 June.

Scenario 4: Flushing after 35 years of commencement of reservoir operation with flushing sediments every year for 30 days (21 June-20 July) has been proposed in the present study and the proposed discharge values of 5,130 m^3/sec at level of 1005m from 21 June to 30 June, 5,851 m^3/sec at level of 1008m from 1 July to 10 July, 6,300 m^3/sec at level of 1010m from 11 July to 20 July.

Reservoir operation rule curves for different scenarios is shown in figure 5. Rule curve for design flushing outlets has been used for first three scenarios and proposed flushing curve has been adopted for scenario 4.

Simulation of sediment flushing has been carried out till the year 2100 using HEC-6KCmodel for all four scenarios mentioned aboveassuming commencement of reservoir operations on 31December, 2020. Sediment inflow and outflow during the periods in which sediment flushing has been executed for each scenario is given in table 2.

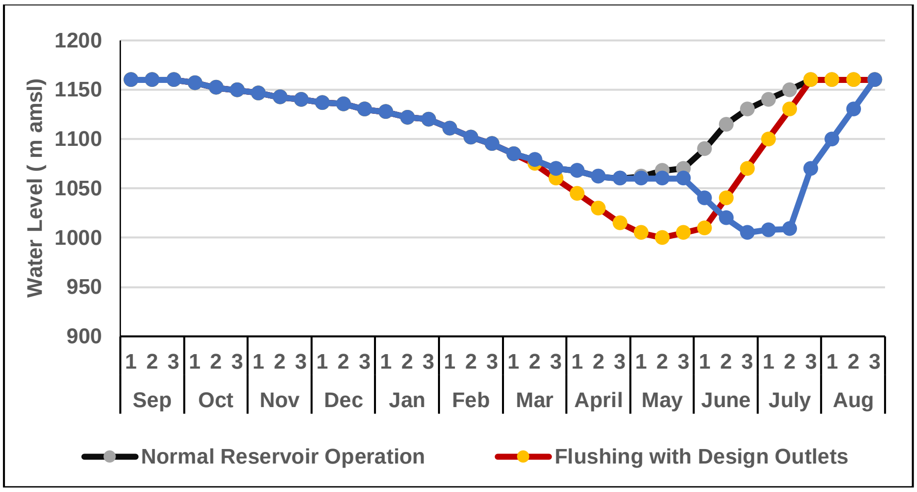

Figure 5. Reservoir operational rule curve for different operational scenarios

Table 2. Sediment flows under different flushing scenarios (Million Tons)

Period	Sediment Inflow	Flushed Sediment Outflow			
		Scenario 1	Scenario 2	Scenario 3	Scenario 4
2051-60*	1773.3	697.8	-	-	-
2056-60	895.9	-	603.7	1021.7	1238.1
2061-70	2012.7	1063.0	1178.9	1254.5	1728.4
2071-80	1964.9	1069.6	1134.7	1272.0	1741.6
2081-90	1752.5	1087.0	1300.4	1237.4	1689.7
2091-2100	1908.0	993.4	1274.6	1374.9	1787.2

* For first scenario of flushing

An average of 50 years of flushing operation is used to determine the value of flushing indicators. These computed values are based on simulation of multiple flushings.

Table 3. Computation of flushing effectiveness indicators

Scenario	Flushing Discharge (Cumecs)	Flushing Level (m amsl)	Flushing Period	Flushing Interval (Year)	SBR	LTCR
1	1,453-3,071	1,000 to 1,010	11 May-10 June	10	0.52	0.44
2	1,453-3,071	1,000 to 1,010	11 May-10 June	5	0.62	0.41
3	1,453- 3,071	1,000 to 1,010	11 May-10 June	1	0.75	0.45
4	5,130 -6,300	1,005 to 1,010	21 June-20 July	1	0.96	0.48

Sediment balancing ratio (SBR) for the first three scenarios is well below 1. Atinkson (1996) recommended flushing in high flows when sediment balancing ratio is small. Therefore, it is proposed in present study to increase the capacity of existing outlet so that high discharges can be passed during the flushing. When the discharge for the flushing is increased above 5,000 m^3/sec and sediment flushing is carried out for 30 days anually, sediment balancing ratio nearly approaches 1 which satisfy the flushing criteria. This value of discharge can be attained from 21 June to 20 July from historical data analysis. Since flood season ends in September every year there has been enough flows after 20th July to refill the dam. LTCR value for all 4 scenarios satisfies the criteria for successful flushing as all the values are greater than 0.35. So, based upon the above analysis, scenario 4 satisfies the criteria for effective flushing.After analysis and simulation of sedimentation and flushing for 80 years of reservoir operation, the longitudinal profile of the reservoir is shown in figure 6.

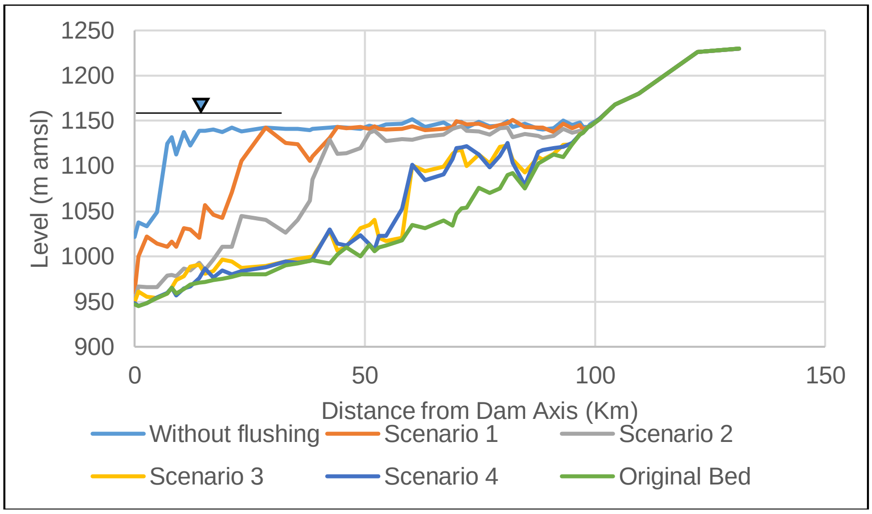

Figure 6. Longitudinal profile of river bed for different scenarios of flushing

3.3 Impact of sediment flushing on storage capacity of reservoir

Reservoir life will increase from 70 years to more than 100 year for scenario 1 and 2 and it will increase to more than 120 year for scenario 3. Whereas reservoir life will become double to the life without flushing in case of scenario 4 (i.e. 140 Years). Loss in reservoir capacity for different scenarios is presented in figure 7.

Results show that there has been a minor decrease in the capacity of Diamer Bhasha reservoir over the period of 45 years (2056-2100) of operation if the reservoir is operated under scenario 4. Therefore, the reservoir can be used for long term without any significant loss in the storage capacity. From the fact and figures narrated above, scenario 4 is the best option for sediment management through flushing for Diamer Bhasha Dam reservoir and it will make the reservoir sustainable for long term.

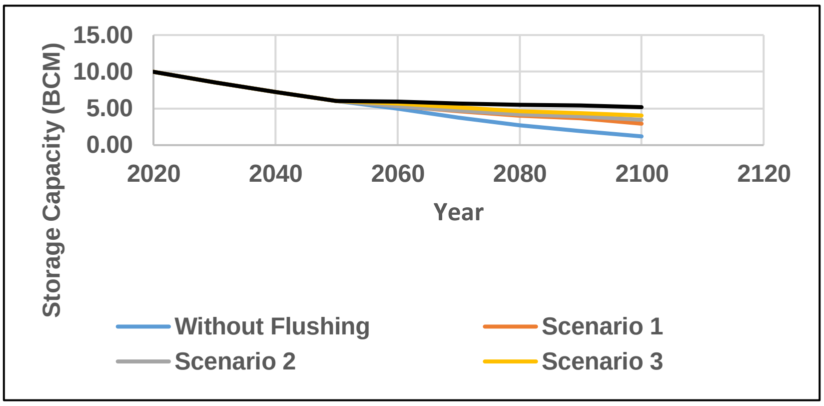

Figure 7. Storage capacity of Bhasha Dam reservoir under different scenarios

4. CONCLUSION

Simulation of sedimentation using HEC-6KC model has been carried out in the present research. Without any sediment management measure the dam will lose its useful storage capacity in 70 years of operation with 1.16% loss in storage capacity annually. It is proposed to carry out flushing not earlier than 30 year of reservoir operation in order to restrict sediment delta towards the dam and also to prevent Tarbela reservoir from heavy sedimentation during its useful life.

It is found that sediment balancing ratio (SBR) of nearly equal to 1 and long term capacity ratio (LTCR) of 48% can be achieved if drawdown flushing is carried out by maintaining reservoir level between 1005 m to 1010 m amsl and the discharge is maintained between 5,130 to 6,300 m^3/sec for 30 days annually (21 June-20 July). This proposed scheme will increase the life of reservoir to more than 140 Years.The capacity of the existing flushing outlets of Bhasha dam needs to be enhanced in oder to carry the proposed discharge.

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