Study on Sediment Management Strategy of Sandy River Reservoir

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Abstract. The establishment and operation of one hydropower complex will change the movement law of water flow and sediment of the river way, and sediment deposition is difficult to avoid. Due to the characteristics of “high utilized water head, small reservoir storage, high sediment content and particle hardness” of proposed Upper Arun Hydroelectric Project, this paper applies one-dimensional hydrodynamic & sediment model to studying the movement law of flow and sediment of 3 different sediment management strategy, then finding the rational one which can not only maintain a sustainable live storage of the reservoir by sediment flushing, but also reduce sediment abrasion to turbines. The results show that, when the proposed fully open of all low-level outlets for sediment flushing being implemented during high flow periods, the difference of sedimentation is relatively minor, which all 3 options can effectively maintain the live storage of the reservoir thereby minimizing deposition of sediment at the places that will affect project operation. Therefore, the selection of sediment management strategy should depends on the comprehensive technical and economic comparison. Due to the advantages of relatively short outage periods, conventional technology of construction and the largest Net Present Value, the appropriate sediment desilting operation mode is applying a sediment bypass tunnel with its intake located in the middle of reservoir, and meanwhile utilizing the reservoir's sedimentation effect, to reduce sediment content transported through the turbines.

1. Introduction
The establishment and operation of one hydropower complex will change the movement law of water flow and sediment of the river way, and sediment deposition is difficult to avoid [1].

Upper Arun HEP is located in Sankhuwasabha district, Kosi Zone in the eastern development zone of Nepal along the Arun River, with a straight-line distance to Katmandu of about 200 km, and the location map is as shown in Figure 1. The dam site is located in a narrow valley about 350 m upstream of the confluence with Chepuwa khola in Chepuwa Village. The powerhouse site is located near Hatiya Village, which is about 500 m upstream from the confluence of the Arun River and Leksuwa Khola. The project is a PROR-type hydropower plant, with reservoir storage under FSL of 4.96 million m$^3$, installed capacity of 670 MW, average annual power generation of 32.56 million kW•h.

The dam site controls the drainage area of 25,700 km$^2$ and has long term average annual runoff of 6.69 billion m$^3$ and long term average annual total sediment runoff is 23.72 million tons, including sus-pended load sediment runoff of 19.77 million tons and bedload sediment runoff of 3.95 million tons. Due to the characteristics of “high utilized water head, small reservoir storage, high sediment
content and particle hardness”, the desilting operation mode design is one of the major technical issues for proposed Upper Arun HEP [2]. In this paper, one-dimensional hydrodynamic & sediment model was applied to studying the movement law of flow and sediment in reservoir, in order to find the rational flushing operation mode, by comparing deposition of different sediment management strategy.

2. FLOW AND SEDIMENT CHARACTERISTIC ANALYSIS

2.1. Runoff
The Arun River is a tributary of the Sapt Kosi River, originates from a glacier on the North Slope of Mt. Xixabangma Feng at an elevation of 8012 m, part of the Himalayan range, in the south part of the Tibetan highland [3]. The total length of the Arun River is about 510 km and the total drainage area is about 30400 km². Its runoff is mainly recharged by precipitation, supplemented by melt water and groundwater. The mean annual runoff at dam site is 6.69 billion m³ and mainly concentrated in May to October which accounts for 84.6% of the whole year (Table 1.).

Table 1. Mean Monthly and Annual Runoff & Suspended Sediment Distribution.

| Month | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 | Annual |
|-------|----|----|----|----|----|----|----|----|----|----|----|----|--------|
| Flow (m³/s) | 542 | 548 | 62.1 | 74.9 | 125 | 295 | 523 | 570 | 426 | 195 | 858 | 642 | 212 |
| Runoff (10⁸m³) | 1.5 | 1.3 | 1.7 | 19 | 33 | 76 | 140 | 153 | 110 | 52 | 22 | 1.7 | 67 |
| Percentage (%) | 22 | 20 | 25 | 29 | 50 | 114 | 21.0 | 228 | 165 | 78 | 33 | 26 | 100 |
| Sediment Concentration (mg/l) | 15.5 | 16.2 | 22.1 | 42.1 | 474 | 2171 | 4304 | 4847 | 3593 | 1002 | 513 | 243 | 2955 |
| Monthly Sediment (10⁴t) | 0.2 | 0.2 | 0.4 | 0.8 | 16 | 166 | 603 | 740 | 397 | 52 | 1.1 | 0.4 | 1977 |
| Percentage (%) | 0.0 | 0.0 | 0.0 | 0.0 | 0.8 | 84 | 305 | 374 | 201 | 27 | 0.1 | 0.0 | 1000 |

2.2. Sediment
Main sources of the sediment in the Arun Basin are the soil erosion from the watershed. The soil erosion can be divided into three categories as surface (sheet erosion), Rills erosion and gulley erosion in high steep slope. Besides the artificial reasons, natural land slide, mass failure and debris flow are
major sources of generating the sediment in Nepalese river. The mean monthly and annual suspended sediment distributions are shown in Table 1. Suspended sediment is mainly concentrated in May to October which accounts for 99.11% of the whole year, more concentrated than the annual distribution of runoff.

2.3. Various flow grade and sediment characteristics analysis
As a basis for sediments management, a discharge versus cumulative sediment load curve is developed according to a 5-year (1994~1998) of daily flow and sediment data at dam site of UAHEP, as shown in Figure 2. The number of days with incoming flow more than 410 m³/s, 675 m³/s and 725 m³/s are respectively 65 d, 20 d and 13 d, as well as cumulative incoming sediment during these periods accounts respectively for 90%, 50%, 35% of the yearly total. This characteristics can be used for sediment management strategy formulation, combined with the corresponding engineering layout.

3. Formulation of Sediment Management Strategy
Due to the water head of this Project is higher than 500 m, meanwhile, the capacity of the reservoir is relatively small and the ratio of the reservoir capacity to annual sediment discharge is approx. 0.3, the sediment management strategy shall be based on the following principles: 1) The high flood discharge, during the monsoon seasons, shall be utilized for flushing the sediments accumulated in the reservoir. This should help maintain the live storage of the reservoir thereby minimizing deposition of sediment at the places that will affect project operation. 2) Reduce the quantity of sediments transported through the turbines. This should facilitate in reducing the maintenance and replacement periods of the nozzles and the runners of the turbines. 3) Maximize the power generation of the plant keeping into consideration factors, such as, the reservoir live storage and the turbine wear.

Based on the foregoing principles and taking into account the topographical and geological conditions of the river reach of the Project location, three design and operational sediment management options for the UAHEP peaking ROR are proposed as follows: Option A, Sediment Bypass Tunnel (SBT) at the peaking reservoir. Option B, Peaking ROR with underground Desanders. Option C, Reservoir for settling of sediment particles and Enforced Outage.

3.1. Option: A – Sediment Bypass Tunnel
This Option is represented by applying a sediment bypass tunnel with its intake located in the middle of reservoir, and meanwhile utilizing the reservoir's sedimentation effect, to reduce sediment content transported through the turbines. The reservoir's level will be lowered from the FSL (1640 m) to a Sediment Flushing Level (SFL of EL.1,615 m) during the period from June to September each year. Based on the analysis and calculation, an inflow of 675 m³/s, which is a discharge corresponding to 50% of the total sediment load (as per Figure 2), is set as a threshold of inflow. When the inflow exceeds 675 m³/s and keeps increasing, all units will be shut down. At this time, the operation will be shifted to the maximum sediment flushing mode, which means the SBT and all the low-level outlets will be fully open for sediment flushing.

Figure 3. Layout of the proposed structures under Option: A.
3.2. Option: B – Conventional Peaking ROR with underground Desanders

The Option: B is conventional Peaking ROR with underground desanders located on the left bank, to reduce sediment concentration before entering the water into the headrace tunnel for power generation. The reservoir will be operated in sluicing drawdown mode during the monsoon. When the discharge at dam site is larger than 725 m³/s, there is no enough flushing time for the desanders, which can't meet the operation requirement, so the inflow of 725 m³/s is set as a threshold of inflow.

![Layout of the proposed structures under Option: B.](image)

3.3. Option: C – Reservoir for settling of sediment particles and Enforced Outage

The Option: C is represented by applying enforced outage of units to avoid operation when there is very high sediment concentration in the wet seasons, and carry out periodic flushing through the low-level outlets to remove accumulated sediments. After the analysis and calculation, an inflow of 410 m³/s, which is a discharge corresponding to 90% of the total sediment load (as per the Figure 2), is set as a threshold of inflow.

![Layout of the proposed structures under Option: C.](image)

4. Analysis of desilting effect

4.1. Conditions and Method of Analysis

In order to analyse the desilting effect of the above three sediment management strategy, “HELIU-2” reservoir 1D sediment mathematical model was applied to calculating reservoir sediment accumulation, the detailed construction and validation of which referred in papers of Wan [4,5].

The daily water and sediment records, for the period of 1994-1998, were used in the analysis and calculations. For the purpose of a representative value of the water and sediment being utilized, annual average water and sediment values which were deduced according to the daily record by scaling...
method were adopted in the analysis. The typical annual water and sediment values recorded during the years 1994-1998, after scaling, are shown in Table 2.

| Year | Runoff (10^8 m³) | Deviation | Sediment Runoff (10^4 t) | Deviation | Concentration (kg/m³) |
|------|------------------|-----------|--------------------------|-----------|----------------------|
| 1994 | 57.8             | -13.99%   | 1187.9                   | -39.92%   | 2.06                 |
| 1995 | 76.7             | 14.16%    | 2424.2                   | 22.62%    | 3.16                 |
| 1996 | 70.4             | 4.80%     | 2312.0                   | 16.94%    | 3.28                 |
| 1997 | 55.2             | -17.88%   | 1203.2                   | -39.14%   | 2.18                 |
| 1998 | 75.8             | 12.91%    | 2757.7                   | 39.49%    | 3.64                 |
| Average | 67.2             |           | 1977.0                   |           | 2.94                 |

4.2. Sediment Deposit within the Reservoir

The ratio of reservoir capacity to the sediment discharge of this Project, is very small (approx. 0.3). The Full Supply Level at upstream of the dam is foreseen to be higher than the annual average discharge corresponding to the natural water level. This will result in significantly changing the flow characteristics under natural conditions, reduces the potential of sediment transport of the river channel and consequently a large volume of sediment settling as deposits within the river. The results of the analysis of sediment deposit volumes for each of three options, as detailed earlier, are presented in Table 3 and Figure 6. The results, of a comparison of the different options, show that the difference of sediment deposit volumes, over various periods, is minor.

The Option: C results demonstrate that due to the longest time of water level lowering to the SFL (EL. 1,615) for a fully open of low-level outlets to flush the sediments during the flood seasons, the conclusion thereof is that the sediment deposit volumes, in the reservoir area, are minimum for Option C. The Option: B results, compared with the Option: C, show lesser time of water level lowering to the SFL (EL. 1,605 m) for the sediment flushing during the flood season. However, due to the FSL is decrease from EL. 1,615 m to EL. 1,605 m and resultantly, the sediment deposit volumes in the reservoir increase, in comparison with Option: C. The Option: A results, compared with the Option B, can effectively alleviate sediment deposition in the reservoir as the runoff will be discharged through the SBL. In this case, the SBT diverted flow and sediments accounts for 37.8% and 39.6% of the annual average runoff of the reservoir. However, consideration needs to be given to the raising of the SFL by 10 m to EL. 1,615 m during the flood season and the sediment deposits, in the reservoir, are shown to be marginally higher in comparison with the Option: B.

### Table 3. Comparison of sediment deposition amount of each option.

| Operating years | Option:A |         |         |         |         |         |         |
|-----------------|----------|---------|---------|---------|---------|---------|---------|
|                 | Total sediment deposition | Sediment delivery ratio | Total sediment deposition | Sediment delivery ratio | Total sediment deposition | Sediment delivery ratio |
| 5 years         | 0.0078   | 99.18   | 0.0074  | 99.22   | 0.0063  | 99.34   |
| 10 years        | 0.0123   | 99.53   | 0.0111  | 99.61   | 0.0103  | 99.58   |
| 15 years        | 0.0171   | 99.49   | 0.0140  | 99.69   | 0.0137  | 99.64   |
| 20 years        | 0.0205   | 99.64   | 0.0165  | 99.74   | 0.0165  | 99.70   |
| 25 years        | 0.0233   | 99.70   | 0.0189  | 99.75   | 0.0187  | 99.77   |
| 30 years        | 0.0265   | 99.66   | 0.0213  | 99.75   | 0.0208  | 99.78   |

4.3. Reservoir Sedimentation Evolution Process

Due to the lowering of the water level for sediment flushing during the flood seasons, the sediment deposits in the reservoir, for all three options, may increase at upstream of the dam during the initial operation stage of the reservoir. The evolution process of the longitudinal sections for sediment
deposits are presented in Figure 6: Longitudinal profiles of sediment deposition in reservoir for all options after 10-year operation.

After a comparison of all three options, it is found that Option: C takes the longest time of the fully open of low-level outlets to implement sediment flushing during the flood season. Meanwhile, the longitudinal sections of the deposits, in the reservoir area, are relatively low. Compared with Option C, Option: B has significantly shorter time of the fully open low-level outlets to implement sediment flushing during the flood season, due to the SFL being reduced by 10 m, and the longitudinal profile of deposition in the reservoir increase marginally. Compared with Option B, the SFL, during the flood season, for Option: A increases by 10 m to EL. 1,615 m. However, the flushing of sediments, through the SBT, the reservoir sediment deposits can be effectively reduced and the longitudinal profile of deposition in the reservoir, increase lesser in comparison to Option: B. Refer to Table 3 for the sediment delivery ratio for each option. The results, of the analysis, show that the sediment delivery ratio at the initial operation stage of the reservoir, for each option, can reach above 99%. However, due to the very small ratio of reservoir capacity to sediment discharge, for UAHEP, although most of the sediments can be flushed from the reservoir, a small amount of sediments continues to settle and deposit, resulting in a slow gradual increase of sediment deposition in the reservoir.

The longitudinal profiles of sediment deposition in the reservoir after different periods of operation, i.e. 10-year, 20-year and 30-year, of each option are shown in Figure 7, Figure 8 and Figure 9, respectively.

4.4. Elevation of Sediment Deposition U/S of Dam and Loss of Reservoir Capacity

The variations, of the sediment deposition elevations, at upstream of the dam and the intake section, under different years of reservoir operation, are shown in Table 4. Calculation results show that after 10 years operation of the reservoir, the thalweg elevations, at the upstream of the dam and in front of the intake, gradually stabilize, and change marginally with the evolution of sedimentation in the reservoir. A comparison of all three options shows that when the proposed fully open of all low-level outlets for sediment flushing being implemented during high flow periods, the deposit elevation difference, at the section upstream of the dam, is relatively minor.
Figure 8. Longitudinal profiles of sediment deposition in reservoir for all options after 20-year operation.

Figure 9. Longitudinal profiles of sediment deposition in reservoir for all options after 20-year operation.

Table 4. Variations of sediment deposition elevations U/S of the dam for all options.

| Operating years | Option:A | | Option:B | | Option:C |
|-----------------|----------|----------------|----------|----------------|----------|
|                 | U/S of Dam (m) | Intake (m) | U/S of Dam (m) | Intake (m) | U/S of Dam (m) | Intake (m) |
| 5 years         | 1583.98 | 1585.45 | 1587.58 | 1588.12 | 1587.54 | 1587.83 |
| 10 years        | 1590.62 | 1590.73 | 1592.35 | 1591.04 | 1592.42 | 1591.49 |
| 15 years        | 1592.75 | 1593.13 | 1593.4 | 1594.62 | 1592.17 | 1594.55 |
| 20 years        | 1594.04 | 1593.36 | 1592.91 | 1593.97 | 1592.27 | 1594.37 |
| 25 years        | 1593.47 | 1594.44 | 1592.56 | 1593.45 | 1592.48 | 1593.59 |
| 30 years        | 1591.77 | 1594.17 | 1592.08 | 1593.2 | 1592.05 | 1593.03 |

Sediment deposition in the reservoir will cause the loss of reservoir capacity, and this will continuously decrease with the increase of sediment deposition in the reservoir. The variations, of the reservoir capacity, under different years of the reservoir operation, are shown in Table 5. A comparison of all three options shows that when the proposed fully open of all low-level outlets for sediment flushing being implemented during high flow periods, the loss of reservoir capacity difference is relatively minor.

Table 5. Variations of reservoir capacity for all options.

| Operating years | Option:A | | Option:B | | Option:C |
|-----------------|----------|----------------|----------|----------------|----------|
|                 | Percentage of remaining capacity at FSL | Percentage of remaining regulated capacity | Percentage of Percentage of remaining capacity at FSL | Percentage of remaining regulated capacity | Percentage of Percentage of remaining capacity at FSL | Percentage of remaining regulated capacity |
| 5 years         | 87.30% | 96.55% | 88.89% | 96.55% | 90.48% | 96.88% |
| 10 years        | 80.95% | 96.55% | 84.13% | 96.55% | 84.13% | 96.88% |
| 15 years        | 76.19% | 96.55% | 79.37% | 96.55% | 79.37% | 96.55% |
| 20 years        | 71.43% | 93.10% | 76.19% | 93.10% | 76.19% | 96.55% |
| 25 years        | 66.67% | 89.66% | 71.43% | 89.66% | 73.02% | 89.66% |
| 30 years        | 63.49% | 86.21% | 68.25% | 86.21% | 69.84% | 89.66% |

Meanwhile, analysis of sediment abrasion of the units showed that [1], the three sediment management options can effectively alleviate the turbine abrasions to the same degree.
In summary, all 3 options can effectively maintain the live storage of the reservoir thereby minimizing deposition of sediment at the places that will affect project operation. The selection of sediment management strategy should depend on the comprehensive technical and economic comparison. Due to the advantages of relatively short outage periods, conventional technology of construction and the largest Net Present Value, the Option: A is obviously superior to the Option: B and the Option: C.

5. Conclusions
Due to the characteristics of “high utilized water head, small reservoir storage, high sediment content and particle hardness” of Nepal Upper Arun Hydroelectric Project, the 1D hydrodynamic & sediment model was used to analyse the effect of three different sediment management strategy. The following conclusions are drawn:

1) Although Option A will have a reservoir water level 10 m (to 1,615 m) higher in flood seasons than that in Option B, and it will have an obvious shorter flushing time than those in Option C. However, since the sediment bypass tunnel is able to divert sediment in an amount that accounts for 39.6% of the annual average sediment runoff, the sediment deposition in the reservoir area only will have a slight increase when compared with Option B and Option C; the loss of storage capacity at NPL will have a slight increase, and the regulated reservoir capacity will basically remain the same.

2) Since sediment flushing measures are taken during large flow, and the elevations of sediment deposition at the intake in the three options only have slight differences, and the siltation elevation at the intake in Option A is slightly lower than that in Option B and Option C.

3) All three options can effectively maintain the live storage of the reservoir thereby minimizing deposition of sediment at the places that will affect project operation. The selection of sediment management strategy should depend on the comprehensive technical and economic comparison. Due to the advantages of relatively short outage periods, the appropriate sediment desilting operation mode is Option A, which applying a sediment bypass tunnel with its intake located in the middle of reservoir.

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References
[1] Han, Q.W. (2003) Reservoir Sedimentation. China Science Publishing, Beijing.
[2] CSPDR-SINOTECH. (2019) Updated feasibility study & detailed engineering design of Upper Arun Hydroelectric Project, Phase I: Project Optimization and Updated Feasibility Study Report. Changjiang Survey, Planning, Design and Research Co., Ltd, and Sinotech Engineering Consultants, Ltd, Kathmandu.
[3] Xavier, I.V. (2011) Development of Lower Arun Hydropower Project in Nepal. Express Water Resources & Hydropower Information, 32:35-39.
[4] Wan, J.R., Zhang, J., Zhang, X.B. (2002) Sediment accumulation calculation on Danjiangkou Reservoir for Water Transfer Project from South to North. Journal of Yangze River Scientific Research Institute, 19: 40-43.
[5] Xie, J.H. (1992), Modeling of Rivers. China WaterPower Press, Beijing.