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EVALUATION OF SEDIMENT MANAGEMENT STRATEGIES ON RESERVOIR STORAGE DEPLETION RATE: A CASE STUDY

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Sedimentation aspects have a major role during the design of new reservoir projects because life of the reservoir mainly depends upon sediment handling during reservoir operation. Therefore, proper sediment management strategies should be adopted to enhance the life span of reservoirs. Basha Reservoir is one of the mega water resources projects which are being planned to construct on the Indus river. Under this study, the efficiency of four sediment management strategies were evaluated by using the RESSASS model. The reservoir management strategies considered for sediment simulation of Basha reservoir include the normal operation, raising of MoL, draw-down the MoL (flushing) and controlling the sediment inflows. Under normal operation, the model predicted the life span of Basha reservoir around 55 - 60 years. But by raising of Mol 2.0 m/year implemented after 35 years of operation may add 10 - 15 years more to the life-span of the reservoir. However, by adopting the flushing operation to draw-down the MoL at El. 1010 m initiated after 35 years of operation, it may also add about 15 - 20 years more. Moreover, the results obtained by considering 50% reduction in sediment inflow due to implementation of river basin management projects upstream of Basha within 30 years of reservoir operation, depicts that the life of the reservoir will be more than 100 years. It is therefore concluded that proper sediment mitigation measure can significantly enhance the life-span of planned reservoirs.

Key Words : *flushing, minimum operation level (MoL), full reservoir level (FRL), Indus river, reservoir sedimentation, draw-down, rule curve, reservoir operation strategy*

1. INTRODUCTION

Irrigated agriculture is the backbone of Pakistan's economy (World Bank[32)]). The agricultural sector in Pakistan is mainly relying on water supplies from reservoirs. But irrigated agriculture is seriously confronted with major problems of water scarcity, unequal distribution of irrigation water, low productivity and increasing soil salinity (Tahir and Habib[23)]). The country is already facing a serious shortage of food due to fastly growing population and lack of sizeable water storage (Pakistan Water Partnership[18)]). With the present rate of population growth and reduction of water availability due to siltation of existing reservoirs, Pakistan is likely to reach the stage of "water short country" by the year 2012 when the per capita surface water availability will be reduced to 1000 cubic meter per year (Farooqi[8)]). Rising pressure to produce more food with less water demands not only for the efficient and integrated use of available water resources but also demands the construction of new water reservoirs.

The two existing reservoirs in Pakistan, Tarbela and Mangla are rapidly losing their storage capacities due to sedimentation. The gross storage capacities of Tarbela and Mangla reservoirs at the time of first impoundment were 13.938 and 7.253 BCM respectively. These reservoirs collectively lost about 25% of their storage capacity by the end of the year 2003 (Ali et al.[3)]). The hydrographic survey of 2000 showed that the Mangla dam had lost about 20% of its gross storage capacity (Ali et al.[3)]). According to the hydrographic survey of 2005, Tarbela dam had lost about 30% of its gross storage capacity (DBC[7)]). It is generally known that the annual loss of storage in reservoirs is roughly 1% corresponding to about 50 km^3 worldwide (Mahmood[13)]). But some reservoirs may have much higher storage loss, e.g., the Sanmenxia Reservoir in China looses about 1.7% annually (Sloff[21)]).

In order to meet the growing requirement of water in the country, the Government of Pakistan (GoP) through the Water & Power Development Authority (WAPDA) plans to construct some mega water resources projects in additions to small and medium storage projects on the Indus river. Basha reservoir is one of the mega water resources projects which are planned on the Indus river. The proposed Basha reservoir will be located 315 km upstream of Tarbela reservoir. But without any mitigation measures, the viability of existing and planned reservoirs will become questionable under the current high storage depletion rates. Therefore it is essential that proper attention should be paid to sedimentation aspects in the management of the existing reservoirs as well as in the design of new reservoirs. If proper sediment mitigation measures are adopted, life of the reservoir could be extended for a much longer time.

The reservoir depletion rate can be minimized in two different ways i.e. by controlling the sediment inflow rate to the reservoir or by adopting different reservoir operation strategies. The sediment inflow rate can be controlled by adopting sediment management practices in the upstream catchment area (Huang and Zhang[9)]). Nevertheless, two reservoir operation strategies are being commonly used globally for sediment management in reservoirs to conserve the storage capacity and keep the power-intakes free from sediment i.e., draw-down the minimum operation level (flushing) and raising of the minimum operation level. Flushing is one of the most economic methods that partly recovers the depleted storage without dredging or other mechanical means of removing sediment. The success of flushing may depend upon the catchment and reservoir characteristics (White[31)]). Qian[20)] also argued that the flushing solution is only suitable in reservoirs where annually an excess amount of water is available. For the Tarbela reservoir, the raising of Minimum operation Level (MoL) sediment management strategy has been adopted to reduce the speed of delta movement towards the dam body (TAMS[24)]).

Several one-dimensional numerical models are being globally used for reservoir sediment simulation e.g., RESSASS (Wallingford[29)]), HEC-6 (HEC[27)]), GSTAR (Yang et al.[33)]), Fluvial (Chang[5)]). These models have been used as a tool to predict the storage capacity losses and reservoir bed levels after a certain specified simulation period due to sedimentation. RESSASS is a one-dimensional model which was developed by HR-Wallingford, UK, in 1995 to simulate a long-term average pattern of scour and deposition in reservoirs. The model input includes geometrical, hydrological and morphological data. The model output describes the flow velocities, water surface profile, trapping efficiency, storage depletion rate and reservoir bed levels. In this study, the RESSASS model was used for simulation of the sediment dynamics in the proposed Basha Reservoir. The main aim of this study was to investigate the effects of different reservoir operation strategies on the expected life-time of the planned Basha reservoir.

2. THE STUDY AREA

The planned Basha damsite is located about 315 km upstream of Tarbela Dam on the Indus river and 165 km downstream of the Northern Area capital Gilgit and 40 km downstream of Chilas town. The proposed dam is designed for a maximum height of 260 m (NEAC[17)]). The total drainage area of the Indus river above the damsite is 153,200 km^2, which extends from Pakistan into Tibet and Kashmir. The major tributaries that join the Indus river above the proposed damsite include the Hunza river, the Gilgit river, the Astore river and the Shyok river (**Fig. 1**). The sub-basins formed by these tributaries have distinct morphologic, climatic and hydrologic characteristics. Poor vegetal cover, steep slopes, and the fact that the soils and rocks of the Indus valley are geologically young and easily erodible are some relevant features of the drainage basin responsible for high sediment concentration in the water of the Indus river at the proposed damsite (Sloff[21)]).

The Basha reservoir with full reservoir level (FRL) at El. 1160 m will have a gross storage volume of 10.008 BCM and a dead storage level (MoL) at El. 1060 m with dead storage volume of 2.10 BCM. Two power-houses are planned at El. 1040 m, one on each side of the main dam with total installed power generation capacity of 4500 MW and low-level outlets are planned at El. 975 m (NEAC[17)]). The mean annual unregulated flow of the Indus river at the damsite is 61.12 BCM that carries about 199.40 million

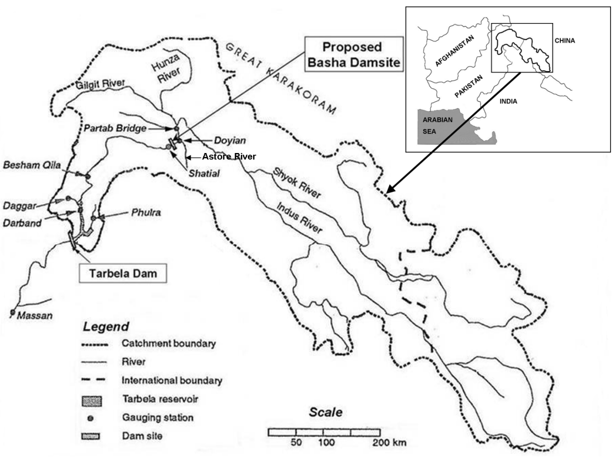

Fig. 1 Map showing the proposed Basha damsite with key gauging stations and main tributaries.

tons of sand, silt and clay sized particles (NEAC[17]). The stream flow data important for this study are from different agencies of WAPDA, mainly by the Surface Water Hydrology Project (SWHP) and the Water Resources Management Directorate (WRMD). Because no flow measuring and sediment sampling station exists at the planned dam-site, the stream flow and sediment data of Partab bridge, Shatial and Besham Qila hydrometric stations have been used. The Partab bridge gauging station is located on the periphery of the Basha reservoir, whereas the Shatial and Besham Qila gauging stations are located downstream of Basha reservoir. The proposed dam project covers an area of 110 km^2 and extends 100 km upstream of the damsite up to Raikot Bridge on Karakoram Highway (KKH).

3. MODEL DESCRIPTION

RESSASS (Reservoir Survey Analysis and Sedimentation Simulation) is a one-dimensional steady state windows-based program which was developed by HR Wallingford, UK in 1995 (Wallingford[29]). The model is basically a combination of three sub-models i.e. Volume Analysis, Volume Prediction and Numerical Model. Under the current study, the volume analysis and numerical components of RESSASS model were applied to assess the storage volume and predict the storage depletion rate in the Basha reservoir. Due to the non-availability of hydrographic survey data (after first impoundment), the volume prediction component was not applied. Volume Analysis was applied for the computation of initial reservoir volume. This component uses the "Stage - Width Modification Method" (Lea[11]) to develop the stage - volume curves for the reservoir. The Numerical Model simulates the time varying sediment buildup, delta formation, trapping efficiency and remaining storage capacity in the reservoir.

The RESSASS model simulates water flow and sediment movement for each time step and section along the river. The model calculations are based on two sequential steps: backwater and sediment transport computations. In the first phase of computations, the standard step method is used for backwater computations to compute flow depth and velocity at each cross-section along the selected river reach. The model performs the hydraulic calculations which includes the determination of water surface profiles (flow velocities and water depths) along the study reach. The water surface profile calculations are initiated from the downstream boundary (where the water levels are known) and proceeds upstream.

During the second phase of computations, the computed flow velocities and depths from backwater computation, are used in determining the potential sediment transport rates from a sediment transport formula. If sediment transport capacity at any cross-section exceeds sediment inflow rate, scour would occur. While on the other hand, if it declines, then there would be deposition to bring the flow system into equilibrium. The sediment transport computations are initiated at the upstream boundary and proceed downstream. Two empirical sediment transport equations are available in the RESSASS model for the computations. The transporting capacities of coarse sediments (> 0.063 mm) are calculated by using the revised version of Ackers & White[1] sediment transport equation (Wallingford[28]). Whereas, the Westrich & Jurashek's[30] method is used to calculate the transport capacities of fine sediment (< 0.063 mm).

The density of settled sediment is needed to convert the mass of sediment deposited or eroded to a volume change. There are two aspects that are considered when deriving the representative sediment density. The density of newly deposited sediment which depends on the relative proportions of sand, silt & clay and consolidation of settled material which results in an increase in density with time. A method based on the Lara and Pemberton[10] equation (1) is used to estimate the initial densities and the Miller[15] equation (2) is used for the prediction of consolidation.

$$W_0 = W_c \cdot P_c + W_s \cdot P_s + W_{sa} \cdot P_{sa} \tag{1}$$

$$W_t = W_0 + 0.4343(k)\left[\frac{t}{t-1}(\ln t) - 1\right] \tag{2}$$

Where W_0 is the initial density, P_c, P_s and P_{sa} are the ratios of clay, silt and sand, W_c, W_s and W_{sa} are the initial densities for clay, silt and sand, W_t is the average dry bulk density after t years of consolidation and k is the compaction factor.

The model provides output in various degrees of detail which is controlled by the user. The level of detail ranges from limited output to the output that contains information of all major calculations. The model is usually used to make predictions over periods of years with a time-step of one day by default. Typical output combinations from an annual simulation would be trapping efficiencies, bed level changes, stage - storage capacity curves, water surface profiles and flow velocities.

4. RESSASS MODEL APPLICATION

(1) Data categories

The required data have been collected from different agencies of WAPDA and project reports (NEAC[17], DBC[6]). Data required for the model were divided into four main categories; topographical, hydrological, morphological and reservoir operation, and details about each category are discussed

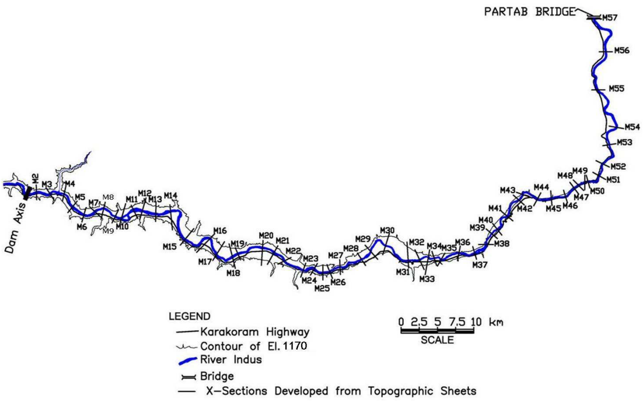

Fig. 2 Schematic layout of the proposed Basha reservoir with location of cross-sections.

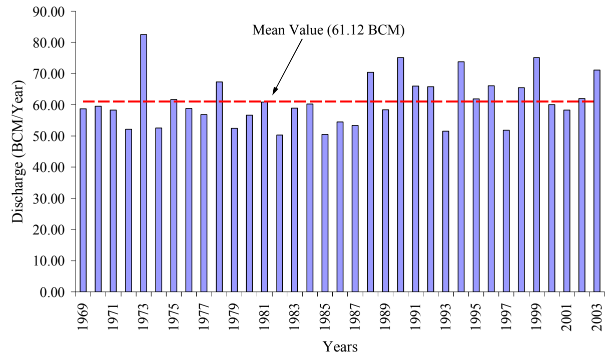

Fig. 3 Indus river inflows at Basha.

below:

a) Topographic data

The proposed Basha reservoir was represented in the model by a series of 57 cross-sections from the dam-site to a point located beyond the upstream extent of the reservoir (**Fig. 2**). DBC Consultants[6] have derived a digital map of the Basha reservoir with 5 m contour interval from the 70 topographic sheets of the reservoir area (1:7500). The digital reservoir model was used to derive the river cross-sections of Basha reservoir. Several minor tributaries enter into the Basha reservoir from both banks and these tributaries contribute approximately five percent to the total storage capacity of the Basha reservoir (DBC[6]). However, due to unavailability of detailed information about these tributaries, only two tributaries were considered to represent the storage capacity of all side valleys, located 8 and 14 km upstream of the dam on both right and left bank.

b) Hydrological data

Inflow time series at the proposed damsite were derived by DBC Consultants[6] by using the daily discharge data of Shatial and Partab bridge gauging stations. Daily inflow time series were available for the period from 1969 to 2003. These 35 years of records were converted into 10-daily discharges (by taking the average), which were used as input data in the RESSASS model for the reservoir sedimentation study. The mean annual discharge (1969 - 2003) estimated at the damsite was 61.12 BCM (**Fig. 3**). A considerable variation from one year to the other was observed and believed that it is a good indication of probable future conditions and could cover all the possible hydrological cycles, with some exceptions. However for simulation periods exceeding 35 years, the time series was extended for the next 35 years period on the basis of a stationary stochastic process (Mutreja[16]). So these 70 years 10-daily discharges (the historical 35 years of record and extrapolated discharges for next 35 years) were used in the model.

c) Sediment data

A sediment rating curve for the planned damsite was derived from sediment rating curves of Partab Bridge and Besham Qila stream gauging stations (NEAC[17]). From these rating curves, it was estimated that mean annual suspended sediment load at Partab Bridge and Besham Qila was 151.57 and 215.54 million tons, respectively. The suspended sediment yield at the Basha damsite was calculated by linear interpolation. NEAC Consultants[17] used USBR[26] guidelines to estimate unmeasured bed load at the damsite on the basis of suspended sediment concentration and found that the bed load is approximately equal to the 10% of suspended load. Therefore on the basis of the NEAC[17] results, the total annual sediment inflow to Basha reservoir was estimated as 199.40 million tons consisting of 181.27 million tons of suspended sediment and 18.13 million tons of bed load.

Grain size analyses of suspended sediment samples of Partab Bridge station were also available and included 46% of sand and 54% of silt & clay (NEAC[17]).

d) Boundary conditions

NEAC[17] Consultants developed the rule curves for normal and flushing operation by keeping in view the downstream requirement of water as well as filling of the reservoir. These rule curves were selected to analyze the sediment deposition patterns and storage capacity depletion rate in Basha reservoir. Additionally, another scenario was also considered to study the effect of implementation of watershed management projects in the upper Indus Basin on sediment inflows. The following four scenarios were considered as downstream hydraulic boundary conditions for reservoir sediment simulation of Basha reservoir:

Scenario 1: Under normal operation, the reservoir level varies every year between Full Reservoir Level (FRL) of El. 1160 m and Minimum Operation Level (MoL) of El. 1060 m (**Fig. 4**).

Scenario 2: Under raising of MoL, six reservoir op-

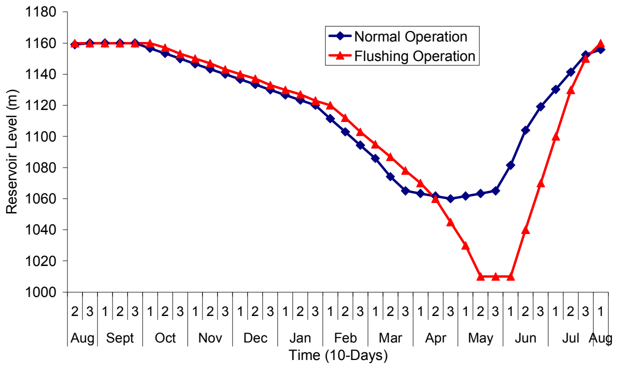

Fig. 4 Rule curves for Basha reservoir under normal and flushing operation.

eration strategies were considered. For this purpose, 1.0 and 2.0 m/year gradual increase in MoL after 30, 35 and 40 years of operation were considered. However, the MoL remained at El. 1060 m before the aforementioned periods.

Scenario 3: Under flushing operation, the drawdown of MoL from El. 1060 m to El. 1010 m was considered after 35, 40 and 45 years of operation (from the time of first impoundment). The flushing reservoir level (El. 1010 m) was maintained annually for a period of 30 days (from 11th May to 10th June) (**Fig. 4**). This period was selected because it is not possible to keep the reservoir at the minimum operating level during the peak flow period (July and August) due to the constraints of reservoir filling.

Scenario 4: Under the last part of this study, the effect of implementation of watershed management projects was considered. In past, few studies have been carried out to evaluate the impact of sediment management practices on sediment yield. Solaimani et al.[22] worked out the relationships between land use pattern, erosion and the sediment yield in the Neka River Basin, Iran. Their results indicated that the total sediment yield of the study area has notably decreased to 89.24% after an appropriate land use/cover alteration. Minella et al.[14] studied the reduction in sediment yield as an impact of improved soil management practices in southern Brazil. Their work verified a 22% reduction in the sediment yield over the study period.

Ali and De Boer[2] found that the main sediment sources in the Indus valley includes channel erosion, gully erosion, and steep hill-slope erosion due to the combination of continuing tectonic instability, glaciers melting and heavy monsoon rains. It is the need of hour to practice river basin management techniques to reduce sediment yield. Therefore, It was assumed that the watershed management projects in the Indus river basin may reduce the sediment inflow rate to 50% (99.7 million tons/year) and may be implemented within 30 years after execution of Basha reservoir. While the sediment inflow remains 199.40 million tons/year from the time of its first impoundment till 30 years of operation.

(2) Model parameters interpretation

Normally before making predictions with RESSASS model, the model results are calibrated with observed hydrographic survey data to ensure that the appropriate sediment parameters are selected for modelling the depletion rate and deposition patterns. Since Basha reservoir has not been constructed yet, no hydrographic survey data exist. Therefore, information from previous studies in Pakistan was used to ensure adequate model results.

The RESSASS model was already successfully applied by DBC Consultants[7] and TAMS Consultants[24] on Tarbela reservoir. Tarbela and Basha reservoirs are more or less under the similar climatic, hydrological and geographical conditions because both are located on the same river i.e. the Indus (NEAC[17]). Therefore, the experience gained from the application on Tarbela is useful for the design of Basha reservoir. DBC Consultants[7] used detailed hydrographic surveys of the Tarbela reservoir for the years 1979, 1997 and 2005 for calibration and verification of the model. Initially they calibrate the model for the period from 1979 to 1997. As a confidence building measure, verification runs of the model were carried out for an additional period from 1998 to 2005. TAMS Consultants[24] calibrated the RESSASS model with hydrographic survey of Tarbela reservoir for the year 1996. The results obtained under both the studies were good. The sediment parameters calibrated under both the aforementioned studies were in the same range. The results obtained under these studies leads to building up strong confidence in the model predictions. Therefore similar range of sediment parameters was selected for sediment simulation of Basha reservoir as selected under Tarbela reservoir sedimentation studies and these were as follows:

Number of sand fractions:	2
Specific gravity of sand particles:	2.77
Particle size for each sand fraction (mm):	0.30 & 2.0
Number of silt fractions:	3
Specific gravity of silt particles:	2.10
Settling velocities of silt (mm/s):	0.002 - 3.8

5. RESULTS

The sediment simulation of Basha reservoir was carried out for the period of 60 years under each selected reservoir operation strategy. During the numerical simulation, the average annual sediment inflow

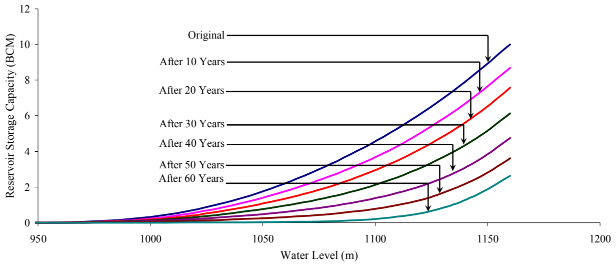

Fig. 5 Predicted stage - storage capacity curves for the Basha reservoir under normal reservoir operation.

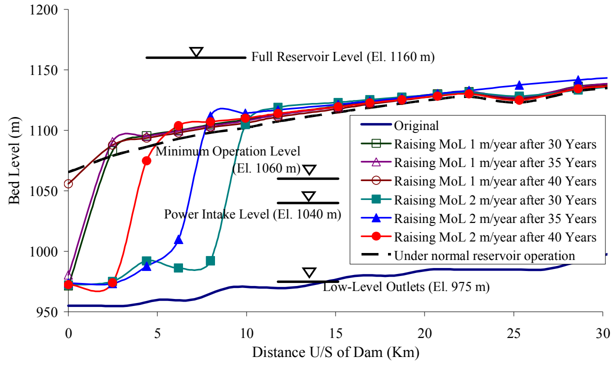

Fig. 6 Deposition pattern of sediment in Basha reservoir after 60 years of reservoir operation under different raising MoL scenarios.

rate to the Basha reservoir was equal to 199.40 million tons for the entire simulated 60 years period that comprised 46% of sand and 54% of silt & clay. The results obtained under each selected reservoir operation strategy are discussed below.

(1) Scenario 1: reservoir sediment simulation under normal reservoir operation

Under normal reservoir operation, the gross storage capacity may reduce from 10.008 BCM to 2.63 BCM with an active storage capacity of 2.59 BCM after 60 years of reservoir operation (**Fig. 5**). This shows that 7.37 BCM storage capacity will be depleted within 60 years of reservoir operation. The model also predicted that the average annual depletion rate would be 0.123 BCM (1.23%). The sediment outflow rate gradually increases with the passage of time and after 60 years of operation may reach the value of 2,218 million tons. This gradual increase in sediment outflow causes a reduction in trapping efficiency of the reservoir. The model predicted the trapping efficiency at the start of the operation 83% whereas after 60 years of operation the trapping efficiency reduces to the level of 12%. The model results indicate that there is a need for the adoption of sediment management measures to extend the life span of the Basha reservoir.

(2) Scenario 2: reservoir sediment simulation under raising of minimum operation level (MoL)

One of the reservoir sedimentation management measures is the gradual increase of Minimum operation Level (MoL), which is successfully applied on Tarbela reservoir (TAMS[24]). In case of Tarbela reservoir, a significant reduction in the advancement of the sediment delta was observed due to the increase of MoL from 396 m to 417 m until 2006. For Basha reservoir, 1.0 and 2.0 m/year gradual increase in MoL after 30, 35 and 40 years of operation were considered and potential effects were analyzed in the advancement of the sediment delta. The same boundary conditions were applied for the sediment simulation as selected under normal conditions except the gradual incremental rate of MoL after 30, 35 and 40 years of simulation. From the model results (**Fig. 6**), it was concluded that the gradual rise of MoL at the rate of 1.0 m/year did not reduce significantly the delta movement. Nevertheless, raising of MoL at an annual rate of 2.0 m resulted in the highest retardation of the advance of the deposition delta when implemented after 30 years of simulation. The predicted deposition pattern after 60 years of operation by annual increase of 2.0 m initiated after 30 and 35 years of operation were comparable. But the annual increase of 2.0 m after 30 years is too early and would negatively affect the storage capacity (Project benefits). Therefore, the annual incremental rate of 2.0 m initiated after 35 years of operation was selected as the optimal option.

Under the selected annual raising rate of MoL (2.0 m/year) commencing after 35 years, the model predicted the gross storage capacity after 60 years of operation was 2.57 BCM and live storage capacity was 2.33 BCM (**Fig. 7**). Under this scenario, the average annual storage depletion rate would be 0.124 BCM (1.24%). The sediment outflow may reach the value of 2,250 million tons after 60 years of operation. The model predicted the trapping efficiency after 60 years of operation was 68%. The economic losses of gradually raising of MoL, thus reducing the active storage at Basha, are expected to be less compared to the consequences of reservoir flushing due to its negative effect on power generation at Basha.

(3) Scenario 3: reservoir sedimentation under flushing operation

The effect of reservoir flushing on storage capacity and sediment deposition pattern was studied considering different years when annual reservoir flushing may be implemented. The same boundary conditions were applied for the sediment simulation as selected under normal operation except the Minimum opera-

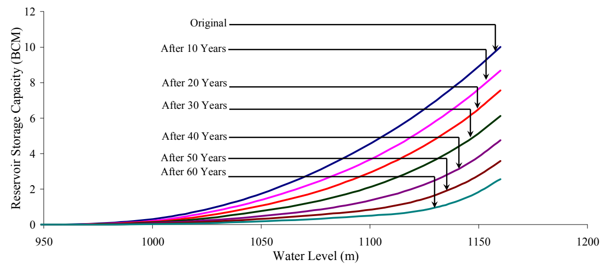

Fig. 7 Predicted stage - storage capacity curves for Basha reservoir by raising the MoL 2.0 m/year implemented after 35 years of operation.

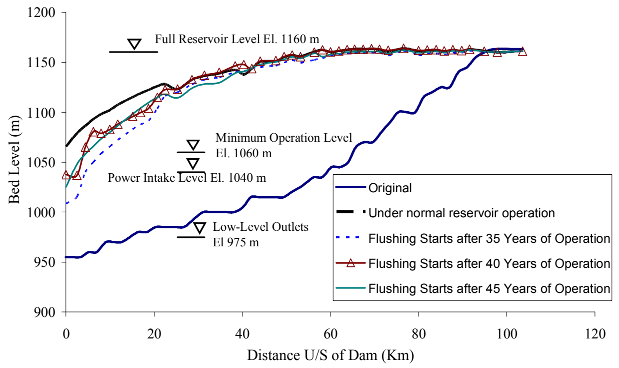

Fig. 8 Deposition pattern of sediment after 60 years of reservoir operation under different flushing scenarios.

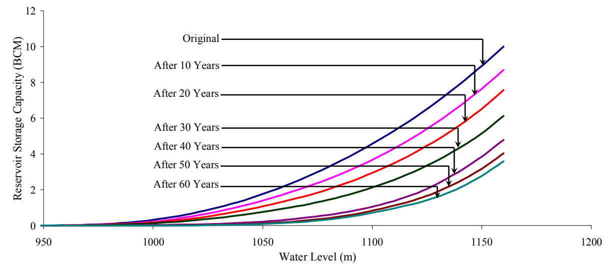

Fig. 9 Predicted stage - storage capacity curves for Basha reservoir by starting flushing after 35 years of operation.

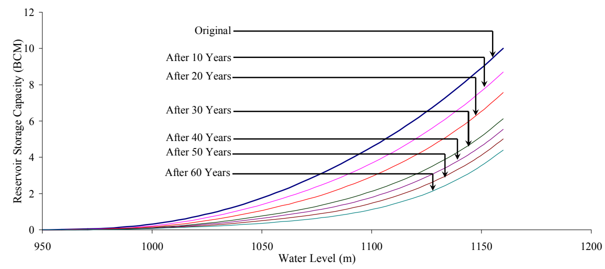

Fig. 10 Predicted stage - storage capacity curves for Basha reservoir by reducing the 50% sediment inflow initiated after 30 years of operation.

tion Level (MoL) which was considered at El. 1010 m. The MoL (El. 1010 m) was maintained annually for a period of 30 days (from 11th May to 10th June). The reservoir sediment simulation of Basha reservoir was performed by varying the beginning of this operation mode starting 35, 40, and 45 years from the time of first impoundment. From the model results (**Fig. 8**), it was observed that an early start of reservoir flushing i.e. after 35 years of project implementation will keep the power-intakes free of sediment even after 70 years of operation. However a further delay in flushing may result in the early blockage of power-intakes due to sedimentation. The corresponding sediment deposition patterns after 60 years of operation under selected flushing scenarios are given below.

When flushing is implemented after 35 years of reservoir operation, the model results shows that the life time of Basha Reservoir can be extended beyond 70 years (**Fig. 9**). The remaining gross storage capacity after 60 years of operation was 3.58 BCM and live storage capacity of reservoir remained at 3.43 BCM. The model predicted that the average annual storage depletion rate would be 0.107 BCM (1.07%). After 60 years of operation, the sediment outflow may reach the value of 3,563 million tons. The model predicted the trapping efficiency after 60 years of operation was 5% whereas under normal operation it was 12%.

From the above results, it is clear that the flushing will result in removal of significant quantities of the incoming sediments and retards further reservoir sedimentation. Extended flushing periods could probably restore additional active storage. The main disadvantage of flushing is the shutdown of power-houses during the flushing period. So the longer the period of draw-down of the MoL, the higher would be the reduction in the project benefits. Therefore, the quantity of sediments which can be flushed out depends largely on available flushing discharge and the duration of the flushing period.

(4) Scenario 4: reservoir sedimentation under controlled sediment inflow

The impact of river basin management practices was analyzed by simply reducing the sediment inflow. It was considered that the watershed management projects will be implemented within 30 years from the time of its first impoundment. The same boundary conditions were applied for the sediment simulation as selected under normal operation except the sediment inflow which was considered 99.7 million tons/year after 30 years of operation.

Under this scenario, the remaining gross storage capacity after 60 years of operation was 4.40 BCM with remaining active storage capacity of 3.94 BCM (**Fig. 10**). The model predicted the average annual storage depletion rate was 0.093 BCM (0.93%). After 60 years of operation, the sediment outflow may reach the value of 1,602 million tons. It was observed from the numerical model results that the implementation of river basin projects may significantly extend the life span of Basha reservoir. From an assumed reduction of the sediment inflow of 50%, the life time of Basha reservoir was extended to approximately 100 years. The present analysis is of hypothetical nature and requires serious investments in river basin projects that can reduce the sediment transport in the Indus river. However, the results show the potential positive effect of watershed management projects in the upper Indus Basin.

6. DISCUSSION AND CONCLUSION

In order to mitigate the potential sedimentation dangers for the planned Basha reservoir, several sediment management strategies were evaluated and their impacts on reservoir storage depletion rate were studied. The operation of the Basha reservoir under different sediment management strategies exhibited substantial variation in storage capacity depletion rates (**Table 1**). Under normal reservoir operation, the RESSASS model calculated the annual storage loss of Basha reservoir is 1.23%, which is slightly higher than the global average annual depletion rate i.e. 1% (Mahmood[13)]). Also the already existing reservoir in the Indus river, i.e. Tarbela loses about 1% of storage annually (DBC[7)], Ali et al.[3)]). Considering the economic importance of hydropower reservoirs for Pakistan, there is a clear need for sediment management strategies to extend the lifetime of the planned Basha reservoir.

The selected sediment management strategies exhibited some advantages as well as disadvantages on the economic performance of the planned reservoir. The best reservoir operation strategy would be one which is environmental friendly and can significantly enhance the reservoir's life. **Table 1** presents the gross storage capacities for the different scenario's of Basha reservoir. The gradual raising of MoL (scenario 2) has no effect on the lifetime of Basha reservoir, and results in exactly the same annual storage depletion as the normal operation (scenario 1). However, the raising of the MoL could reduce the movement of the sediment delta towards the dam, because the flow velocities are reduced. Due to low flow velocities, the coarse and fine sediments may deposit at the head of the reservoir (**Fig. 6**).

Flushing of the reservoir will positively affect the lifetime of the planned reservoir (**Table 1**), with approximately 1 BCM more storage capacity after 60 years of operation. However, the flushing operation would be negatively affecting the life-span of the downstream Tarbela reservoir, because the flushed sediments will be transferred downstream and enter into the Tarbela reservoir. Also, flushing sediments from a large reservoir that is subject to high sedimentation rates is more difficult than for small reservoirs with low sedimentation rates (Liu et al.[12)]). So both the flushing and raising of MoL would not be the preferred options, although these strategies may add 10 - 20 years to the life-span of Basha reservoir.

Table 1 Temporal development of gross storage capacities in Basha reservoir for different sediment management scenarios.

Year	Gross Storage Capacity (BCM)			
	Sce 1†	Sce 2*	Sce 3$^{\#}$	Sce 4$^{!}$
Original	10.008	10.008	10.008	10.008
After 10 Years	8.69	8.69	8.69	8.69
After 20 Years	7.56	7.56	7.56	7.56
After 30 Years	6.13	6.13	6.13	6.13
After 40 Years	4.75	4.75	4.79	5.54
After 50 Years	3.61	3.58	4.03	5.01
After 60 Years	2.63	2.57	3.58	4.40

†Scenario 1: Reservoir Sediment Simulation under Normal Reservoir Operation; *Scenario 2: Reservoir Sediment Simulation under Raising of Minimum Operation Level (MoL); $^{\#}$Scenario 3: Reservoir Sediment Simulation under Flushing Operation; $^{!}$Scenario 4: Reservoir Sediment Simulation under Controlled Sediment Inflow

The last scenario evaluated assumed a 50% reduction of inflow of sediments into the reservoir, and increases the life span of the reservoir significantly (**Table 1**). However, reducing the sediment transport in the Indus river requires large scale river basin management projects upstream of Basha. It is questionable if this can actually be achieved due to the high investment required. The major sources of sediment are (Poesen and Hooke[19)]): (1) the river bed and banks, (2) large gullies and (3) steep slopes draining directly into the river system and where severe erosion may take place under heavy monsoon rains and glacier melting. So, reducing the sediment quantities in the Indus river requires reductions of erosion from all three sources. This means stabilization of river banks, control of gullies and protection of steep slopes in the upstream river basin. Gully control and river bank stabilization are civil engineering problems that require physical structure like gabions, gully plugs and other engineering works. Erosion control on steep slopes has been dealt with in physical geography and agricultural science. For the latter erosion models have been developed to study erosion processes and quantities of sediment delivery to streams, and also to design erosion control measures. Unfortunately, the performance of many of the developed models is still poor (Beven[4)]), and it requires more basic research to develop tools that can assist in the planning of erosion control measures, especially in an environment as extreme as the Indus river basin.

The model results showed that the reservoir life could be more than 100 years if the sediment inflow would be reduced to 50% by implementing river basin management projects in the catchment area. Ali and De Boer[2] already identified the main sediment sources in the Indus valley which includes channel erosion, gully erosion, and steep hill-slope erosion. Therefore, the current challenge for the researchers is to identify the areas that are under high risk of soil erosion and also quantify their respective contribution in annual sediment yield. The following river basin management practices can be adopted, which are being globally used to abridge the erosion rate under channel, gully, and steep hill-slopes.

i. Due to meandering river patterns of the Indus, the river banks are unstable because of the rapid lateral erosion, especially on the outside of meander bends (Ali and De Boer[2]). So the river banks should be protected by establishing vegetation and by placing rock-filled gabions (Toy et al.[25]). The plantation of trees can help to stabilize the river banks as well.
ii. Under gully erosion, the detachment and transport of sediment could be due to high flow velocities and steep slopes, which can be controlled by constructing check dams to reduce the flow velocities (Zhou et al.[34]). The check-dams would be effective in both the glacier melt and rain induced areas.
iii. The soil losses on hill-slopes are mainly due to interrill and rill erosion. Therefore, the detachment and transport capacity on hill slopes can be reduced by introducing strips of dense vegetation, terraces, flow diversions and armored waterways for runoff disposal (Toy et al.[25]). The vegetation must be appropriate for the local climate and soil conditions.

The river basin management projects would not only have positive impacts on the life of Basha reservoir, but may also extend the life of projects that are being planned to construct upstream and downstream of Basha. The proposed watershed management practices may enhance the agriculture production in the area, which would have direct impact on the life of local people.

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