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Reservoir Modelling to assess the Releases and Energy Generation for a Projected Scenario of Tarbela Reservoir in Pakistan

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ABSTRACT

Reservoirs are normally formed by the construction of dams across rivers, but off-channel reservoirs may be provided by diversion structures and canals or pipelines that convey water from a river to natural or artificial depressions. The behaviour of the flow due to construction of dam leads to change in a fluvial process leads to deposition of sedimentation in reservoir. In this research, reservoir modelling has been carried out by using HEC-ResSim for Tarbela reservoir in Pakistan. In Pakistan, the Tarbela Reservoir is the largest reservoir on Indus River and it is the backbone of Pakistan's agriculture sector and economy. The model was calibrated for year 2014 and validated for year 2020 in terms of outflow and power generation. The results show close comparison between simulated and observed outflow and power values for different scenarios. On the basis of 30-year histogram cycle, the future prediction of releases/outflows, power/energy generation in year 2035 has also been made. After 2035, Tarbela reservoir is expected to become the run-off the river type project due to decrease in the gross storage capacity. As per simulated results of the projected scenario (2035), the releases/outflows from reservoir and energy generation will increase in summer season by 7% and 36% respectively and decrease in winter season by 50% and 37% respectively. Further, the reduction in gross storage capacity due to sedimentation would result in the reduction of annual energy generation by 6.5% in year 2035.

Keywords: Reservoir Modelling; HEC-ResSim; sedimentation; Tarbela Reservoir; energy generation; projected scenario

INTRODUCTION

Reservoir, an open-air storage area (usually formed by masonry or earthwork) where water is collected and kept in quantity so that it may be drawn off for use. The role of water- storage reservoirs, therefore, is to impound water during periods of higher flows, thus preventing flood disasters, and then permit gradual release of water during periods of lower flows to fulfill different purposes. Simple storage reservoirs were probably created early in human history to provide water for drinking and for irrigation.

The development of reservoir helps the whole world to fulfill the need of food and fibre by providing water for agriculture and hydropower generation for swift monetary growth and controlling flood. At the same time the storage capacities of present reservoirs of the world are also decreasing which adversely affects the agriculture sector and hydropower production. Storage facility showing is the technique drawn in with making a three-layered portrayal of a given stock considering its petrophysical, land and geophysical properties. These properties are portrayed during store portrayal where geoscientists and modelers gather all physical and compound information to extrapolate those attributes commonly through the storage facility (Deane 2015).

A reservoir operation policy specifies the amount of water to be released from the storage at any time depending upon the state of the reservoir, level of demands and any information about the likely inflow in the reservoir. The operation problem for a single purpose reservoir is to decide about the releases to be made from the reservoir so that the benefits for that purpose are maximized. For a multipurpose reservoir, in addition to the above, it is also required to optimally allocate the release among several purposes (Izhar-ul-Haq and S.Tanveer Abbas 2007).

All lakes and reservoirs created on natural rivers are subjected to reservoir sedimentation. The sedimentation over the years, results in decreased capacity of reservoir independent of its use (irrigation, energy or flood control, and water supply). In extreme case, the reservoir may fill up with the sediments. There is a lack of accurate data regarding rates of reservoir sedimentation worldwide, all over the world, average annual reduction in reservoir storage capacity due to sedimentation varies from 0.1-2.3%, while the average annual world reservoir storage loss is about 1.0% (Asif Choudhry and Habib-ur-Rehman 2010).

The Tarbela Dam (Lattitude: $34^0$5'23" N, Longitude: $72^0$41'54" E) was constructed in 1976 on the Indus Stream as part of the Indus Waters Strategy (IWS) signed by Pakistan and India in 1960. The IWS had provisions to construct three storage reservoirs, namely Tarbela, Mangla, and Chashma, six barrages and eight link canals to mitigate the effect of the loss of water due to the restriction on the flows of the rivers in Eastern Pakistan as shown in Figure 1. Besides the primary function of mitigating the effect of loss of water from the eastern rivers and providing a firm base for the development of the irrigation system, a subsidiary goal of hydropower generation was also introduced during the planning phase (Izhar-ul-Haq and S.Tanveer Abbas 2007).

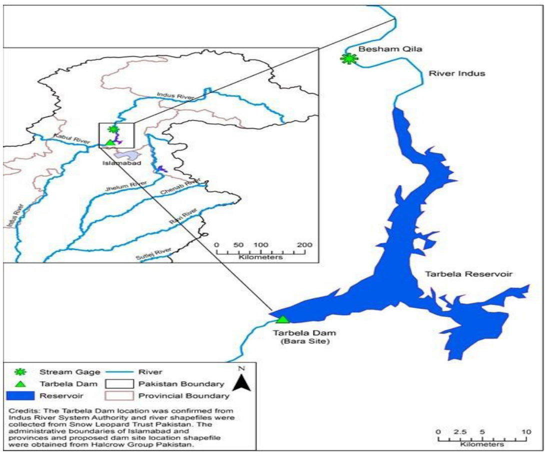

FIGURE 1 Location map of Tarbela Reservoir
Source: WAPDA (2014)

The height of Tarbela dam is 148 m above the riverbed and the surface area of Tarbela Lake is approximately 250 km^2.The average advancement rate of sediment delta pivot point is 0.386 km/year by operating the reservoir according to current NESPAK operations. The location of Tarbela dam on Indus River and Tarbela powerhouse, respectively. Tarbela reservoir primarily holds the Indus River's waters, which carry high volume of sediment load in reservoir. The reduction in reservoir capacity due to sedimentation will reduce irrigation releases and their duration, gross power and power duration (WCD 2000).

LITERATURE REVIEW

Worldwide reduction in reservoir storages due to problem of sedimentation is very significant. The maximum reservoir storage reduction in China is 2.3%, while the minimum storage loss in UK is 0.1% (Asif Choudhry and Habib-ur-Rehman, 2010).

Certain reservoirs due to their topographic nature are more vulnerable to sedimentation than others. One third of storage capacity of Welbedacht reservoir (South Africa) was lost during the first three years of its life due to sedimentation (Huffaker and Hotchkiss, 2006).

The International Commission on Large Dams has estimated that worldwide there are more than 42,000 large dams, and due to sedimentation problem, the resulting worldwide rate of storage loss and storage capacity are approximately 0.5% to 1% and 7,000 km^3 annually, respectively (ICOLD, 1988).

To compensate this loss rate, 50 km^3 of storage volume is added per year worldwide, with a replacement cost of approximately 13 billion dollars each year in 2003, or 18 billion dollars in 2015. (Palmieri et al. 2001)

A dependably expanding global population enhance this circumstance undoubtedly. Individuals rise, so does the fundamental for water limit, ignoring the contraction of overall storing volume (Juracek, 2014). A decrease in dam progression speed, combined with store sedimentation, resulted in a decrease in the overall net stock accumulation limit (Kondolf et al. 2014)

If the region allowed vaults putting away capacity decreases, the water need will eventually push toward the stock, causing a widespread water emergency (Annandale, 2020). Similarly, Tarbela reservoir supply in Pakistan captures an important volume of water from the Indus Stream. Its unique arranged storing volume was reduced by 20% over the first twenty years of development (Palmieri et al. 2001).

HEC-ResSim is a reservoir system simulation model that has been developed by the Hydrologic Engineering Center of the United States Army Corps of Engineers to help planners and engineers in predicting the behavior of reservoir systems in water management studies and to aid reservoir operator's releases practically during emergency conditions and day-to-day operations. The capabilities of HEC-ResSim version are; data storage, management capabilities, simulate reservoir operation, reporting and graphics facilities (Salient Features 2020).

The governing equation in HEC-ResSim is storage continuity equation. (User Manual, 2020)

$$St+1 = St + It - Rt - Et – Ot \qquad (1)$$

Where St is the storage at the start of a time period t, It is the reservoir inflow during the period t, Rt is the release required for the specified power generation for the period t, Et is the evaporation of a period t and Ot is the spillway release during the period t from the reservoir.

The HEC-ResSim model was developed for the Lancang Cascade to determine the influence of the cascade on the Lower Mekong River. The model was simplified model using preliminary data for the Chinese dams (Mckinney 2011).

In Ethopia, HEC-ResSim model was applied for Omo Gibe River basin to simulate cascade dams on the river and reservoir operations to optimize water for hydropower energy generation, and flood management. The new reservoir operation rule selected by modelling of cascade dams from HEC-ResSim model increases energy generation of the Omo Gibe River basin 28-45% (Seyoum and Theobald 2014).

HEC-ResSim was used to simulate reservoir releases and power generated from Mosul dam in Iraq (Baraa 2016). HEC-ResSim model was employed to Tucuruí Dam´s reservoir's daily observed data from 2001 to 2006 of pool elevation, inflow and outflow discharge (Lara et al. 2014).

HEC-ResSim software was to recreate and update water balance analysis of Kajakai reservoir in Afghanistan, performed by Water and Power Consultancy in 1979, half study of this research was based on extension of the hydroelectric station and half study was based to achieve information on possible reservoir operation alternatives for Kajakai reservoir. (HEC, 2007)

DATA COLLECTION

Selection of an appropriate data and its collection from the relevant sources is an essential part of a research work. For modelling of the Tarbela reservoir operations, the data has been collected mainly from NESPAK as shown in Table 1. The data includes storage capacities of reservoir at different elevations, time series flow data, time series power generation pattern, area-elevation capacity tables, rule curves, and evaporation data of the reservoir for different years.

TABLE 1. Tarbela dam and reservoir data collection

Data	Year	Source
Tarbela Reservoir Outflows and Power generation	2008,2010,2014 and 2020	TDP (NESPAK)
Tarbela Reservoir Area-Elevation-Capacity Tables, Rule Curves	2008,2010,2014 and 2020	hydrology and Survey TDP (NESPAK)
Tarbela Reservoir Levels	2008,2010,2014 and 2020	hydrology and Survey TDP (NESPAK)
Evaporation Data	2008,2010,2014 and 2020	SWHP (NESPAK)
Future Reservoir Capacities	2035	NESPAK

MODEL SETUP

Based on available data, the model setup in HEC-ResSim has been done by using its three modules as mentioned below:

1. Watershed Setup
2. Reservoir Network
3. Simulation Module

Watershed Setup module's main objective is to give a setup to create watershed. The watershed setup module includes all the streams, projects (reservoirs), time-series locations, impact areas, computation points and hydraulic and hydrologic data points for the watershed area. Tarbela reservoir watershed is related alignment of u/s and d/s streams of Indus River and the Tarbela reservoir in watershed as illustrated in Figure 2.

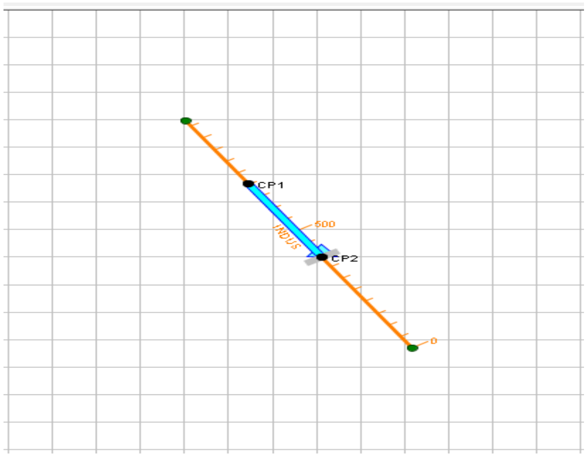

FIGURE 2. Watershed Setup for Tarbela Reservoir

Reservoir Network is the next step in the development of the model after the watershed set up. Reservoir Network is the most complicated module of the software. In Reservoir Network module, the river and reservoir schematic diagram show the operational elements and the physical parts of model. The base of Tarbela reservoir network has been developed using configurations that are developed in the watershed setup module. Then the river reaches and remaining network elements have been connected to accomplish the network scheme as shown in Figure 3.

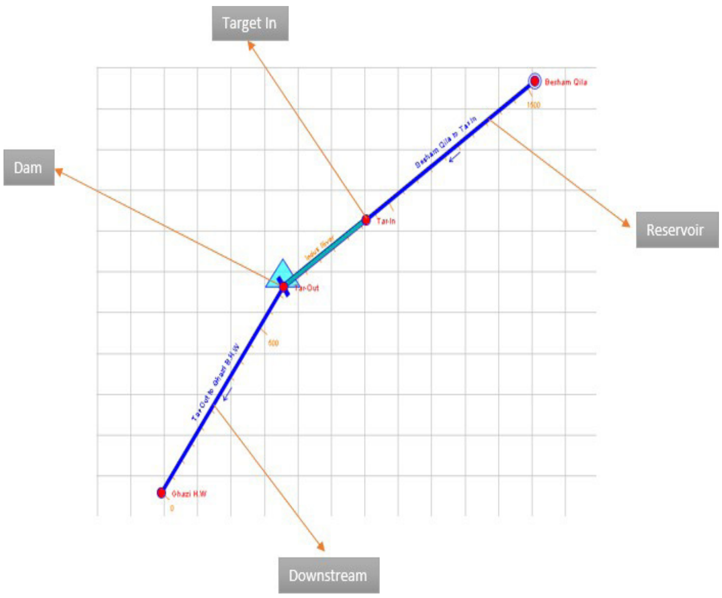

Figure 3. Reservoir Network for Tarbela Reservoir

Simulation module is used to separate the output results from the development of the model. After the completion of model, the simulation module was used to run the simulation.

MODEL CALIBRATION

Based on the Input data HEC-ResSim model was calibrated for the outflow and power generation for the year 2014 as shown in Figure 4 and 5. respectively. Observed and Simulated discharge for year 2014 almost remain the same throughout the year except a minor difference at almost mid of the year. The difference has been seen in the month of June and July which could be mainly due to some over simplification in data entry in the model i.e. the same value of seepage and evaporation throughout the year or may be due to some error in observed data provided by the relevant department.

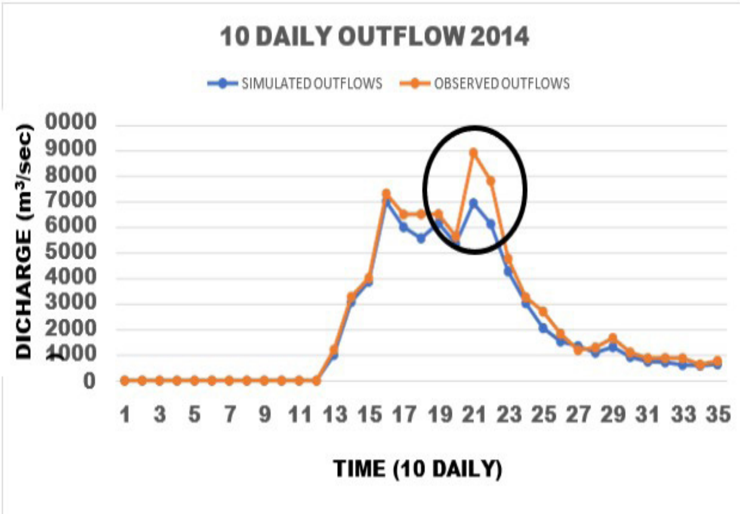

FIGURE 4. Comparison of Outflows for year 2014

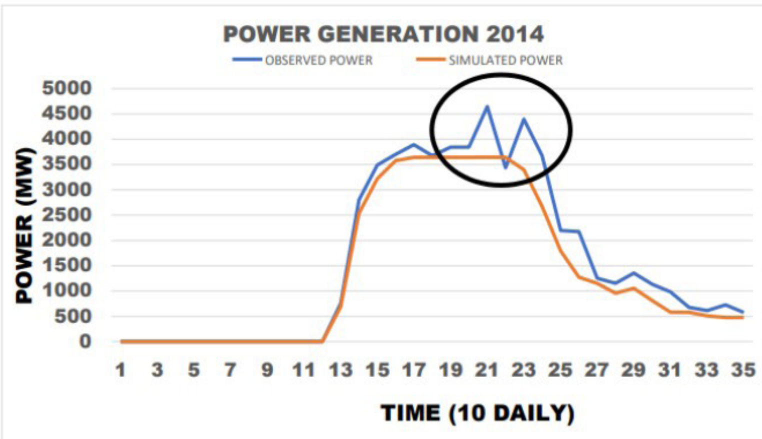

FIGURE 5. Comparison of Power Generation for year 2014

The observed and simulated values of power are very close to each other throughout the year except the mid of the year as shown in Figure 5, due to changes in the respective outflow values as mentioned earlier.

MODEL VALIDATION

The model was validated for the year 2020. The outflow and power results for the validation scenario have been shown in Figure 6 and 7 respectively. In this scenario, the observed and simulated discharges almost remain constant throughout the year and have a minor difference at the end of year.

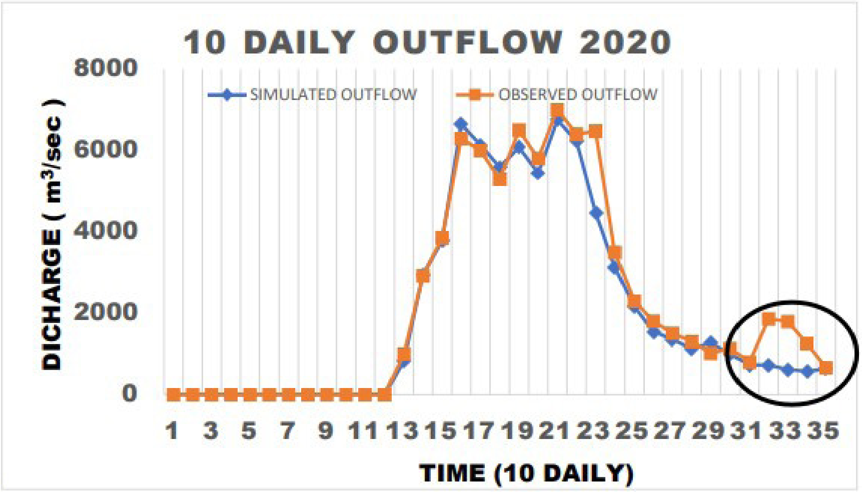

FIGURE 6. Comparison of Outflows for year 2020

The observed and simulated power also almost remain constant throughout the year except minor differences at the middle of year as shown in Figure 7.

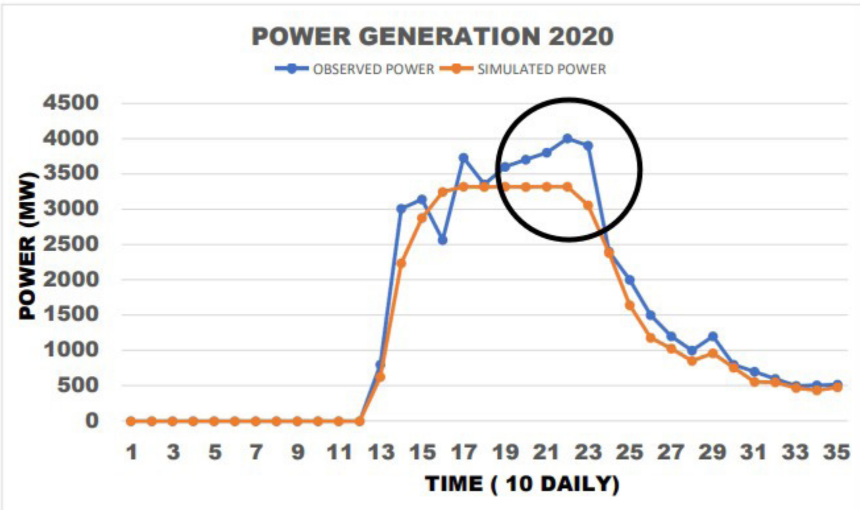

FIGURE 7. Comparison of Power Generation for year 2020

PROJECTED SCENARIO 2035

INFLOW HYDROGRAPH FOR 2035

The 30-years histogram cycle has been used for future prediction. Comparison of the inflow data of 1976 and 2005 has been done as shown in Figure 8 and the results show almost the similar trend. So, for future projection of year 2035, inflow hydrograph of year 2005 was used as input data.

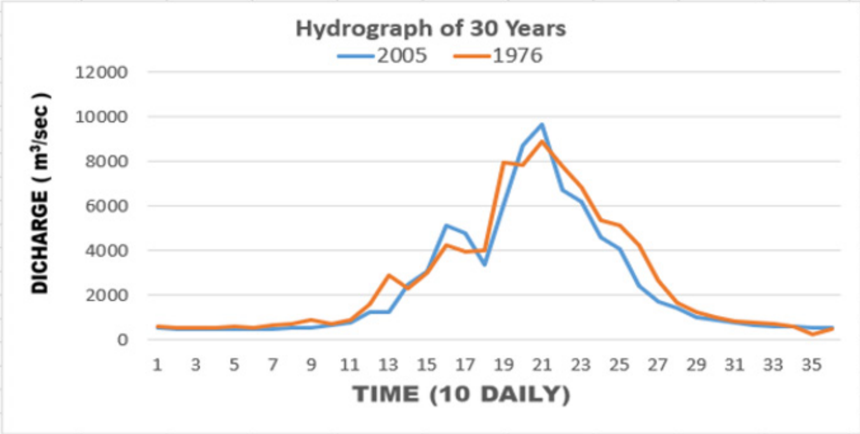

FIGURE 8. Comparison between Hydrographs of 1976 and 2005

FUTURE PREDICTION RESULTS

It has been observed that power available in the months of May, June, July and August is higher than other months of the year. This is because the releases in these months are higher and cannot be stored in the reservoir due to lost storage in year 2035 which lead to inflows equal to outflows as shown in Figure 9. Further maximum power is most likely to be available in the month of August and minimum power will be available in the month of January.

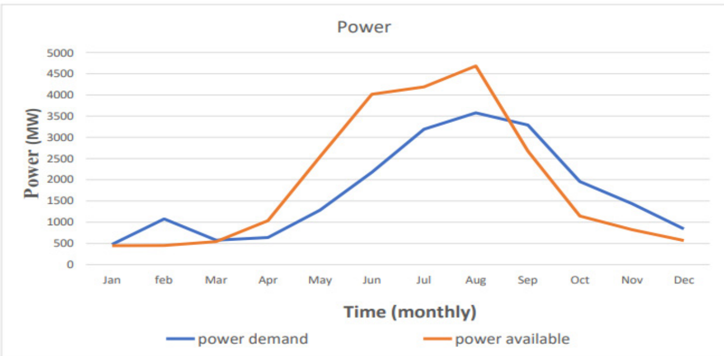

FIGURE 9. Comparison of power demand and power available (2035)

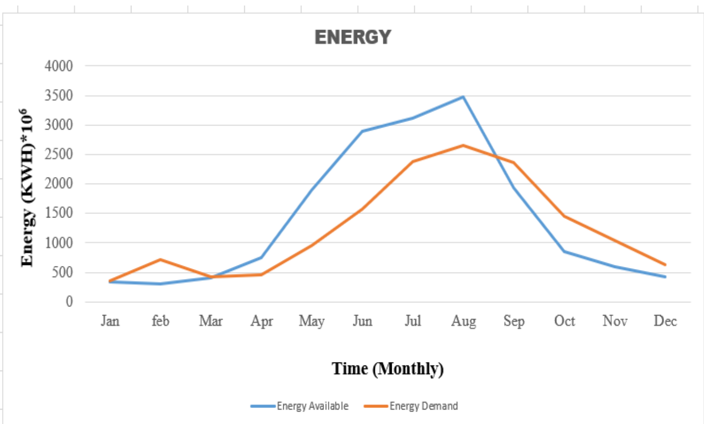

FIGURE 10. Comparison of Energy available and Demand of energy (2035)

From Figure 10, it is observed that energy available in the months of April, May, June, July and August is higher than other months of the year. This is because the releases in these months are higher and cannot be stored in the reservoir due to lost storage in year 2035 which leads to inflows equal to outflows.

Based on the comparison of the estimated values with the respective average base values of recent five years as given by Water Resource Division NESPAK, Lahore (Table 2), it is expected that after 2035, the project will become the runoff the river type and the outflows will increase in summer and decrease in winter by 7% and 50%, respectively and the energy generation will increase in summer and decrease in winter by 36% and 37%, respectively. The effect of reduction in gross storage capacity of Tarbela reservoir in future would result in reduction of annual energy generation by 6.5 %.

TABLE 2. Comparison of Outflow and Energy for 2035

Parameters	Season*	Predicted value (2035)	Average Base Value** (NESPAK)	% Change
Outflow/Releases (m^3/s)	Summer	19142.43	17890.12	7%
	Winter	3974.236	7947.944	-50%
Energy (KWh)	Summer	$14056.46*10^6$	$10310.63*10^6$	36%
	Winter	$2904.71*10^6$	$4617.03*10^6$	-37%
Annual Energy (KWh)	Per Annum	$16961.17*10^6$	$18146.55*10^6$	-6.5%

*Season includes 'Summer' from April to September and 'Winter' from October to March
** Average base value of recent five years given by NESPAK.

CONCLUSIONS AND SUGGESTIONS

Tarbela reservoir is an important part of Indus Basin Irrigation System and plays a vital role to fulfill the irrigation demands and energy demands of Pakistan. But due to continuous advancement rate and rise rate of the reservoir's sediment delta pivot point, the gross storage capacity of the reservoir is depleted day by day. In order to investigate the future operations of Tarbela reservoir, HEC-ResSim model was utilized.

The results of all flooding scenarios show almost the same pattern of values for observed and simulated 10-daily outflow and power. After 2035, Tarbela reservoir is expected to become the run-off the river type project due to decrease in the gross storage capacity. As per simulated results of the projected scenario (2035), the irrigation releases will increase in Summer and decrease in Winter by 7% and 50%, respectively and the energy generation will increase in summer season and decrease in winter season by 36% and 37 %, respectively. Further, the reduction in gross storage capacity due to sedimentation would result in reduction of annual energy generation by 6.5 % in year 2035.

It is suggested to utilize HEC-ResSim model to estimate the impact of reservoir storage capacity on future outflows, power and energy generation for other reservoirs in Pakistan as well as in other parts of the world.

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DECLARATION OF COMPETING INTEREST

None

REFERENCES

Annandale, G. 2020. Quenching the Thirst: Sustainable Water Supply and Climate Change. Create Space Independent Publishing Platform, North Charleston, SC.

Asif Choudhry and Habib-ur-Rehman. 2010. Worldwide experience of sediment flushing through reservoirs. *Journal of Mehran University of Engineering and Technology* 31(3): 395-408.

Baraa, E. Jebbo, A. and Taymoor, A. 2016. Simulation Model for Mosul Dam Reservoir using HEC-ResSim 3.0 Package. *Zanco Journal of Pure and Applied Sciences* 28: 92-98.

Deane, M.H. 2015. Energy Security in Asia –Himalayan Hydropower. M.Sc. Thesis, School of Environment and Life Sciences, University of Salford, Salford.

Hydrologic Engineering Centre. 2007. Water Balance and Regulation Alternative Analysis for Kajakai Reservoir using HEC-ResSim. US Army Corps of Engineers, Phase1 and II Final Report.

Huffaker, R. and Hotchkiss, R. 2006. Economic dynamics of reservoir sedimentation management: Optimal control with singularly perturbed equations of motion. *Journal of Economic Dynamics and Control*, 30(12), pp. 2553-2575.

ICOLD. 1988. World Register of Dams. International Commission on Large Dams, Paris, France.

Izhar-ul-Haq and S.Tanveer Abbas. 2007. Sedimentation of Tarbela and Mangla Reservoirs. Pakistan Engineering Congress, 70th Annual Session Proceedings, Lahore, pp.24-45.

Juracek, K. E. 2014. The Aging of America's Reservoirs: In-Reservoir and Downstream Physical Changes and Habitat Implications. *Journal of the American Water Resources Association*, 51(1), pp. 168-184.

Kondolf, G. M. et al. 2014. Sustainable sediment management in reservoirs and regulated rivers: Experiences from five continents. Earth's Future. 2(5), pp. 256–280.

Lara, P.G., Lopes, J.D., Bonuma, N.B. 2014. Reservoir Operation Employing HEC- ResSim: Case Study of Tucurui Dam, Brazil. 6th International Conference on Flood Management, Sao Paulo, Brazil.

McKinney, D.C. HEC ResSim Model of Lancang Cascade Dams. 2011, pp. 1–9. Available online: https://www.google.com.hk/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwjMwafv_8f5AhW2RmwGHZhNBasQFnoECAMQAQ&url=https%3A%2F%2Fn-h-i.org%2Fwp-content%2Fuploads%2F2017%2F02%2FMcKinney__HEC_ResSim_Model_of_Lancang_Cascade_Dams.pdf&usg=AOvVaw1bCDfwZxOXtpocc0GeAmzR (last accessed on 29 October 2023).

Palmieri, A., F. Shah and A. Dinar. 2001. Economics of Reservoir Sedimentation and Sustainable Management of Dams. *Journal of Environmental Management*, Vol. 61, No. 2, Feb 2001, pp. 149-163.

Salient Features of HEC-ResSim, Reservoir System Simulation, US Army Corps of Engineers: (http://www.hec.usace.army.mil/software/hec ResSim / features.aspx), 2020.

Seyoum, T. and Theobald, S. 2014. Modeling of Cascade Dams and Reservoirs Operation for Hydropower Energy Generation" ICHE Hamburg 2014.

User Manual HEC-ResSim, Hydrologic Engineering Centre - Reservoir System Simulation Version 3.1, 2020.

WAPDA.2014. Recommendations for Sustainable Sediment Management: Tarbela Reservoir, Pakistan. Report published by WAPDA, Lahore, Pakistan.

WCD. 2000. Tarbela Dam and Related Aspects of the Indus River Basin Pakistan. World Commission on Dams, Final Report, Islamabad, Pakistan.