Sustainable reservoir management through sediment flushing: A case study of Betan Karnali hydroelectric project, Nepal

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1. ABSTRACT:

Sediment deposition decreases the life of a reservoir and has adversely affected the sustainability of many projects in the world. Along with reducing the benefits obtained from the project, it can also have adverse long-term socio-economic impacts. Betan Karnali Hydroelectric Project is designed as a PRoR project located in the western region of Nepal. It is geologically located in the Himalayan region, a region with high sediment inflow (about 19.5 Million Ton/ year). Various sediment management alternatives are being studied for this project. This paper presents the sediment management of BKHEP reservoir by passing the sediment through the dam body via hydraulic flushing with 1D HEC RAS 5.04 model. The result shows that the reservoir which would have otherwise filled with sediment in 10 years is sustainable even at the end of 47 years if hydraulic flushing with an average of 8.7 flush days per year and 1800 m^3/sec flushing discharge is introduced.

Key word: *Sedimentation, Hydraulic Model (HEC-RAS), Reservoir Operation*

2. INTRODUCTION:

Sedimentation is one of the major hurdles for reservoir sustainability. It causes loss of reservoir capacity which affects the functionality of the system, especially for hydropower plants (Javed 2016).The declining storage reduces and eventually eliminates the capacity for flow regulation and with it all water supply and flood control benefits, plus those hydropower, navigation, recreation and environmental benefits that depend on releases from storage (Morris & Fan, 2010).

It is natural for a reservoir to continue accumulating sediments as it ages and with it there is increase in the sediment related problems. Reservoir sediment management is essential for ensuring life of the reservoir by protecting the storage capacity and decreasing the long-term maintenance cost (Annandale, Morris & Karki, 2016). The twentieth century focused on the construction of new dams but because of the lack of proper knowledge of the rate of sediment deposition in the reservoir and the importance of proper sediment management, controlled reservoir capacity reduction was not achieved and as a result reservoirs worldwide are losing storage capacity as fast as 1 % per year. As it is not feasible to build new dams to replace the reservoir volume and also not possible to sustain the projected levels of population and economic activity if the storage reservoirs are lost to sedimentation, the 21st Century is focused on combating sedimentation to extend the life of existing infrastructures (Morris & Fan, 2010)

If the land areas of the world are ranked according to their susceptibility to natural erosion, the Himalayas will rank among the most vulnerable (Tejwani 1987). The sediment inflow rate is even higher in the Himalayan region because of the fragile and complex geology, tectonic activities and climate. In this region, the sediment concentration is relatively much higher in the monsoon compared with the dry period. Landslides and mass wasting which are common during the monsoon area also plays a major role in it. Because of the complex nature of sediment concentration and deposition pattern, sediment management techniques vary widely from one site to another and the suitable management technique can only be developed after studying and analyzing the specific site

The most common methods of sediment management are sediment routing and removal of sediment deposition. Sediment routing includes any method to manipulate reservoir hydraulics, geometry or both to pass sediment through or around storage or intake areas while minimizing objectionable depositions. Sediment routing commonly includes methods like drawdown sluicing and sediment by-passing (Morris & Fan, 2010).

Removal of sediment deposition as the name suggests includes periodic removal of the sediments that have been deposited in the reservoir either through mechanized efforts or natural methods. The commonly used methods of sediment removal include flushing and dredging. Because of the narrow size of the reservoir and its ability to be refilled quickly when the outlets are closed, sediment flushing has been proposed and used as a method of sediment management for this project.

Sediment flushing through reservoir may be the most economic strategy as compared to other techniques. Atkinson presented a report on the flushing efficiencies of some of the successfully flushed reservoir and the criteria for estimating the flushing efficiency (Atkinson, 1996). Flushing is generally of two categories, free flow flushing, and pressure flushing. Free flow flushing is more efficient compared to pressure flushing (Morris & Fan, 2010). Free flow flushing has been used for this study. Different flushing rules can exist for any project depending upon the inflowing sediment data and tradeoff between maximizing the generated energy and compromise of reservoir storage capacity. Any flushing rules generated during the study, however, must be optimized based on the data monitored during the operational period of the project (Morris & Fan, 2010).

3. STUDY AREA:

The Karnali River is a perennial trans-boundary river in the Western part of Nepal originating in the Tibetan Plateau near lake Mansarovar. It cuts through the Himalayas in Nepal and eventually joins the Ganges. The Betan Karnali Hydro Electric Project is located along the lower limb of the Karnali River, in the mountainous region of Achham/Surkhet District.

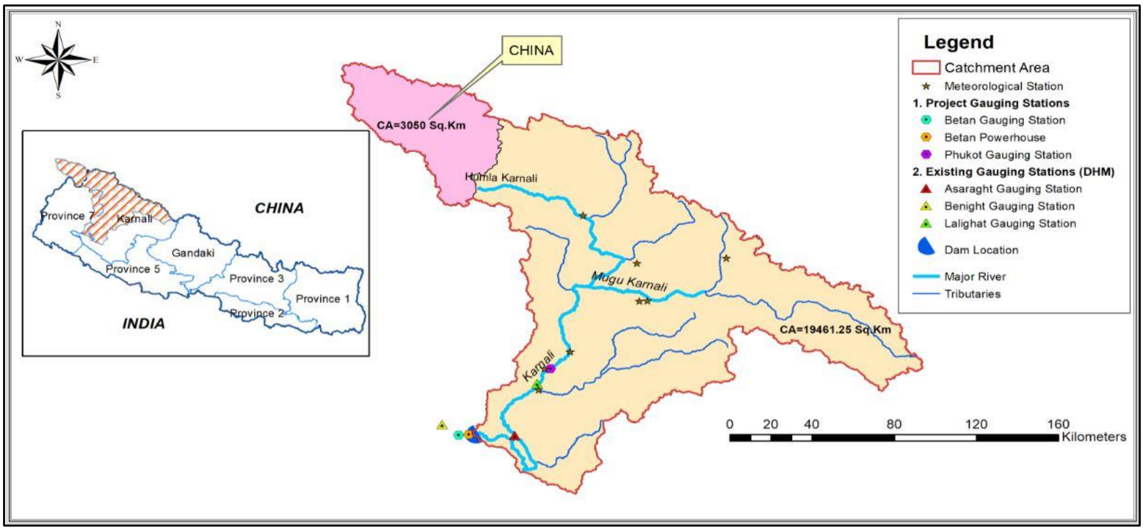

Figure 1. Catchment area of BKHEP

The project site is near Betan, within Chaukunne rural Municipality of Surkhet District. The project boundary lies between 28˚50'57" and 28˚56'04" North and between 81˚11'43" to 81˚24'42" East. The project headworks has a catchment area of 22,511.25 km^2, out of which 3050 km^2 falls in China. More than half (52 %) of the BKHEP catchment lies in between 3000m to 5,000m elevation. The zone below 3000 m is the zone of predominant monsoon rainfall (or rain-fed zone). The 5000m elevation corresponds to the limit of perennial snow and ice accumulation area.

Table 1. Characteristics of Betan-Karnali catchment

S. N	Features	Unit	BKHEP Catchment
1	Catchment area (A)	km^2	22,511.25
2	Area below 3,000 m	km^2	5691.65
3	Area between 3,000 to 5,000 m	km^2	11,735.76
4	Area above 5,000 m	km^2	5083.84
5	Longest flow path (L)	km	449.38
6	Maximum elevation (Z_{max})	masl	7678.00
7	Minimum elevation (Z_{min})	masl	402.00
8	Mean elevation (Z_{mean})	masl	3883.82

4. CHARACTERISTICS OF THE PROJECT:

Betan Karnali Hydroelectric Project (BKHEP) is a peaking run of river (PRoR) scheme project on the Karnali river with 4 to 6 hours daily peaking depending on the inflowing discharge. BKHEP is designed with a dam height of 80 m (from riverbed level.) with crest level at 477 masl and having length of about 198 m. The reservoir has a total storage of about 161.5 MCM and active storage of 36.19 MCM. The full supply level (FSL) of the project has been proposed at 473.30 masl and the minimum drawdown level (MDDL) of 466 masl has been provide. It is designed with a design discharge of 536 m^3/s and gross head of about 100 m producing 442 MW.

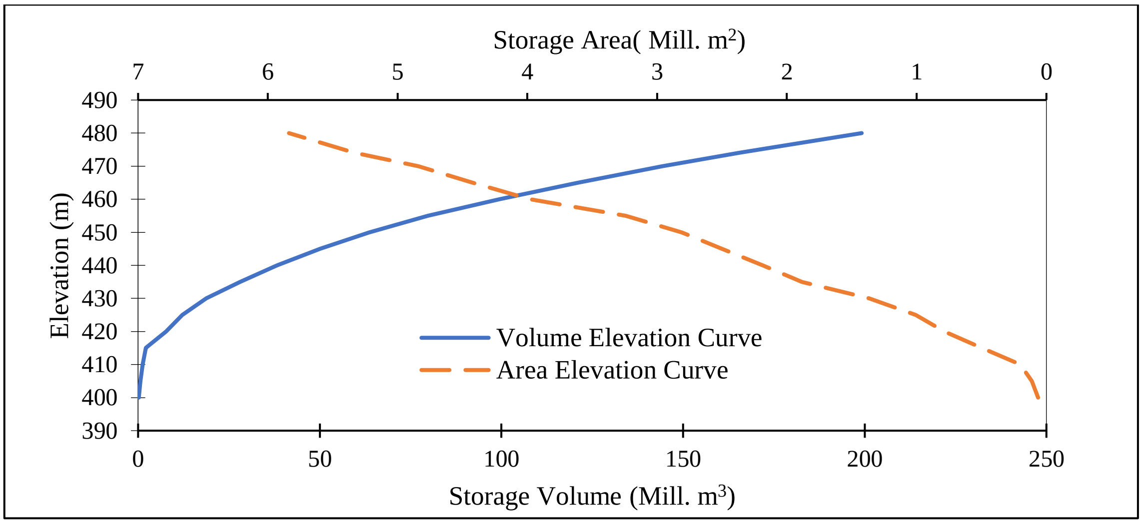

Figure 2. Reservoir storage elevation curve

It produces a total average annual energy of about 2320.42 GWh with an average annual dry season energy production of about 659.33 GWh and an average annual wet season energy of about 1624.09 GWh. The project area is estimated to have a flood of 8530 m^3/s, 11,548 m^3/s, 14,560 m^3/s and 22,604 m^3/s for a return period of 100, 1000 and 10000 years respectively. The Probable Maximum Flood (PMF) for the project has been estimated as 22604 m^3/sec

The RCC dam is provided with 6 overflow spillway of size 10 m X 12 m (B x H) for water level regulation, 1 overflow spillway of size 8 m x 8m (B x H) for floating trash passage and 6 sluice spillway of size 8 m X8 m for sediment flushing. Combinedly, the spillways have been designed to safely evacuate the probable maximum flood estimated for the project.

5. HYDROLOGICAL AND SEDIMENT DATA:

There are three hydrological stations set up and operated by the Department of Hydrology and Meteorology (DHM), Nepal in the river reach relevant to the project area which have been presented below:

Table 2 Details of hydrological stations operated by DHM

Name	Watershed Area (Km^2)	Northing	Easting	River Elevation (m)	Years of Data	Quality of Data
Lalighat	16,960	29°9’32”	80°33’23”	590	1977-2006	Fair
Asaraghat	20,860	28°57’10”	81 °26’30”	629	1966-2012	Good
Benighat	22,664	28 °57’10”	81 °07’10”	320	1963-2015	Fair

Moreover, the consultants have established both manual and automatic gauge station near headworks of BKHEP project and has been collecting stage, discharge and sediment data since May 2018. Based on the manual gauge measurement of discharge at the project location, rating curves for stage below and above 5 m have been prepared. The rating curves developed for BKHEP are:

$$Q = 72.7 * (H - 1.542)^{1.615} \quad (\, for\ stage\ below\ 5.00\ m) \tag{1}$$

And

$$Q = (H/0.259)^{2.132} \quad (\, for\ stage\ below\ 5.00\ m) \tag{2}$$

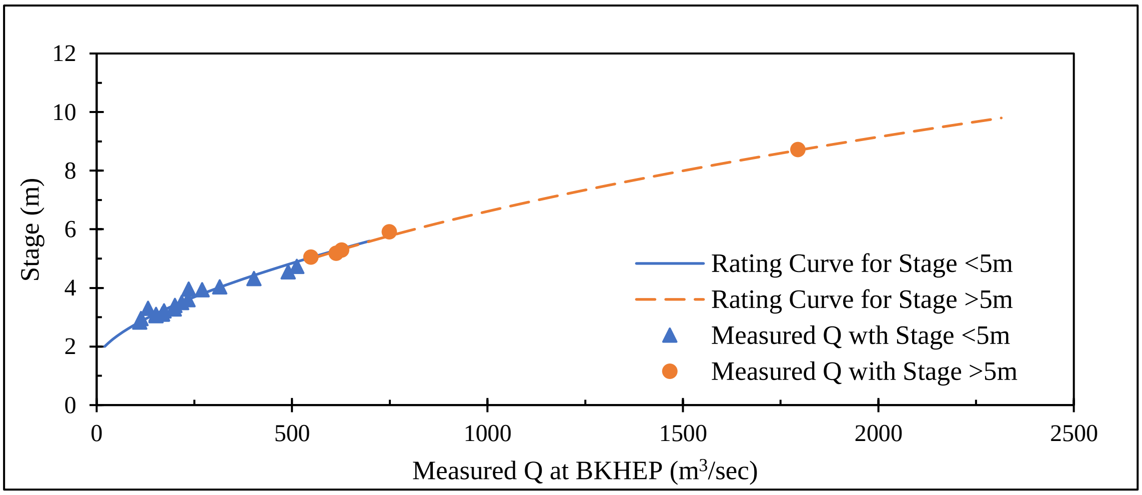

Figure 3. Stage discharge variation in BKHEP

Except Asaragaht other gauging stations have discharge data only. As there is only two years of measured data at the BKHEP headworks and since Asaraghat is close to BKHEP headworks, discharge from Asaraghat has been used to generate the long-term hydrological data set at BKHEP required for sediment modeling.

6. SEDIMENT CHARACTERISTIC AND LOAD ESTIMATION:

Till date 44 Particle Size Distribution (PSD) measurements at different time periods of the year have been carried out and its results are shown in Figure 4. The sand predominately comprises of quartz contributing to about 60 % of the total mineral composition, followed by mica and feldspar. The heavy red dot line as seen in Figure 4 corresponds to the PSD of the inflowing sediment used for modeling. There are two reasons for selecting the curve with higher sand contribution: (1) suspended sediment load is measured from a trail bridge located at the site and there exist high chance that the sand transported at the bed of the river gets under sampled the sand concentration is underrepresented and (2) a higher sand load represents a more critical condition for modeling.

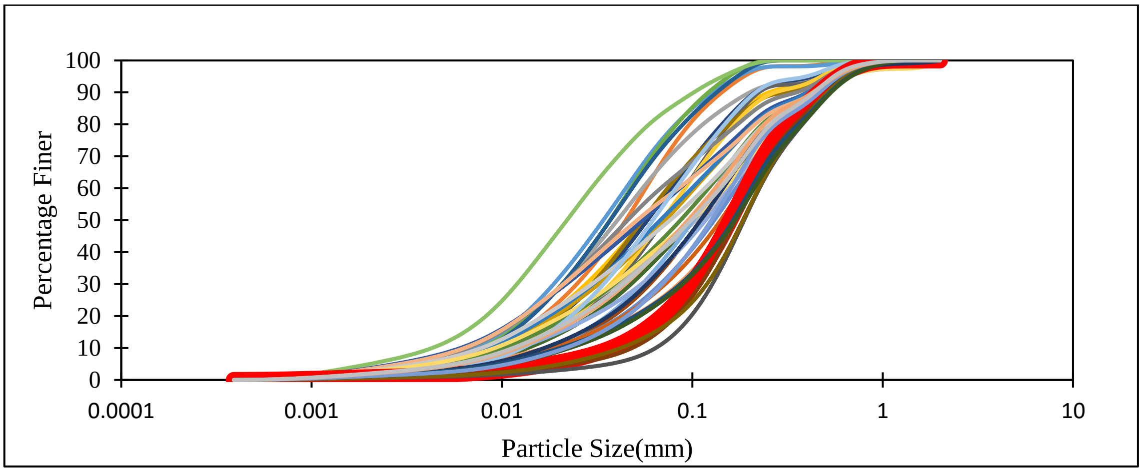

Figure 4. PSD variation observed in BKHEP headwork

The consultant is also designing another project (Phukot Karnali Hydroelectric Project (PKHEP) on the upstream reach of Karnali. Based on the discharge derived at Headworks of BKHEP and PKHEP and their corresponding concentrations monitored at the site, a rating equation for estimating the sediment was developed for the project. Long term discharge data prorated at BKHEP headworks using Asaraghat gauging station was used to estimate the total sediment load for the Project. The suspended sediment load estimated at the headwork of the project is 15.5 MT and the total average annual sediment load is estimated as 19.5 MT. Variation of sediment concertation with discharge observed at site in relation to the Asaraghat gauging station is shown in Figure 5

Sediment rating equation used for BKHEP:

$$C = 0.0033\, Q^{1.78} \text{ (Suspended Sediment)} \tag{3}$$

$$C = 1.25 * 0.0033 * Q^{1.78} \text{ (Total Sediment)} \tag{4}$$

$$\text{Sediment Load (Tones/ Day)} = 0.000288 * Q^{2.78} \tag{5}$$

Where, C= Concentration of the sediment for corresponding discharge and Q = Daily discharge (m^3/sec)

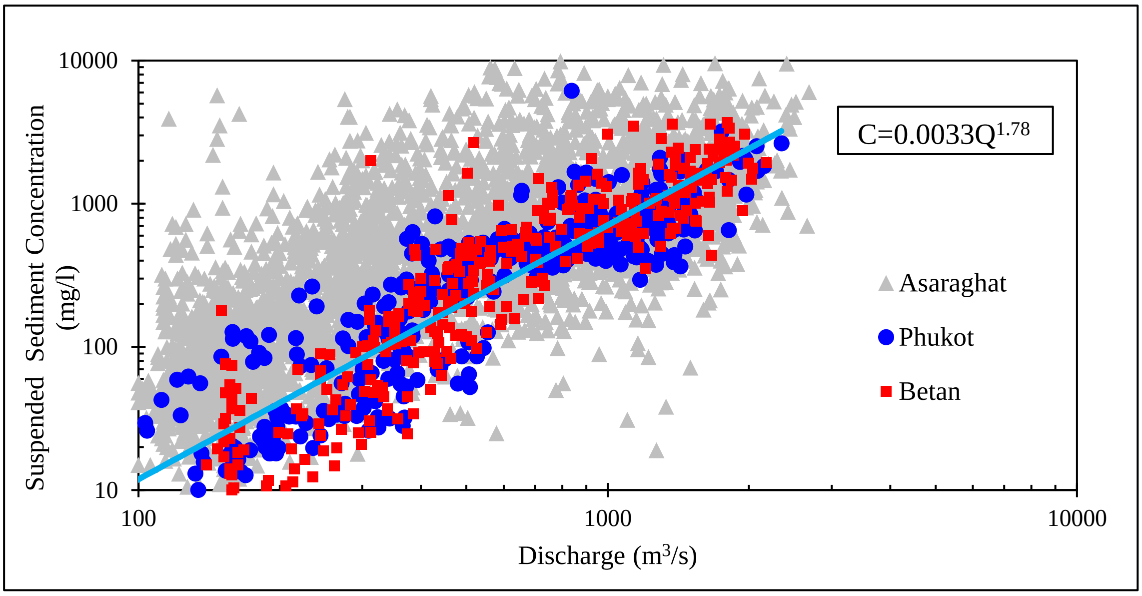

Figure 5. Concentration variation observed at PKHEP, BKHEP and historical data of various discharges

There are no bed load measurements carried out at the project site. The bed materials are very coarse and flow velocity is very high making it impractical to measure the bed load by conventional method. Hence to address the unmeasured bed load (primarily sand and gravels) bed load correction factor of 25% has been added to compute the total load for the modeling purpose.

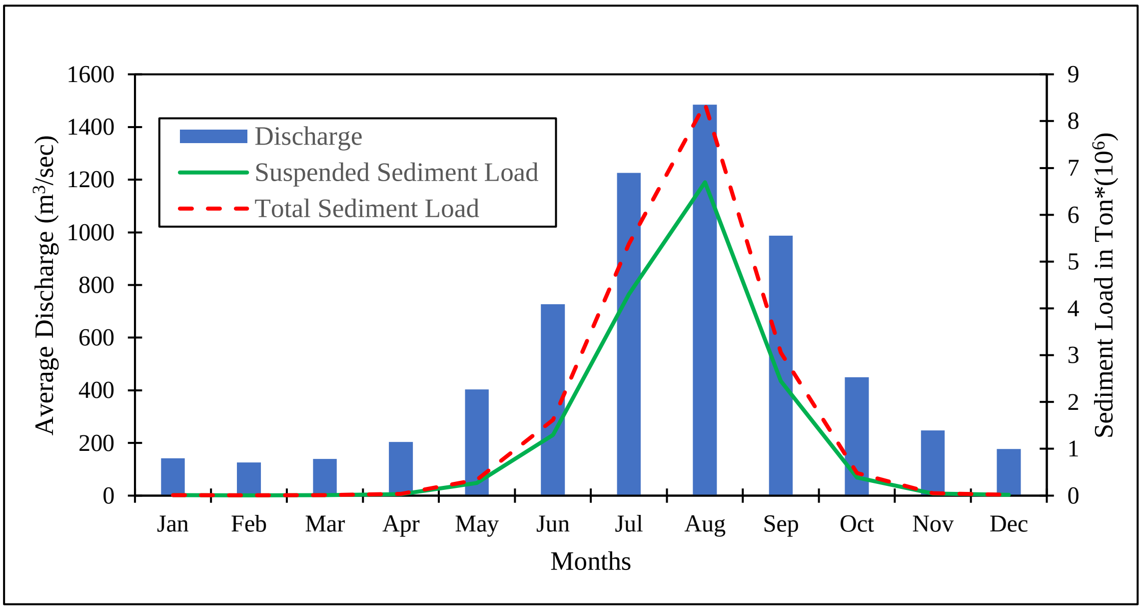

Figure 6 : Average monthly discharge and sediment load variation at BKHEP headworks

7. 1-DIMENSIONAL MODEL HEC RAS:

7.1. Description

In this study 1-D HEC-RAS Model developed by US Army Corps of Engineers at Hydrological Engineering Centre (HEC) was used to simulate the sediment deposition in the reservoir. It has the capability to model steady and unsteady flow for variety of hydraulic cases and simulate mobile bed sediment transport phenomenon (Iqbal, 2018). Stabilizing the model with unsteady flow regime is very painstaking, and hence, sediment transport has been simulated using quasi steady flow regime.

A Quasi-Unsteady approach assumes constant hydrodynamic properties over the duration of a given flow. Quasi-Unsteady Flow Model divides the time into three-time steps: Flow Duration, Computational Time Step and Bed Mixing Time Step. Computational Increment is the hydraulic and sediment transport time steps which is further divided into Bed Mixing time step where the bed gradation and bed layers are updated. Several sediment transport methods (functions) have been implemented in HEC RAS to compute transport potential which includes: Ackers and White(1973), Englund-Hansen (1967), Laursen (1958), Myer-Peter-Muller (1948), Toffaleti (1968), and Yang (1972). The bed material and load are divided into 20 grain classes with the material in each grain class approximated with the diameter midpoint of the division.

Transport potential is calculated for each grain size at each cross section as if the sediment load were comprised 100% of that material. Transport capacity for each grain size class is then computed as the product of the transport potential and the fraction of that material in the active layer. The total sediment capacity is the weighted average of the transport potentials computed for each grain size in proportion to the relative abundance of each grain size in the active bed.

Once transport capacity is computed, the sediment continuity equation is solved over each control volume. A control volume is represented as the distance from the midpoint between the upstream cross section and the current one, to the midpoint between the downstream cross section and the current section. Continuity principal is applied for each grain size as the capacity is compared to the inflowing supply. If transport capacity exceeds supply, material is removed from the control volume, while deposition results if supply is greater. This is quantified by the Exner (sediment continuity) equation. (HEC, 2016)

$$\left(1-\lambda_p\right)B\frac{\partial n}{\partial t}=-\frac{\partial Qs}{\partial x}$$

Where n is the bed elevation, B is the width of the control volume, Qs is transported sediment load, λ_p is bed porosity, x is a distance, t is the time.

7.2. Geometry and parameters

A geometric model comprising of 50 sections spaced at 500 m spacing (750 m max) was prepared for a total length of 25.25 km with 22.75 km located upstream of the dam. The geometric file comprises of information about the cross sections, hydraulic structures, riverbank stations and other physical attributes of the river. The manning's roughness coefficient is one of the most sensitive parameters for the model and has been set to 0.03 and 0.035 to the channel and bank respectively.

7.3. Boundary conditions and transport function

Like any other hydraulic model HEC-RAS requires boundary conditions to simulate the sediment transport phenomenon. Four boundary conditions are provided for modeling purposes. Daily flow hydrograph and sediment rating curve have been used as the upstream flow boundary condition. Similarly, timewise stage relationship considering flushing were developed as the internal boundary condition at the dam location and normal depth was used as the downstream boundary condition.

Sediment transport capacity and after flush profiles were estimated using different transport functions and compared. Out of various transport functions available, Engelund and Hansen transport function along with Ruby Fall Velocity Method with Copeland (Exner 7) sorting method was found to best represent the transport capabilities for BKHEP. As the contribution of sand sized particles is dominant in BKHEP and Engelund and Hansen is a total load transport function best suited for relatively uniform particles ranging from 0.19mm to 0.93 mm, it has been used for the reservoir sediment modelling.

8. FLUSHING CONSIDERATIONS:

In BKHEP, discharge ranging from 1000 -2000 m^3/sec contributes to almost 75% of the average annual sediment inflowing into the reservoir as shown in Figure 7. Considering inflowing discharge-sediment contribution, this paper presents one of the possible scenarios in BKHEP with 3-day flush duration (flushing discharge 1800 m^3/sec) and minimal flush interval of 21 days. To avoid the excessive sediment inflow and deposition into the reservoir, force flush is activated at 2400 m^3/sec. To ensure evacuation of the deposited sediments by the end of monsoon, a force flush on 15th September for 3-days duration has been set each year. With all these considerations, this study has used average 8.7 days flush per year.

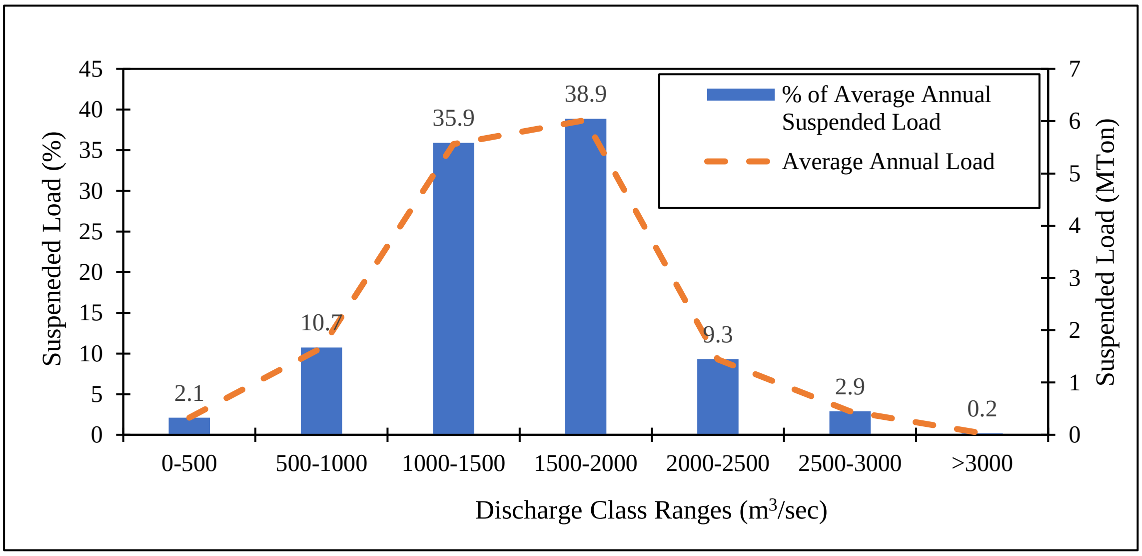

Figure 7. Contribution of discharge to inflowing sediment in BKHEP

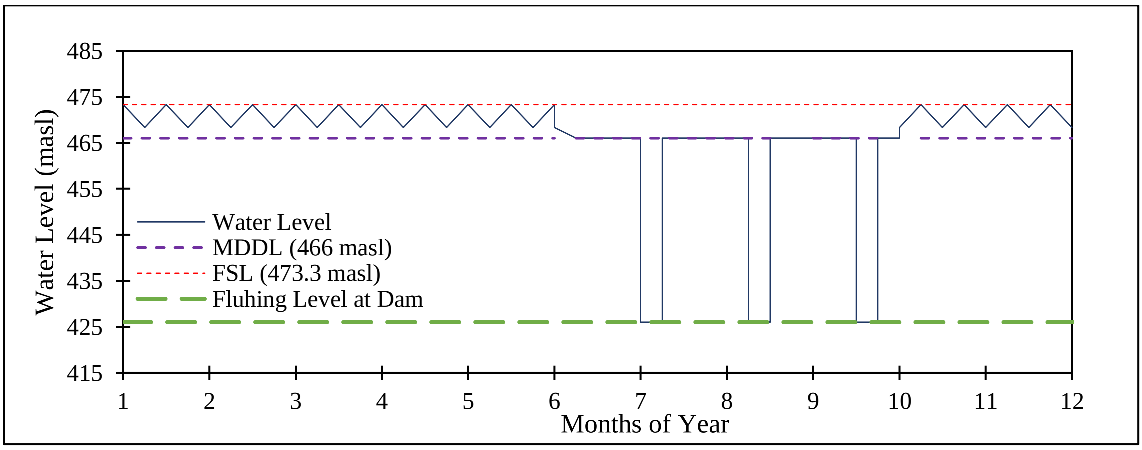

Figure 8. Conceptual diagram for reservoir operation in BKHEP

Two water levels have been fixed for year-round operation at BKHEP. During Dry season, water level is fixed to FSL (473.3masl) while during the monsoon it is dropped to MDDL (466 masl) to avoid the sediment deposition and loss of live storage volume of the reservoir. The conceptual variation of water level is presented in Figure 8. Water levels during the flushing durations has been computed based of the discharging capacities of the 6 Sluice Spillways.

9. METHODOLOGY:

Sediment modeling needs various data sets namely, geometry data, flow data, sediment load, flushing detailing and water levels, bed gradation and sediment concentrations and detailing of inline structures etc.

To begin with, available data set for discharge and sediment was collected and analyzed to prepare the discharge and sediment rating curves and estimate the total load. Geometric file of the reach under consideration was prepared and physical attributes of the inline structures and reservoir were provided to the HEC-RAS Model. Boundary conditions were set based on the available data and the model was run under different transport function and sorting and armoring conditions to get the satisfactory result. Figure 9 shows the sequential methodological approach adopted for the study.

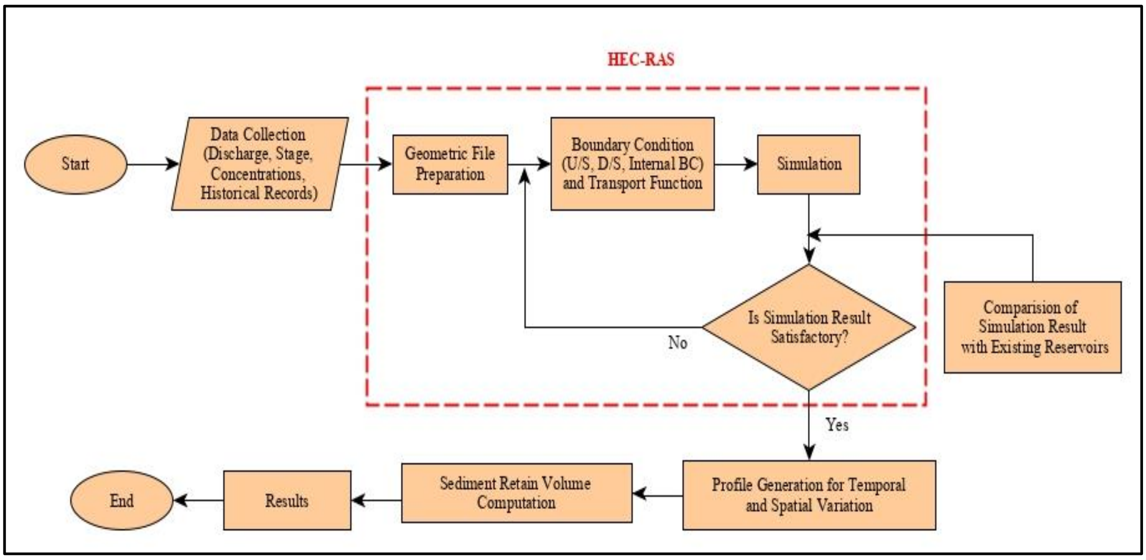

Figure 9. Methodological framework

10. MODEL CALIBRATION AND VALIDATION:

As the project is in study phase, there is no data for the proposed reservoir that can be used for calibration. In absence of the calibrating data, two different procedures have been used for model validation to check model behavior for reasonableness of the results. The first validation procedure was to simulate the existing river profile in HEC-RAS. The profiles of the Himalayan rivers are continuously influenced by the input of materials from landslide and debris flow, but the reach under study does not have recent perturbations of this type and may be relatively stable with respect to its longitudinal profile. The model was run for the river in normal scenario and inflowing load of the coarse bed material was adjusted until the riverbed stabilized, neither aggrading nor degrading to an appreciable degree.

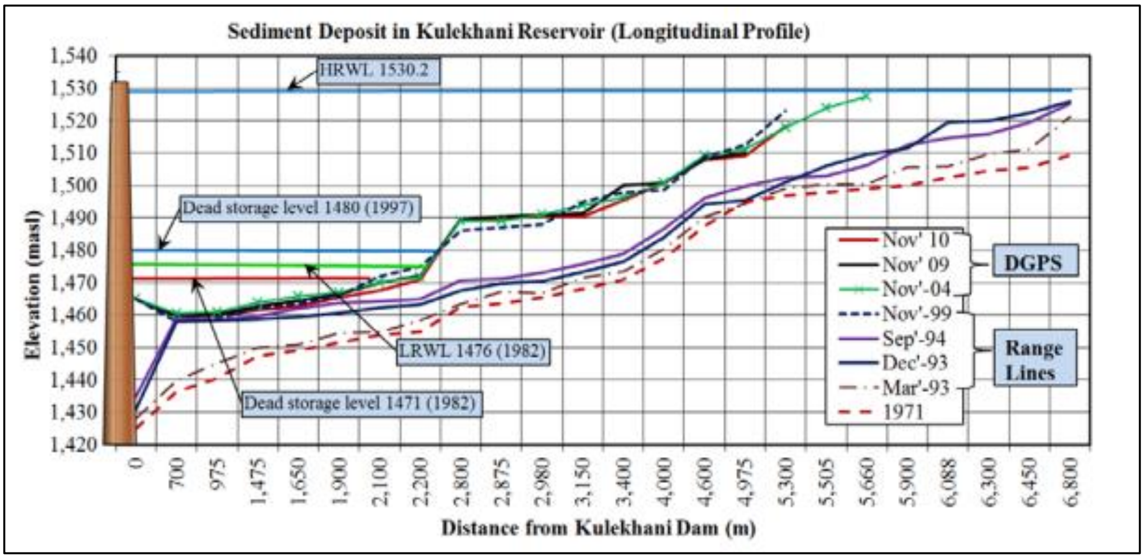

Figure 10. Longitudinal profiles for Kulekhani reservoir (Shrestha 2012)

The second validation procedure was to confirm that the overall geometry of the delta developed within the reservoir during the simulation is similar to the pattern observed in other reservoirs subject to extensive annual drawdown (flushing). Reservoir sedimentation data of Kulekhani-I (60 MW), one and only reservoir type project of Nepal, was referred to see the resemblance of sedimentation considering temporal and spatial sediment deposition pattern. (Shrestha, 2012)

11. RESULTS:

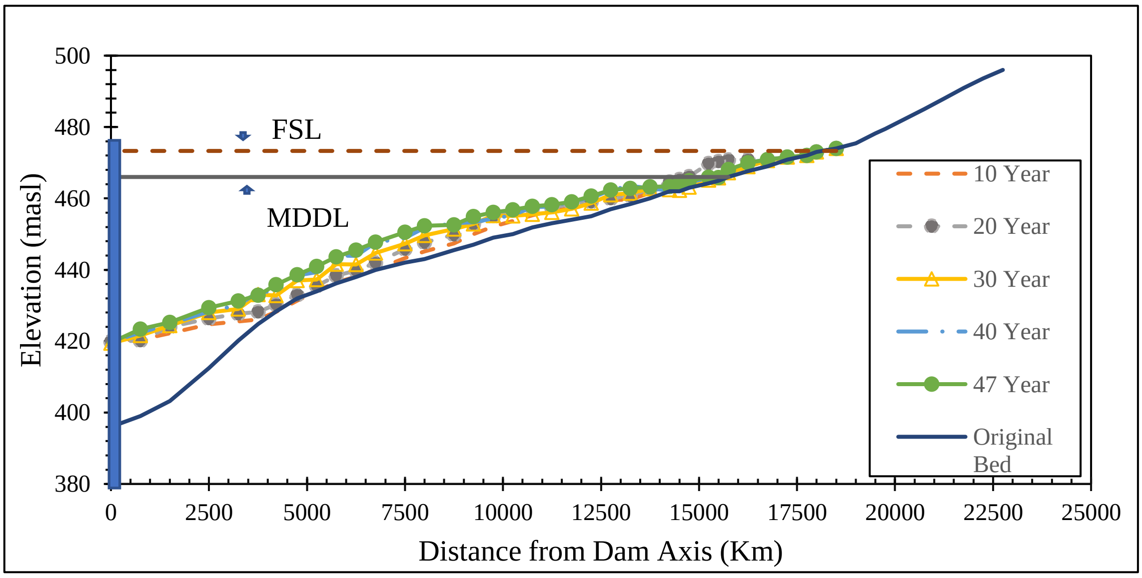

Figure 11. Evolution of sediment bed profile over simulation years

Simulations were run for a total duration of 47 (1966-2012) years to observe the sediment accumulation and effectiveness of the flushing operation with 6 sluice spillways of 8m x 8m provided at an invert of 418 masl. Evolution of the bed profile over the simulation period (decadal basis) is shown in Figure 11. Most of the sediment gets accumulated at the beginning of the reservoir and tends to propagate toward the dam but with the flushing event the delta gets eroded and flushed. Simulation results showed that, with the flushing strategy adopted, the live storage capacity of the reservoir is retained even at the end of the simulation period (47 year). Moreover, the dead storage capacity of the reservoir only gets reduced by 15% at the end of the simulation ensuring the adequacy of the existing sediment flushing arrangements and strategy adopted.

12. CONCLUSION:

There might be various strategies and operational rules for sediment management in any project. This study considers sediment management through the reservoir using only sluice spillways with 8.7 days of annual drawdown. It is seen that under the flushing consideration made for this case study in BKHEP, the size and number of sluice spillway allocated to the project is adequate to retain the live storage volume even at the end of simulation period. However, in absence of the calibrating data for this numerical simulation, physical modeling must be carried out to support and validate the simulation results. During operation phase the sediment deposition must be monitored regularly to optimize the reservoir flushing. Bathymetric survey is recommended each year before and after sediment flushing to determine the changes in the geometry of sediment deposits over time.

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