EXPLORING SEDIMENT MANAGEMENT OPTIONS OF MANGLA RESERVOIR USING RESSASS

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ABSTRACT: *Until 2010, Mangla reservoir has lost the gross storage capacity of about 22% due to sedimentation since its impounding in 1967. To enhance the life of the reservoir by reducing the sediment inflow, watershed management programs were implemented soon after the operation of the reservoir. Considering the high sediment inflow to the reservoir, option of raising the dam was kept in original design and the dam was raised by 9 m and conservation level by 12 m in 2008-09 which will provide additional storage of about 3.55 BCM to compensate the storage capacity loss. Consequently the revised sedimentation rate in the reservoir after the raising of dam becomes 0.35% per annum. Still the storage capacity loss due to sedimentation is alarming and delta is advancing at an average rate of 0.5 km/annum and currently the pivot point of delta is standing at about 5.2 km away from power intakes which may cause threat of its chocking in future years. In present study sediment inflow to the reservoir is evaluated by considering all tributaries of the reservoir i.e. Jhelum, Poonch, Kanshi and Khad. The numerical Model RESSASS is used for sediment simulation. Model results show that the Model was well calibrated & validated for years 2005, 2010 hydrographic surveys, respectively. After validation, future modeling is carried out considering three scenarios i.e. 1) Existing conditions 2) Flushing after 10 years 3) Flushing after 20 years in line with the study of several sediment management techniques adopted at Sanmenxia reservoir of China. The results indicate that the raising of dam will cause in reduction of delta advancement and sediment deposition rate which shall extend life of reservoir up to 2130 without any flushing option. Based on model study results, it revealed that maximum benefits in terms of power and irrigation could be achieved by 150 days flushing after each 10 years. This scenario also extends the life of the reservoir for another 40 years.*

Key Words: Reservoir Sedimentation; Flushing; Mangla Dam Raising; Delta Advancement Rate; Sediment Deposition Rate

1. INTRODUCTION

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. Reservoir sedimentation is caused by reduced velocity of water and sediment into the reservoir. There are over 50,000 large dams exist that are used for hydropower, irrigation and drinking purposes whose estimated storage capacity worldwide as a volume is about 7000 km^3 and storage capacity loss is 50 km^3/year [1]. The global mean annual storage loss of reservoirs is about 1% and varies significantly between 0.1 - 2.3% among river basins due to different geological conditions [2]. For example, in China the Sanmenxia reservoir on the Yellow River has lost about 70% of its gross storage capacity since completion in 1970, with one third of its capacity was depleted within the first three years [3]. In Pakistan, the Tarbela reservoir has lost 30% of its original capacity during period 1974-2006, with mean annual storage loss equal to 1% or a total storage loss of 0.132 BCM [4]. A similar situation is going on with other large dams of Pakistan.

Worldwide large dams and annual storage capacity loss is shown in Figure 1. It depicts that in Asia region the rates of storage loss are usually higher than the world average of 1%. India and China are annually losing 0.5 and 2.3% respectively of storage capacity because of the low forest cover (India 23% and China 16.5%) and high erosion. However, the annual loss rates in Southeast Asia and Japan are only 0.3% and 0.15% respectively due to relatively low sediment yield and the high forest cover [5].

As Mangla reservoir plays a vital role in the provision of water for Irrigation, flood control and power generation. It had initial gross capacity of 7.25 BCM, which has been reduced about 22% since impounding in 1967, with an average loss 0.5% per annum and it is expected to be reduce further with the passage of time due to sedimentation.

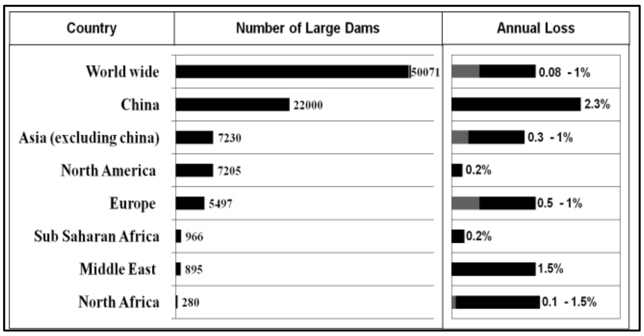

Figure 1: Worldwide large dam and annual storage capacity loss

Due to depletion of water storage, hydel generation has remained significantly low which is seriously affecting industry, domestic consumers and economy of the country. Agriculture is also being badly affected and commodities prices have increased because of higher prices of tube well water. In addition to damage due to scarcity of irrigation water, the country also suffers serious flood damages periodically which may cause of spoil hundreds of lives as well as loss of billions of rupees by a single high flood. For example, damages of 1992 flood have been estimated at about 50 billion rupees which is too close to the cost of Mangla raising project [6].

To prolong the life of Mangla dam, reservoir operation curve is followed by lowering water level from 366 m to 317 m for twenty days from 11th March to 30th March every year and reservoir is allowed to refill again to its maximum conservation level before September if permitted by inflows and irrigation demands. Also, watershed management projects are established soon after its operation, to minimize the sediment contribution by erosion in the catchment area of reservoir. These projects besides of reducing silt entry into reservoir has also improved socioeconomic conditions of the people living in vicinity by improvement of land and resulting increase in agriculture. However, time will be required to achieve further better results [7].

In the Mangla reservoir, sedimentation has always considered a source of problem and storage loss of 1% per year was estimated during 1960. It was also predicted that serious issues of sediment like passing of sediment concentration through power turbines and irrigation valves would increase after 40 years of operation. Available data of sediment inflows and accumulation (from 1967 to onwards) shows less predicted rate of capacity storage loss since the dam construction. Due to sedimentation, the storage capacity loss was a serious concern for the designers and the raising of dam in future was kept in the original blue prints.

The delta will progress to the dam within 20-25 years from 2002 to onwards, without and with dam raising as long as the minimum drawdown level is kept at 317 m (1040 ft). This can be delayed by raising the minimum drawdown level. As the minimum drawdown level is increased the elevation of the top of the delta rises and the time for the delta to reach the dam increases [8].

As a part of the engineering studies for the raising of dam, other possible measures such as dredging and flushing have been given due consideration particularly as a long term strategy. World-wide experience of these practices is very limited on large reservoirs. On basis of raised conditions simulated results interpreted that about 10% less deposition is predicted with 40 days of flushing as compared to 30 days of flushing. The delta is predicted to advance towards the dam at a very high rate with all the sluicing regimes, generally reaching the dam within 5-10 years of the start of sluicing [4].

Table 1: Salient Features of Mangla Reservoir

Components	Original	Raised
Gross Storage Capacity	7.25 BCM (5.88 MAF)	10.82 BCM (8.76 MAF)
Live Storage Capacity	6.58 BCM (5.34 MAF)	10.15 BCM (8.22 MAF)
Dead Storage Capacity	0.67 BCM (0.54 MAF)	0.67 BCM (0.54 MAF)
Additional Avg. Annual Storage	------	3.57 BCM (2.88 MAF)
Max. Conservation Level	366 m (1,202 ft)	379 m (1,242 ft)
Min. Conservation Level	317 m (1,040 ft)	317 m (1,040 ft)
Dam Crest Level from Sea Level	376 m (1,234 ft)	385 m (1,264 ft)
Dam Height from River Bed	115 m (380 ft)	125 m (410 ft)
Spillway Orifice Type Capacity	1,100,000 Cusec	1,100,000 Cusec
Main Spillway Gate Size	11x12.1 m (36 x 40 ft)	11x12.1 m (36 x 40 ft)
Main Spillway Invert Level	331 m (1,086 ft)	332.5 m (1,091 ft)

The Mangla dam height is raised by 9 m and maximum conservation level increased 12 m from 366 m to 379 m which may provide additional average storage of 3.55 BCM (2.88 MAF) per annum, that is more than loss of storage capacity of reservoir during 1967-2010. Extra storage of water will also provide an additional energy generation of 644 GWh annually by upgrading and refurbishment of generating units. Moreover, raised Mangla dam will reduce intensities of high floods as well as fulfill shortage of irrigation demand.

Jhelum River is the major tributary of the Mangla reservoir and Kanshi, Poonch, Khad & Jari are considered as secondary tributaries. Gauging stations installed by Surface Water Hydrology (SWH) at different locations Kohala & Azadpattan, Kotli and Palote at Jhelum, Poonch and Kanshi rivers respectively to measure the daily discharges and sediment loads.

Mangla reservoir salient features are described in Table 1:

1.1. Sediment Inflow to the Reservoir

The average annual sediment load entering Mangla reservoir is estimated as 61.32 MST per year. Adding the contribution of 2,339 km2 (7% of total catchment area at Mangla) un-gauged area between Mangla station and other three stations Kohala, Kotli and Palote (using catchment proportion) the average annual total sediment load entering Mangla reservoir is worked out as 65.61 MST against the previously estimated sediment load of 73.3 MST during design studies in 2004. The estimated sediment load is about 10% less than estimates of detailed design studies which may be attributed to reduction in average inflows at Mangla from 2003 to 2009. Out of total estimated sediment load entering Mangla reservoir, 73 % is contributed by Jhelum main stem, while 24 % and only 3 % contributions are made by Poonch and Kanshi rivers, respectively [9].

Various studies have carried out for assessment of sedimentation at Mangla reservoir. The comparison of these studies is described in Table 2.

Table 2: Comparison of previous sedimentation studies

Study/Source	Sediment data	Est. annual sediment load
Bennie, Deacon & Gurley (1962)	1954-1957	80
Bennie et al (1967)	1954-1965	83
Kirmani (1968)	1954-1965	96
Harza (1969)	1960-1965	111
MJV (2000)	1967-1997	72
MJV (2004)	1967-2000	74
MJV (2010)	1967-2010	60

1.2. RESSASS Model Description

RESSASS is one dimensional model which was developed by HR Wallingford which may quantify storage reduction of reservoirs due to sedimentation. It has the capacity to forecast the delta movement and development in the reservoirs. It may predict effect of reservoir operation policies in reducing sediment deposition rates and the impact of future sedimentation in the storages. It also produces stage-volume curve and distribution of sediment deposits in a reservoir as shown in Figure 2.

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. Acker & White (1973) equation is used for computation of coarse (sand) material transport functions and Westrich & Jurashek's (W&J) (1985) method is used in computation of fine (silt/clay) materials.

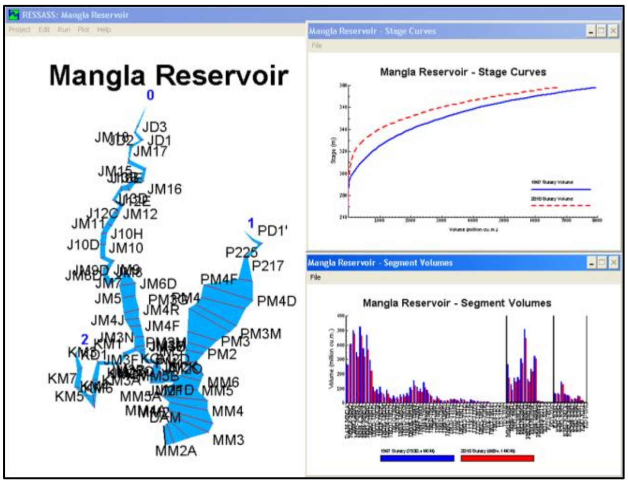

Figure 2: Stage-volume curve and sediment deposition in reservoir

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.

2. MATERIALS & METHODS

2.1. Water Discharge

The average annual inflow to Mangla is 28,500 MCM. The annual runoff is relatively modest due to high proportion of snowmelt. Mangla reservoir discharge may varies between 350 to 1,850 m^3/sec with high monsoon rainfalls during month of July, August and September which also causes sharp floods of short durations. Water inflow to Mangla basin in different years is shown in Figure 3.

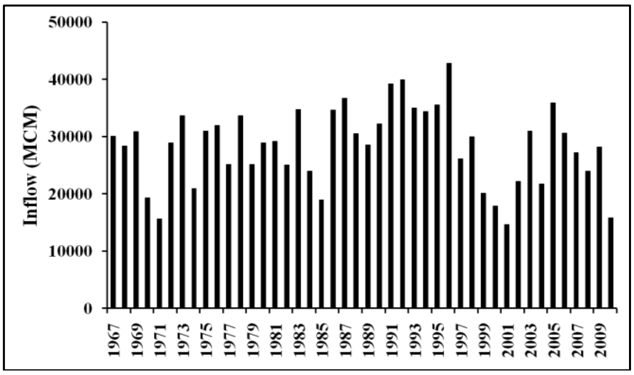

Figure 3: Water inflows to Mangla dam at different years

2.2. Sediment Load

The suspended sediment measurement data sampled on the Jhelum, Poonch and Kanshi River for the period up to 2010 were collected from the records of SWHP (WAPDA). As gauging station at Kohala on Jhelum River has been closed since 1998 but, Azadpattan gauging station is in operation. Other gauging stations like Kotli and Palote are installed on Poonch and Kanshi River respectively to measure the inflow and sediment data. Sediment rating curves were developed with collected data from SWHP to forecast the deposited sediment in the reservoir. The computed annual suspended loads in its tributaries are portrayed in Table 3.

The total sediment load has been estimated by adding 10% bed load in the computed suspended load. This value was originally proposed by Kirmani based on early sediment data and was adopted and confirmed in all subsequent studies.

Table 3: Computed annual suspended load (1967-2010)

Suspended sediment load	Jhelum at Kohala (MST)	Poonch at Kotli (MST)	Kanshi at Palote (MST)
Maximum	122.67	50.85	4.66
Average	40.88	13.33	1.54
Minimum	3.30	0.91	0.24

2.3. Operation Levels

Due to seasonal fluctuation in rivers, the operating levels at dam follow a drawdown and fill cycle in which water levels starts to decrease after month of September, reaching at its minimum level in month of March for 20 days and then rising again during summer season. Operating levels have great influence in advancement of sediment delta towards the power intakes.

Results of the computed delta advancement rates on the basis of hydrographic surveys are shown in Figure 4. It depicts that after 1997, there is no significant movement of delta till flood of 2010. The slope of delta pivot point is rapidly decreasing and is moved very fast during the initial years up to 1993 and the rate of advancement become less after that. The reason being that at the farther end from the dam face i.e. at the start of the reservoir the width of the reservoir is very small so in that region delta moved with the faster rate and as the channel width becomes broader near the dam face, delta movement gets slow down due to large area available for sediment deposition.

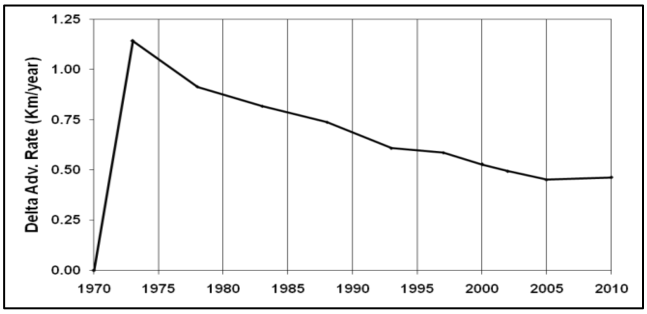

Figure 4: Historical Profile of Delta Advancement Rate

2.4. Application of RESSASS to Mangla dam

For the model calibration and validation, stream minimum bed levels at each cross section were considered as criteria for comparison of the model results with observed value. The numerical model RESSASS was calibrated and validated against the delta profile observed by MDO through hydrographic surveys in year 2005, 2010 respectively as shown in Figure 5 and Figure 6 .

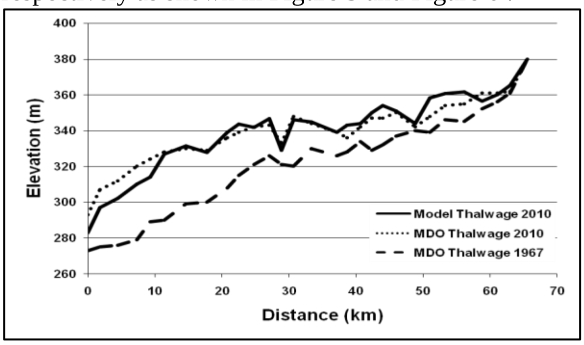

Figure 5: Calibration of Model

Sediment sizes of sand, silt and clay were fixed to provide the better estimation of the observed values. To ensure the conformity between the observed and numerical results, sensitivity analysis is carried out and value of Coefficient of model efficiency (COE) and model determination (COD) are computed as 0.82 and 0.92 respectively.

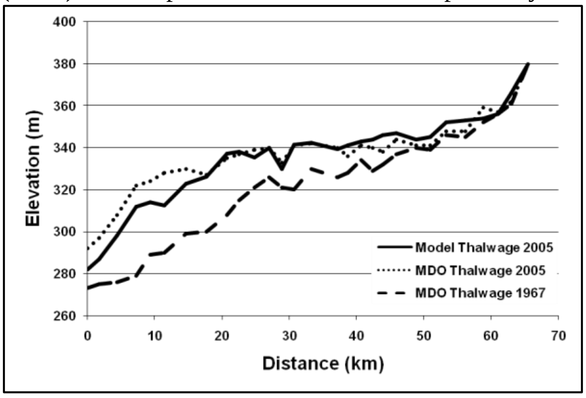

Figure 6: Validation of Model

3. RESULTS AND DISCUSSIONS

The fluctuation of sediment transported by the water in the Mangla reservoir has increased in magnitude since its operation started [10]. This research gives evident that the rate of storage reduction will continue to increase in the future due to water inflows and reservoir operation both influence sediment deposition shown in Table 4. As it is assumed that same inflow 1967-2010 would be recycled in future, various scenarios discussed to reduce the uncertainties of future predictions.

In this study, three scenarios are analyzed: in scenario 1 there is no change in the existing reservoir operation and in scenario 2 and 3 flushing is considered for 150 days after every 10 & 20 years respectively. The numerical model RESSASS results are summarized in Table 4 which shows that currently delta pivot point is 5.2 km away from the dam face.

Table 4: Summary of future modeling results

Scenarios	Delta pivot point distance (KM)	Sediment deposition rate (% / year)	Reservoir life (year)
Present	5.2	0.50	120
Future Prediction 2010-2090			
1	1.8	0.54	120
2	4.4	0.45	160
3	1.8	0.47	140

3.1. Life of Mangla Reservoir

Mangla reservoir is depleting its capacity every year due to sedimentation but the sediment deposition amount has been reduced due to upraising of the dam which has increased the live storage capacity of the reservoir up to 3.55 BCM, 2.9 MAF [9].

Reservoir storage capacity based on past observed delta and future predictions is shown in Figure 7. It is increased due to the raising of dam and reservoir was allowed to fill up to full new capacity 8,900 MCM in 2013. Scenario 1 shows that reservoir would be filled with sediment in 2140 and further storage would not be possible. In two other scenarios it is predicted that reservoir life may extend for another 40 years and even more depends upon operation and structure stability. Also, results show that scenario 2 may extend more life as compared to scenario 3.

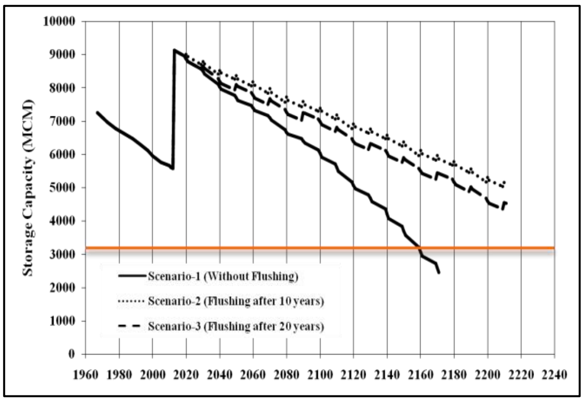

Figure 7: Mangla reservoir storage capacity

3.2. Future Delta Advancement Rate

Pivot point is becoming closer to the dam face on the basis of model results, the advancement of pivot point towards the dam face at an average rate of 0.5 km annually and this rate increases in future [11].

Future predicted delta advancement rate is shown in Figure 8. It depicts that in case of scenario 1, delta is advancing towards the dam face and it would be only 1.8 km away in 2090 which may cause of chocking the power turbines. But trap efficiency is high which causes reduction in storage. In scenarios 2 and 3, delta moves fast towards the dam and more sediment laden water passes through the power intakes but preserving the storage capacity by flushing of sediment.

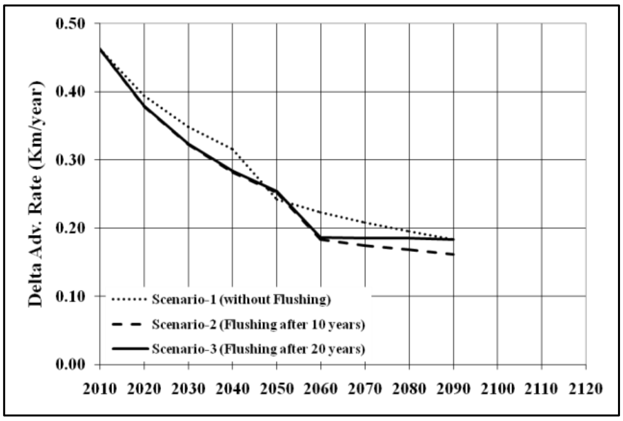

Figure 8: Future Predicted Delta Advancement Rate

3.3. Future Sediment Deposition

Future modeling results of sediment deposition in reservoir are shown in Figure 9. It reveals that scenario 1 will cause 30 MST average annual sediment deposition and on other side, it would be 15 & 17 MST in case of scenario 2 & 3 respectively. Sediment deposition with both scenarios of flushing is significantly less as compared to scenario 1. The variation in deposited sediment quantities between both scenarios of sediment flushing is in the range of 30-50%. About 20% less deposition is predicted in case of scenario 2 as compared to scenario 3. With both flushing scenarios, the storage volume in the reservoir at year 2170 would be in the range of 4.5-5.1 MAF as compared to 2.5 MAF in case of scenario 1.

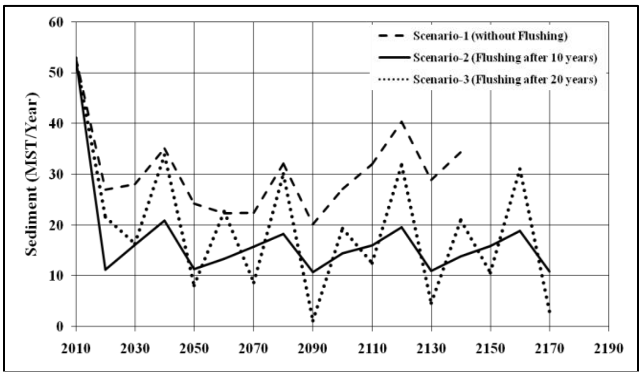

Figure 9: Future Sediment Deposition in reservoir

3.4. Economic Analysis

The primary purpose of the Mangla dam is to store water for power generation and irrigation as discussed earlier. Thus, irrigation and power benefits from the dam are converted into financial terms (PKR) to calculate a simple cost benefit analysis.

As future values for irrigation water and electricity are not known and these are predicted on basis of previous available data by plotting trend lines. In 2007 WAPDA was calculated value of water per acre foot as 2,038/- PKR by forecast the benefits obtained from water supply to analyze the cost benefit ratio of the raising of dam [12]. Currently electricity cost charged to consumers by WAPDA is Rs.12/- for first 300 units and it varies up to Rs.20/- on further units. In this research work electricity prices and water per acre foot values are assumed to be increase on basis of 1% annually.

Economic analysis on basis of benefits in monetary terms is described in Figure 10. Results depict that scenario 2 gives maximum benefit in both power and irrigation as compared to other scenarios. The variations in power and irrigation benefits are in the range of 10-15%. However, better analysis may be drawn by computed actual prediction of prices.

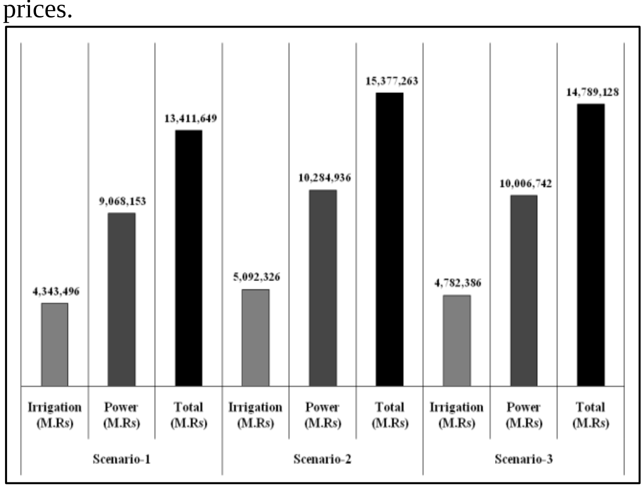

Figure 10: Economical Analysis in monetary terms

4. CONCLUSIONS AND RECOMMENDATIONS

Due to the raising of Mangla dam, delta advancement rate & sediment deposition rate would be reduced and expected life of reservoir would extend up to 2140. In case of flushing for 150 days after every 10 years, maximum benefits in terms of power & irrigation could be gained and, it shall also extend life of reservoir for another 40 years. If future scenarios of flushing are considered, then delta advancement rate and sediment deposition rate is expected to be decreased which will enhance the life of reservoir.

Flushing of Mangla reservoir after 10 years is recommended for maximum benefits however, still there is further need to refine the estimated prices of power and irrigation. While developing the new dams, bottom low level outlets should be introduced to perform the flushing operation especially in developing countries like Pakistan, where there are little chances of future development in this sector. For complete investigation of scouring close to the inlet of the tunnels, 3D numerical models should be used.

5. ACKNOWLEDGEMENT

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