SEDIMENT HANDLING OPTIMIZATION FOR A HIMALayan RUN-OF-RIVER SCHEME

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ABSTRACT

The Vishnugad Pipalkoti Hydro-Electric Project (VPHEP) is a run-of-river-project planned to be located on the Alaknanda River in the western Himalayas. The Alaknanda River carries a high sediment load primarily consisting of quartz which has a high potential for eroding the hydro-mechanical parts of the project. In this paper a simple approach to optimizing the sediment handling of the scheme is presented. This approach is based on an economical balance of capital costs, maintenance costs and revenue loss due to the anticipated downtime in connection with repair work and the loss of storage and thus ability to store water from off-peak to peak hours. Mathematical modeling and desk studies have been used to estimate the costs and revenues.

1. INTRODUCTION

1.1 Hydropower Development in the Himalayas

Fueled by an impressive economical growth and the need for improving the living conditions for a large part of the population the electricity demand in India is increasing rapidly. India is gifted with a high hydropower potential primarily in the Himalayas. However, less than 25% of the hydropower has been developed, so this is one of the potential sources for meeting the growing energy needs of the country. The Government of India has, therefore, accelerated the hydropower development and the development of many projects has been entrusted to both private and (semi-) public organizations.

One of the big challenges in developing the hydropower potential in the Himalayas is management of sediment. Most rivers rising in the high Himalayas has excessive silt in the river water particularly in the rainy season from June to October. The silt primarily consists of quartz which is a “hard” sediment with Mohr hardness of 7. This silt – if not removed - will cause heavy erosion of the turbine blades and other steel structure in the waterways of run-of-rivers hydropower projects.

An illustrative example is the Nathpa Jhakri Hydro Electric Project, which is a run-of-river scheme on the Satluj River in the western Himalayas in India. In spite of the construction of one of the largest desilting chambers in the world both runners and guide vanes were significantly eroded after less than 2000 hours of operation as shown in Figure 1 (after Sharma, 2006). In this case the solutions to the wear problems were relocating of the intake, applying hard coating to essential hydro-mechanical parts and closing down during periods with excessive high sediment load.

1.2 The Vishnugad Pipalkoti Hydro-Electric Project

The planned Vishnugad Pipalkoti Hydro-Electric Project (VPHEP) is also located in the western Himalayas on the Alaknanda River, which is a tributary of the River Ganga. VPHEP is a run-of-river project developed by Tehri Hydro Development Corporation Ltd with an installed capacity of 444 MW. The live storage capacity of the reservoir is 2.47 Mm³ from full reservoir level at 1267 meter above sea level (masl) to minimum draw down level at 1252.5 masl. In accordance with the preliminary design, the water will be diverted through a power intake, three desilting chambers, and a 13.4 km long head race tunnel to the power house near the village of Pipalkoti. The underground power house will have four Generating Units off 111MW each operating at rated net head of 212.46 m. Maximum discharge through each unit will be 57.22 m³/sec. Tentatively, generating unit speed is proposed to be 250 rpm.
The general preliminary layout is shown in Figure 2. The most striking features are the huge desilting chambers downstream of the power intake which will be excavated in the right bank of the river. The desilting chambers are preliminarily designed to remove (90%) sediments of size 0.2 mm and above. With a length of 350 m the cost of the desilting basin is a significant part of the costs for the entire project.
The catchment of the Alaknanda River at the proposed site for the VPHEP has an area of 4,672 km² which can be divided into two zones; the greater Himalayas which are snow fed and the lesser Himalayas which are normally rain fed. The climate is tropical monsoon type with most of the rainfall occurring in the summer period from June to October. The annual rainfall in the Alaknanda Basin is reported to vary from more than 1,200 mm to 200 mm. The mean annual rainfall at Joshimath located immediately upstream the proposed site for VPHEP is about 1,160 mm. At the higher elevations the snow accumulates from the beginning of November and starts melting from April / May. This snow melt contributes substantially to the river flows. The flow in the Alaknanda River is strongly seasonal with the river starting to rise in April-May and culminating in July at the peak of the monsoon.

Silt data were available from two locations, viz. Lambagarh with a catchment area of 1,275 km² (about 25% of the area of VPHEP) and Rudraprayag a catchment area of 10,675 km² (twice the area of VPHEP) – the later only monthly values but for an extended period of time. The data from the two stations appeared to be consistent and yield approximately the same sediment load per km². The silt data from Rudraprayag were provided for three different size fractions, viz. fine (less than 75 μm), medium and coarse (greater than 200 μm). The sediment data and a rating curve (best fit line) based on the Rudraprayag data are shown in Figure 3.

Sediment rating curves were established for each of the size fractions (fine, medium and coarse sediments) measured at Rudraprayag. A “mean” hydrograph based on long-term observations of discharges were provided and used to derive time series of concentration of the different size fractions as shown in Figure 4. The annual transport of the three fractions can be integrated to 2.0, 1.6 and 0.5 mill m³ for the fine, medium and coarse fractions, respectively. The annual total transport is thus 4.1 mill m³ corresponding to a sediment yield of (about) 0.9 mm/km²/year, which is quite similar to results from other Himalayan basins (see e.g. Singh et al, 2003).
1.3 Approach

The optimization of the sediment handling was based on an economical balance of capital costs for construction of desilting chambers and coating of hydro-mechanical against, revenue loss due to downtime in connection with anticipated repair work, and revenue loss caused by reservoir sedimentation (storage loss) and the corresponding ability to store water from off-peak to peak hour generation as well as down-time during sediment flushing operation.

The basic idea in the optimization is to “follow the sediment” from it enters the reservoir, where part of it will settle and the remaining continue through the intake to the desilting chambers where further settling will take place before the remaining sediment reaches the powerhouse. The amount of sediment settling in the reservoir and in the desilting chambers is associated with a cost/revenue loss and the sediment making its way to the powerhouse has a cost in terms of required repair. A “closed system” that can be optimized is thus established.

The cost and revenue estimates necessary for optimization of the sediment handling involved application of a novel combination of state-of-the-art mathematical models, simple empirical relations and experience from similar project. While this relative quick and inexpensive method may lead to results with scope for refinement it focus further analyses to the key issues and has in the VPHEP project lead to a set of recommendations which have been incorporated in the EPC tender for the hydro-power project.

2. THE STUDY

2.1 Hydro-mechanical Equipment

A detailed research into erosion/wear potential of the sediment in the Alaknanda River was beyond the scope of the project. A thorough review and a comparative study of experiences from other hydropower projects in the Himalayas lead to the conclusions that the optimum speed of 250 rpm is recommended and that that thermal sprayed hard metallic coatings by HVOF (high velocity oxy-fuel) technique or any other proven superior coating shall be applied on runners, guide vanes, top and bottom liner plates and labyrinth seals.
To estimate the repair costs associated with different sediment loads in the water reaching the power house an “erosion index” was used. The rate of erosion/wear of the turbines depends on sediment concentration, particle size, the hardness of the sediment etc as follows

\[ \text{Erosion Index} = (\text{diameter})^3 \times \text{concentration} \times (\text{velocity})^3 \times \text{hardness} \times \text{shape} \quad (1) \]

From this “erosion index” it is evident that trapping the coarse sediment (large diameter) and reducing the (relative) velocity are particular effective for reducing erosion. It is noticed that as the speed of the turbine is reduced the rate of erosion thus reduces as a cubic function of the velocity.

This erosion/wear index was evaluated for the VPHEP and the nearby existing Nathpa Jhakri Hydro Electric Project. The period between necessary repairs for the VPHEP was then estimated by scaling the experienced repair periods from the Nathpa Jhakri (estimated to 3 years) using the erosion/wear index. With the repair period and an estimate of repair costs an estimation of the annual repair costs could be made. It was assumed that generation loss due to repairs could be neglected since the river discharge beyond the flood season is only a fraction of the entire capacity of VPHEP, so one or more turbines will be idle for an extended period each dry season.

2.2 Desilting Chambers

Desilting chambers are provided to force a significant part of the sediment to settle before it reaches the head race tunnel. This is achieved by slowing down the flow in the chambers. The sediment settled in the chambers needs to be flushed out of the desilting chambers through either continual flushing – in which case the combined turbine and flushing discharge needs to be taken through the intake – or through intermittent flushing.

Conceptually the factors affecting settling are obviously 1) settling velocity, 2) depth of the chambers (the required settling distance increases with increasing depth), 3) retention time in the chamber, and 4) the turbulence level. To ensure a large retention time in the chamber the flow velocity needs to be small and the chamber long. In fact the time is given by \( \frac{\text{length}}{\text{velocity}} \). The velocity is discharge divided by cross-sectional area of the chamber, i.e. \( \frac{w}{D} \). To ensure a small settling depth a wide shallow chamber is to be preferred to a narrow deep, but rock mechanical properties will put a limit to how wide the chamber can be made. Low turbulence level comes with a low flow velocity and a “streamlined” inflow arrangement that does not generate flow separation.

The trap efficiency of the desilting chambers was analyzed using an empirical formula proposed by Garde et al. (1990). This approach suggests that the trap efficiency decrease exponentially with the length of the desilting chamber with a length scale depending on the height of the desilting chamber and the ratio \( \frac{w}{u^*} \) where \( w \) is the settling velocity of the sediment and \( u^* \) the friction velocity of the flow. The expression reads:

\[ \eta = \eta_o \times (1 - e^{-kL/D}) \quad (2) \]

where \( k \) and \( \eta_o \) depends on \( w/u^* \) and \( L \) and \( D \) are length and depth of the desilting chamber, respectively. The trap efficiency is further reduced if the sediment trapped in the desilting chambers is flushed continuously.

The trap efficiency of the desilting chamber as function of the length of the chamber and assuming all four units running at full capacity and without continuous flushing is shown in Figure 5. It is obvious that effective removal of grain sizes less than \( d=0.20 \text{ mm} \) would require extremely long desilting chambers and are therefore not feasible. In Figure 5 a width and height of the desilting chambers of 16 m and 21 m, respectively have been assumed.
Using Equation 2 a relation between trap efficiency and the dimensions and number of chambers can easily be established and further using the mean hydrograph shown in Figure 4 a mean annual trap efficiency can be elaborated. To relate trap efficiency to cost a simple “cost model” for the desilting chamber was used, where maintenance costs of the desilting chambers have been assumed to be insignificant compared to the capital costs, and a simple approximation for the capital cost of desilting chambers adopted where the costs is expressed as a function of the number of chambers and the volume of each chamber. This simple model was then calibrated on the cost estimate for the preliminary design. With this “cost model” and the relation between trap efficiency and dimensions of the chambers trapping as function of costs of desilting chambers relative to the costs of the preliminary design can be plotted, see Figure 6.

Figure 5  Trap efficiency as function of length of desilting chambers for different grain sizes.

Figure 6  Trap efficiency as function of relative costs of desilting chamber.
2.3 Reservoir Operation

A 2D (horizontal) mathematical model was used to simulate reservoir sedimentation for various operation scenarios and to simulate sediment flushing of the reservoir. The model used was the MIKE 21C modeling system, which is an advanced two-dimensional mathematical modeling system for simulation of unsteady flow (hydrodynamics), sediment transport and river bed and bank line changes (morphology). The basic steps in such a morphological model are 1) simulation of the hydrodynamic flow field, 2) simulation of sediment transport field based on the flow field, 3) simulation of bed level changes based on the sediment transport field, 4) simulation of bank erosion rates and 5) advancing to next time through updating of model topography and alignment based on the calculated bed level changes and bank erosion rates. In this way the model will describe the dynamic development flow, sediment transport and morphology fully incorporating the feedback from changing morphology on the flow and sediment transport. Of particular importance for the present application are the following model features:

- Curvilinear grids allowing for accurate representation of complex river/reservoir geometry.
- A two-dimensional (depth-integrated) hydrodynamics model based on a very fast parallel coded line implicit solver. This makes long-term simulation feasible.
- Helical flow module, which calculates the secondary (spiral) flow occurring in river bends, and accounts for its adaptation in space (flow inertia).
- Sediment transport divided into bed-load and suspended load (several formulas implemented). Bed-load is calculated with the inclusion of bed slope (gravity) effect and both bed-load and suspended load take secondary flow into account.
- Multiple sediment fractions can be simulated and described dynamically with a substrate model.

A detail of the model setup and example of model output are shown in Figures 7 and 8, respectively.

![Figure 7](image)

Figure 7 Model setup in front of the dam.

Various operation scenarios with intermediate flushing operations were simulated. For each of these simulations the development of the available live storage was extracted from the simulated reservoir bathymetry, see Figure 9. Subsequently, the potential power revenue was evaluated taking into account the utilization of the available live storage (thus a time series) to store water from off-peak to peak hours and thereby increasing the revenue.
Due to excessive sediment concentrations during flushing operation the power plant has to be closed down. The revenue implication of this is a simple linear function of the duration of the flushing events because:

- Flushing to be effective requires a high river discharge hence it is assumed that flushing only will take place when the river discharge is above the intake capacity and the potential power production is at its maximum; and

- Flushing cannot be discontinued and e.g. confined to off-peak hours only, because flushing is effective only when the full drawdown has been established. This means that flushing will not affect the relative distribution of peak and off-peak hour production.
Combining the revenue loss due to downtime during flushing with the revenue implications due to loss of live storage shows that the combined revenue loss compared to the hypothetical conditions with no sedimentation is of the order of magnitude 5% slightly higher both if a large live storage is maintained (thus frequent flushing operations) and in case of a low flushing frequency (thus small live storage). Minimum revenue loss is achieved when the maximum storage loss is (about) 1/3 of the initial storage.

To “close the system” the bathymetry simulated with the 2D (horizontal) model was subsequently introduced into a 2D (Vertical) model to simulate in detail the vertical distribution of sediment transport and flow in order to evaluate the concentration of the sediment entering the power intake and desilting chamber.

A full optimization can now be done. For each reservoir operation and flushing scenario revenue loss and sediment concentration in the intake water can be determined. Beyond the intake the sediment will enter the desilting chamber. Sediment trapping in the desilting chamber and the associated costs have been determined as outlined in Section 2.2, hence the resulting concentration (of the three size fractions) reaching the power house is now available and results in a (recurrent) repair costs which can be discounted to NPV.

3. CONCLUSIONS

In this paper a simple approach to optimizing the sediment handling of the scheme has been presented. The approach was based on an economical balance of capital costs, maintenance costs and revenue loss due to the anticipated downtime in connection with repair work and the loss of storage and thus ability to store water from off-peak to peak hours. The key elements of the approach were:

- A 2D (horizontal) mathematical model was used to simulate reservoir sedimentation for various hydrological events and operation scenarios and to simulate sediment flushing of the reservoir. The development of the available live storage were extracted from the simulated reservoir bathymetry and used to evaluate the potential power revenue taking into account the ability to store water from off-peak to peak hours and thereby increasing the revenue.

- The simulated bathymetry were subsequently introduced into a 2D (Vertical) model to simulate in detail the vertical distribution of sediment transport and flow in order to evaluate the concentration of the sediment entering the power intake. Before reaching the head race tunnel the sediment laden water flows through a huge desilting chamber where part of the sediment is trapped. Through a empirical relation for trap efficiency of desilting chambers a cost could be associated with the concentration and size of sediment reaching the turbines.

- The rate of erosion/wear of the turbines depends on sediment concentration, particle size, the hardness of the sediment etc. An erosion/wear index based on these parameters was evaluated for the VPHEP and a nearby existing plant. The period between necessary repairs for the VPHEP was then estimated by scaling the experienced repair periods from the nearby project using the erosion/wear index and formed the basis for estimation of repair costs.

The optimization of the sediment handling thus involved a novel combination of state-of-the-art mathematical models, simple empirical relations and experience from similar project. While this relative quick and inexpensive method may lead to results with scope for refinement it focus further analyses to the key issues and has in the above project lead to a set of recommendations which have been incorporated in the EPC tender for the hydro-power project.

For sediment handling of the VPHEP a very crucial choice has to be made: whether storage in the reservoir should be maintained through reservoir flushing from time to time or whether the reservoir should be allowed to fill up through sedimentation.

The notion that reservoir sedimentation will be minimal or even that storage can be re-gained by discharging excess water through the gates during the monsoon does not hold. Flow velocities will be very low in (at least) the vicinity of the gates and significant sediment will take place. Effective flushing
(i.e. flushing that regains storage) requires drawdown of the water level, hence the power plant cannot be operated during reservoir flushing.

Advantages of maintaining reservoir storage through regular flushing are mainly 1) the sediment concentration in the intake will be smaller thus repair/maintenance costs of turbines will reduce drastically; and 2) with the storage a larger part of the flow during the lean period can be used for peak-hour production. To achieve the latter benefit flushing would only be required on the falling limb of the hydrograph, whereas the former requires flushing also during rising stage.

The assessment of potential negative environmental effects due to flushing of sediment have not been part of the scope of work for this project and neither the operational challenges that will arise when neighboring projects both up and downstream on the Alaknanda River start operation.

4. REFERENCES


