Proceedings of 11th IOE Graduate Conference
Peer Reviewed
ISSN: 2350-8914 (Online), 2350-8906 (Print)
Year: 2022 Month: March Volume: 11

Reservoir Sustainability and Sediment Management - Case Study: Kimathanka Arun Hydroelectric Project, Shankhuwasabha, Nepal

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Abstract
Sediment deposition decreases the storage capacity of a reservoir and affects many project's economy and sustainability. Kimathanka Arun Hydroelectric is proposed as PRoR project located in the north-east part of Nepal. It is located in the Himalayan region with inflow, which has high sediment concentration, coming entirely from Tibet. This study presents sediment management of KAHEP reservoir by passing the sediment through the dam body via hydraulic flushing with 1-D HEC-RAS model. Simulation of 25 years gave an average flushing days of 7.6 days per year. Regular flushing was done at a flood of 800 m3/s whereas force flushing was triggered at 1000 m3/s. The simulation, using the flushing model, showed furthur increase in flushing days has little impact in sediment deposition.

Keywords
Sediment deposition, Sediment flushing, HEC-RAS, Reservoir Sustainability

1. Introduction

The Himalayan Rivers provide a great potential for hydroelectricity generation because of its perennial rivers originating from the glaciers and the steep gradient. Due to the steep topography, fragile geology and high rainfall intensity, large volume of sediment is transported in these rivers. As much as 2,000 to 6,000 ppm (parts per million), in average values, suspended sediment concentration in Jhimruk river during peak monsoon, was observed while the upper values ranged somewhere from 20,000 to 60,000 ppm [1].

The sediment load causes different kinds of problems: abrasion of turbine leading to its low life expectancy; reduction in efficiency of turbine; decrease in total as well as live storage of reservoir. The Kaligandaki A and the Middle Marsyangdi reservoirs have lost 51% and 65% of their total volume, respectively [2]. The author also found that the total losses within the live storage capacity are in the range of 6.7% and 14.1% of the total live storage capacity, respectively. Sediment quantity largely depends upon the catchment: topography, geology, anthropogenic activities, etc. However, sediment continuity is disrupted by dams, and among them run-of-river plants (RoR) play a crucial role because they significantly alter river morpho dynamics. Similarly, the width of the reservoir and the height of the weir also have a significant effect in the time required to reach equilibrium conditions [3]. A comprehensive study, therefore, is needed to know the short- and long-term effect of sediment in a project that can inform effective functioning of the flushing system. Computer models have been long used for sediment analysis as they are cheap and easy to run than physical models. They are can narrow down to the specifics where physical model ought to be focusing thereby reducing overall cost. There is various software for sediment analysis: HEC-RAS, Flow3D, Delft3D, etc. but for our study we need only one dimensional (1D) analysis for which HEC-RAS would be best suited.

Sediment management is an emerging topic and the hydropower generation is affected by this phenomenon: one of the major issue faced by the sector. The life of reservoir is depleting because of sediment as the storage is continuously being occupied by sediment. Flood carry huge amount of sediment which have to be routed through the dam. During the routing of sediment, usually the power house has to be shut down. The number of days the power house has to be shut down need to be enumerated beforehand so that the project can manage those outages. Also, the strategy of management of sediment in the reservoir needs to be formulated. H. Shrestha used RESCON to review sustainability of Kulekhani reservoir, which is a storage type reservoir in the Himalayan region, snd he learned flushing and hydrosuction sedient removal system sediment management options seemed feasible in the reservoir [2].

The major objective of the study is to, therefore, devise a flushing strategy so that the reservoir bed in KAHEP reaches equilibrium in 12 to 15 years. To achieve our major objective, following specific objective are set:

- To work out average no. of days per year for flushing in a 25 years simulation
- To find out no. of consecutive days for which reservoir has to be continuously flushed.
- To find out minimum interval days between regular flushing.

Sediment volume balance is the major concern of the current study; the mechanism of flushing and sediment deposition pattern are out of the scope of the current study and it is assumed that the designed mechanism will flush the sediment in the vicinity of headworks. Study related to sediment management in various reservoir have been carried out using one-dimensional models in the past. Stanford Gibson and Paul Boyd used HEC-RAS 1-D model for long term alternatives for sustainable sediment management using operational sediment transport rules [4]. Paul Boyd and Stanford Gibson used 1D sediment models to reservoir flushing studies, measuring, monitoring and modeling the spencer Dam with HEC-RAS [5].

2. Study Area

For this study, Kimathanka Arun river, originating from Tibet is selected. The project is located in the upper reaches of Arun Valley in Sankhuwasabha district as shown in figure 1. It is the northernmost Project proposed along the Arun river in Nepal. The selected project is in a river known for high sediment laden flow.

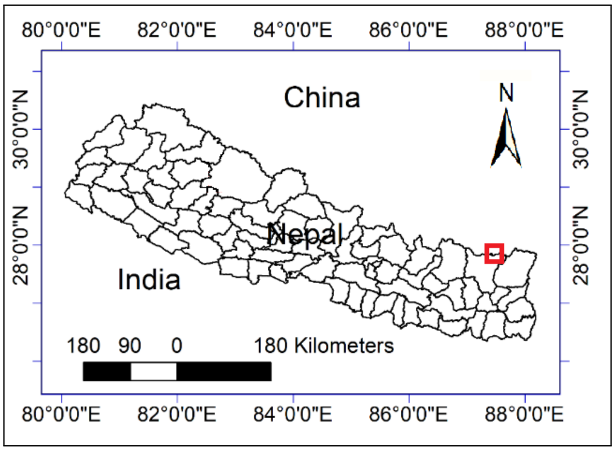

Figure 1: Location of Kimathanka Arun HEP Project

The catchment area, approximately 24,835.58 sq. km., of the project lies almost entirely in Tibet, China—as shown in figure 2. The slope of the river is categorized as steep. The headworks of the project is located roughly 1.5 km south of Nepal-China border. The project features a concrete gravity dam, underground settling basin and a 4.4 km long headrace tunnel.

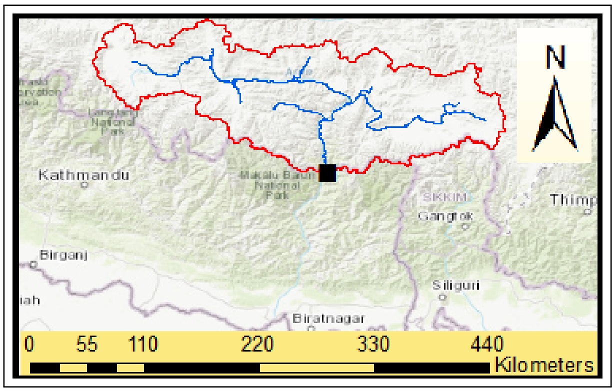

Figure 2: Catchment and Dam location of Project

3. Methodology

3.1 Data collection

Topographical data measured daily discharge data long term estimated flow series and measured sediment was obtained from NEA Engineering and climatic data was obtained from Department of Hydrology and Meteorology. The discharge rating curve and sediment rating curve were developed.

$$C = 0.2635xQ^{1.3993}$$

Where, C= Concentration of the sediment for corresponding discharge, Q = Daily discharge

3.2 Load Estimation

Only suspended load measurement is done at the project site but bed load is not measured. The bedding material is very coarse and the flow velocity is very high which makes it impractical to measure the load of the bed by traditional method. Therefore, 20 percent is added to the suspended load to calculate the total load for modeling purposes. The load taken for the simulation is shown in the figure 3.

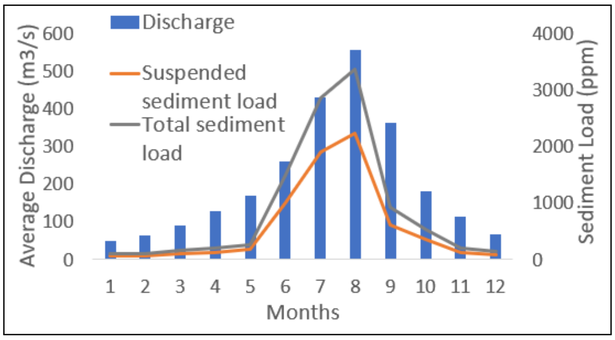

Figure 3: Average monthly discharge and sediment variation

3.3 Calibration of manning's n

The calibration of manning's coefficient was performed by comparing the rating curve obtained from observed data and the rating curves computed form HEC-RAS based on different manning's coefficient. The manning's value used to compute rating curves ranged from 0.020 to 0.040, and among them the manning's coefficient which gave closest resembling rating curve to the observed data was chosen as our required value. The procedure for calibration of manning's value is given in figure 4.

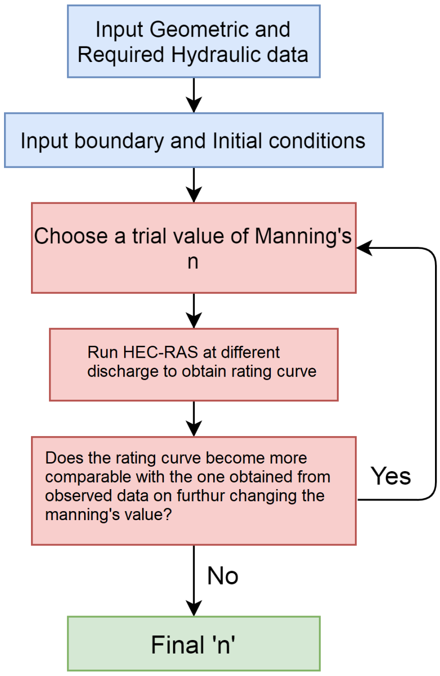

Figure 4: Manning's n calibration flow chart

3.4 Hydraulics and Sediment Modelling

Reservoir sustainability and management is carried out by periodic bathymetric survey and implementation of suitable strategies. For future planning and management tools such as HEC-RAS are implemented. It has capabilities of both 1D and 2D sediment modelling, for estimation of sediment passing through river, however, 1D model is sufficient. It takes in inputs such as cross section data of required reach, sediment data of the river, discharge data for simulating the sediment transport model and hydraulic model of river reach.

For reservoir sediment transport model, a stage time series is introduced in the river reach just upstream of dam which acts as a dam that impounds water. The sediment transport equation is then computed in the new scenario where the water level is at the required operating level of the dam. In the current model a 5 km reach is taken-approximately 1.8 km downstream of the dam and remaining in the upstream. Cross-section geometry data are taken at approximately 250 m intervals. Approximate boundary conditions were given at both upstream and downstream of the reach. The discharge data are given as time series data.

A Quasi-Unsteady approach is taken for sediment transport model for its stability over Unsteady approach. A Quasi-Unsteady approach assumes constant hydrodynamic properties over a given duration of flow. It divides time into three steps: Flow duration, Computational time step–hydraulic and sediment transport time step– and Bed mixing time step—bed gradation and bed layers are updated. An Unsteady model is usually painstaking to stabilize [6] and the accuracy obtained from quasi-steady is comparable to unsteady.

There are various sediment transport equations to choose from in HEC-RAS, and each computes transport capacity of the river and sediment continuity equation is solved over the control volume. Each grain size class is computed differently for transport capacity and compared with inflowing supply. If transport capacity exceeds supply of the river, then material is removed accordingly form the control

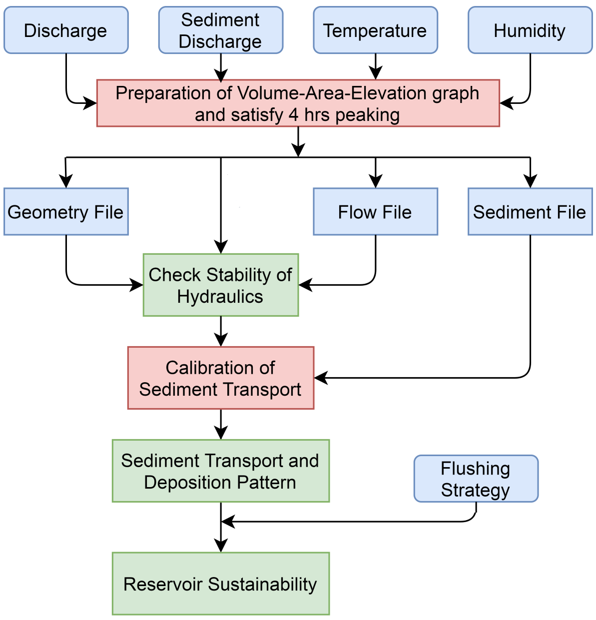

Figure 5: Methodological flow chart

volume, and vice versa for less supply. Exner equation is the default method for calculating the sediment continuity. Long term flow data, sediment rating curve and normal depth was given as boundary condition in the upstream; internal stage was given as boundary condition at the upstream of dam as a way of regulating flow; normal depth was given as boundary condition at the downstream. The internal stage time series also acted as our flush mechanism. The Yang's equation for sediment transport worked well among the different equation available in HEC-RAS for the given river reach. Ruby Fall velocity method along with Thomas (Ex5) sorting method worked will with the given river reach. The contribution of sand particles being abundant in this river and Yang's equation is suited for a variety of conditions and was developed and tested over a variety of flume and field data.

3.5 Model Validation

The project is under design phase, data for validation such as bathymetry survey are not available. For validation of our study, the main governing factor of our study, the sediment equation has been validated by manually calculating the sediment transport capacity based on the discharge of the river and comparing it with the actual measured sediment concentration. The reasonableness of the results is then confirmed by the similarity in observed and calculated. A total of 303 days' worth of discharge and sediment concentration data was available. The sediment transport capacity was calculated by discharge data and temperature data of the region and was checked against the observed sediment concentration. The Nash-efficiency calculated between the two values was found to be 0.56.

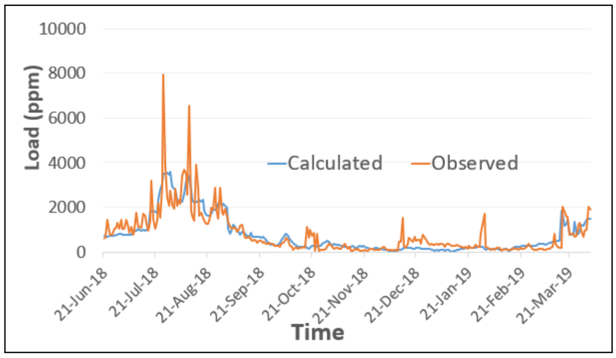

Figure 6: Estimated vs. Observed discharge sediment discharge

3.6 Flushing Consideration

After establishment of the reasonableness of our model, it can be tested on a variety of field situations that may arise in the future, namely the inflow of sediment and performance of the reservoir. Simulation of the reservoir where the sediment collects in the reservoir without any outlet is the first which outlines the lifespan of the reservoir without flushing. Thereafter, we can apply various flushing strategy and find the optimum way to keep the reservoir sustainable. In KAHEP, discharge ranging from 600-1300 m^3/s contributes to the majority of the annual sediment inflowing in the reservoir. Considering the discharge contribution of inflow of sediment in the reservoir, this paper presents a possible scenario of a 3-day flushing with a flushing discharge of 1000 m^3/s and a flushing interval of minimum 20 days. A force flushing case is also recommended at the end of September for evacuation of all the sediment collected in the monsoon season. The conceptual diagram for a flushing model is given in the figure 7 .

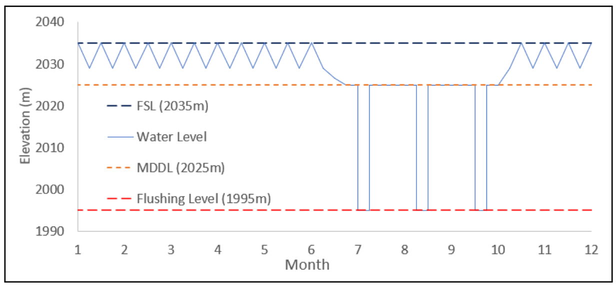

Figure 7: Conceptual Diagram of Flushing Strategy

4. Result and Discussion

Firstly, the hydraulic properties of the channel were studied; manning's coefficient for the channel was calibrated using the discharge versus gauge height data.The channel data comprised of 14 cross sections taken roughly at 250 m interval. Various rating curves were computed in HEC-RAS using different values of manning's coefficient, and the rating curve resembling closest to the curve obtained from observed data was chosen to give our required value of manning's coefficient. The manning's value that gave the rating curve resembling to that given by observed value was found to be 0.032.

After the hydraulic parameters of the channel was checked, sediment analysis was carried out. For sediment analysis, transport equation that is representative of the process of sediment transport in the river was to be selected. Yang's equation was chosen as it performs well in a wide variety of channel and it was validated based on its calculated transport capacity and the actual observed sediment concentration with Nash-efficiency of 0.56. The river channel was also run for a period of 10 years' simulation and the bed invert level and cross section did not change very much and was observed to be stable. This justified the use the various parameters used in the model and also for use of the model for further study.

The sediment deposition pattern without any flushing is as shown in figure 8. The model was run on a data synthetic history data from 1985 to 2010 A.D. (25 years) prepared by extrapolating from discharge relationship to other stations. As shown in the figure, a delta was formed in upstream and it progressed towards the dam while depleting the storage capacity of the dam.

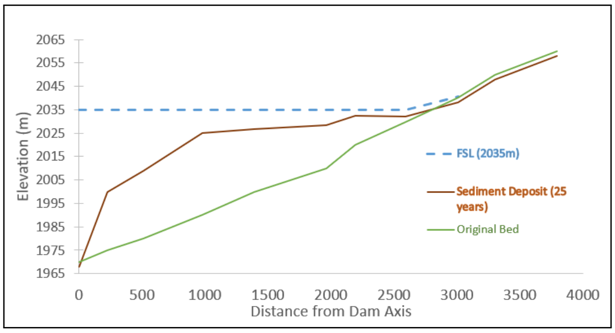

Figure 8: Original and simulated bed level

The sediment flushing was done using 3 radial gates each 6.5m x 9.0m. The invert level, MDDL and full supply level (FSL) are respectively 2040m, 2025m and 2035m. For the simulation under the strategy-I, no flushing was considered for the dry season—October through February—and flushing is done when the discharge is greater than 1000 m^3/s. In this case no significant difference is seen from the sediment deposition pattern. So, this strategy was not effective the flushing. The bed profile under the strategy-I is as shown in the figure 9.

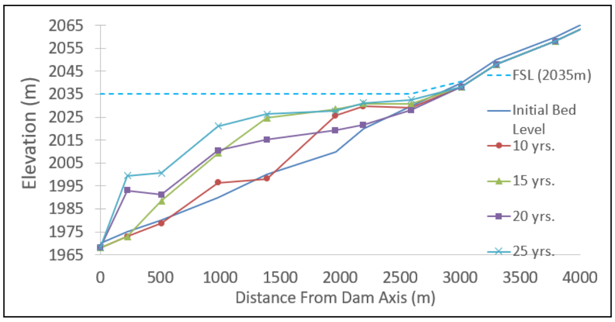

Figure 9: Sediment bed profile over simulated year (Strategy-I)

For the simulation under the strategy-II, no flushing was considered for the dry season and flushing is done when the discharge is greater than 1000 m^3/s, and 15th September of every month. No significant change to the first strategy is seen in this strategy of flushing. At the end of 22 years, complete dead storage was filled and more of the live storage was also filled. So, this strategy was also not efficient for the sustainability of the reservoirs. The bed profile under the strategy-II is as shown in the figure 10.

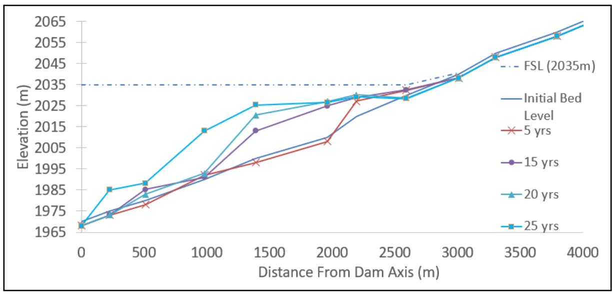

Figure 10: Sediment bed profile over simulated year (Strategy-II)

For the simulation under the strategy-III, no flushing was considered for the dry season, flushing was done when the discharge is greater than 1000 m^3/s, every 15th September of every year and after every 3 weeks of flushing. In this strategy, more of the live storage was retained but not significant. So, this strategy also cannot be adopted for the reservoirs. So, another strategy was studied. The bed profile under the strategy-III is as shown in the figure 11.

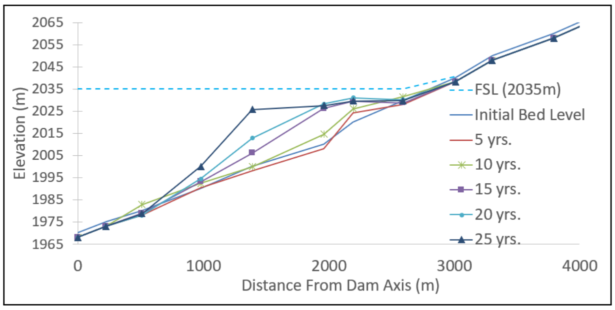

Figure 11: Sediment bed profile over simulated year (Strategy-III)

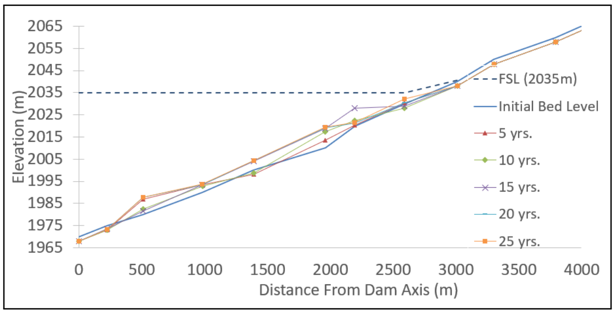

Figure 12: Sediment bed profile over simulated year (Strategy-IV)

In this strategy, there was no flushing during dry season, flushing was triggered at the end of month September and also at flood of 800 m^3/s. There was minimum 20 days interval between these flushing. In case of a flood greater than 1000 m^3/s, flushing was triggered regardless of the flushing triggered in past 20 days. Flushing occurred for 3 consecutive days once triggered. This strategy generated a bed profile as shown in figure 12. The bed profile at the beginning of simulation rose just at the upstream of the reservoir pool due to the formation of delta, where the coarser particle settles down due to reduced velocity and decrease of carrying capacity of the river. The delta slowly progressed towards the dam due to the volume of the sediment deposited. Due to flushing the reservoir did not fill rapidly albeit steadily. During first 10 to 12 years, the rate of filling of reservoir was higher but in later years the rate significantly decreased. Figure 12 shows the different plots of profiles throughout the 25 years simulation. From the figure it is seen that the year 2005 and 2010 have very negligible rise in bed. This was the goal this study originally strived for. The bed is said to be in state of equilibrium and the reservoir can be dubbed as a sustainable reservoir.

Sediment accumulated at the upstream of the reservoir gets flushed out once the sluice gate is opened. From the simulation result we can find that the live storage of the reservoir is retained for 25 years and the reservoir is sustained. Moreover, the dead storage also is not filled completely at the end of the simulation. Various flushing strategy and reservoir operation rules were studied in the simulation. Flushing from the three under sluice gates of each opening 6.5m x 9.0m for three continuous days with a peak discharge of 1005 m^3/s resulted an average of 7.6 days per year of flushing in 25-year simulation period. More days of flushing than that does not improve the results by much.

References

[1] Meg B Bishwakarma. Concept Paper for a Research on Optimum Sediment Handling in Run-Of-River Hydropower Plants. In *International Conference on Small Hydropower - Hydro Sri Lanka*, pages 1–9, 2007.

[2] Hari Shankar Shrestha. Sedimentation and sediment handling in himalayan reservoirs. (July):2015, 2014.

[3] Christine Sindelar, Johannes Schobesberger, and Helmut Habersack. Effects of weir height and reservoir widening on sediment continuity at run-of-river hydropower plants in gravel bed rivers. *Geomorphology*, 291:106–115, aug 2017.

[4] S. A. Gibson and P. Boyd. Modeling long term alternatives for sustainable sediment management using operational sediment transport rules. *Reservoir Sedimentation - Special Session on Reservoir Sedimentation of the 7th International Conference on Fluvial Hydraulics, RIVER FLOW 2014*, pages 229–236, 2014.

[5] Paul Boyd and Stanford Gibson. Applying 1D Sediment Models to Reservoir Flushing Studies : Measuring , Monitoring , and Modeling the Spencer Dam Sediment Flush with HEC-RAS. (July):1–12, 2016.

[6] Gary W. Brunner and CEIWR-HEC. HEC-RAS River Analysis System: User Manual 1D and 2D Version 5.0. *US Army Corps of Engineers*, (February):1–790, 2016.