Study on the ability of maintaining the long-term live storage capacity of sandy river reservoir

Zhao Jinqiong
Changjiang River Scientific Research Institute, Wuhan, Hubei Province, CHINA

Rao Guanghui & Hua Junjie
Changjiang Survey, Planning, Design and Research Co., Wuhan, Hubei, 430010, China

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. Taking the proposed Upper Arun Hydroelectric Project as an example, this paper applies SRH-1D model to studying the ability of maintaining the long-term live storage capacity, based on UAHP's sediment management strategy of "bypass sediment at the end of reservoir, replacing desander with reservoir, flushing intermittently", because of its characteristics of "high utilized water head, small reservoir storage, high sediment content and particle hardness". The results show that, although the sediment deposition in the reservoir area fluctuates during the year due to intermittent sediment flushing and desilting, the whole sediment deposition tends to be cumulative, in the early stage of reservoir operation. After 3 years of reservoir operation, sediment basically will reach a relative equilibrium state of scouring and silting, and there is a certain variation in the cumulative deposition of a year, only due to the siltation in power generation period and intermittent shutdown for sediments flushing. The storage capacity of the main river channel can still be kept well as the intermittent shutdown for sediment flushing, and only little cumulative deposition on both sides of the main channel will affect the regulating reservoir capacity. The ability of maintaining the long-term live storage capacity by this sediment management strategy is strong.

GENERAL INSTRUCTIONS

1.1 *Background*

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 (Han, 2013). Taking the proposed Upper Arun Hydroelectric Project (UAHEP) for example, its sediment inflow is 16.24Mt/yr and the sediment load ratio (gross storage/annual load) is only 0.43, with characteristics of "high utilized water head, small reservoir storage, high sediment content and particle hardness". In order to maintain the long-term live storage capacity and reduce the suspended sediment load on the turbines, the sediment management strategy of "bypass sediment at the end of reservoir, replacing desander with reservoir, flushing intermittently" are applied (CSPDR-SINOTECH, 2019). However, the flushing effectiveness and efficiency, as well as the desanding effectiveness, need to be further studied.

1.2 *Location and salient features*

The UAHEP is located in Sankhuwasabha district, Kosi Zone in the eastern development zone of Nepal along the Arun River, and is planned to be developed by utilising the water discharge from Arun River and a steep-gradient loop along the Arun River between Chepu Khola and Leksuwa Khola. Project location is shown in Figure 1. UAHEP is a Pumping Run of River (PROR) type hydropower project, with a FSL of El.1,640 m and a MOL of El.1,625 m, and a total installed capacity of 1,040 MW for 6 units. Salient features of the UAHEP are shown in Table 1.

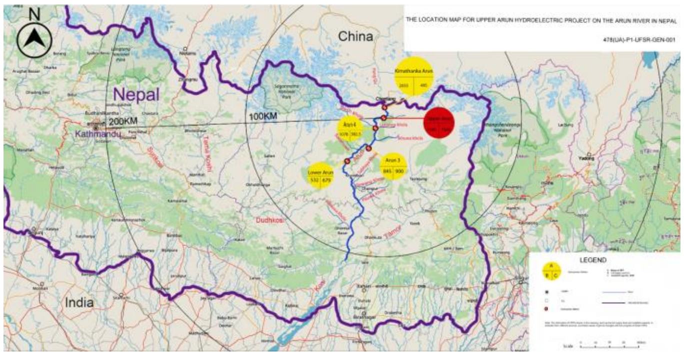

Figure 1. Location of UAHEP.

Table 1. Salient Features of UAHEP

Item	Unit	Value
Mean inflow	m^3/s	217
Sediment inflow: Sus/Bed	Mt/yr	13.81 /2.43
FSL	m	1,640
MOL	m	1,625
Gross Storage	MCM	5.07
Initial Pondage	MCM	2.41
Design discharge	m^3/s	235.4
Installed capacity	MW	1,040

1.3 *Layout*

The project's main hydraulic components includes the headworks, headrace and the underground powerhouse, and sediment bypass works. The headworks consist of a concrete arch gravity dam, 3 Low-Level Outlets (LLOs), an ungated overflow spillway, a 1.3 km long Sediment Bypass Tunnel (SBT), a power intake and an eco-flow power station. The conceptual configuration about sediment management are shown in Figure 2.

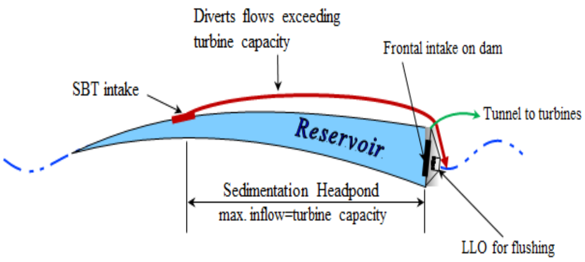

Figure 2. Conceptual configuration.

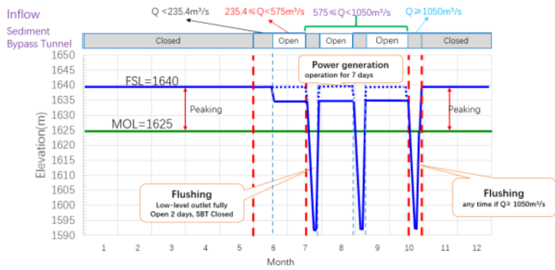

Figure 3. Operational sequence schematic.

1.4 *Operation Rule*

When the inflow is less than the full discharge of the available units (excluding the maintenance units) plus environmental flow, the plant will operate in daily peaking operation mode, which range from 1640m~1625m. When the inflow is larger than 235.44 m^3/s, but less than 575 m^3/s, the SBT will be open, the units available will run at designed discharge and the excess water will be diverted through the SBT. When the inflow is larger than or equal to 575m^3/s, the LLOs will open to lower the reservoir water level for a 2-day continuous sediment flushing. The conceptual operational sequence schematic of UAHEP is shown in Figure 3.

2 FLOW AND SEDIMENT CHARACTERISTIC ANALYSIS

2.1 *Flow and Sediment Conditions*

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 (Xavier, 2011).Both water and sediment discharge at UAHEP exhibits large variation over the year. According to the annual average water and sediment data of the dam site, the annual average suspended sediment discharge is about 13.81 million tons, the sediment concentration is 2.01 kg/m^3. On average, the monsoon period from May through October accounts for 99.6% of the annual sediment yield and 85.5% of the streamflow. It can be seen that the suspended sediment is almost all concentrated in the rainy season, and the amount of sediment is more concentrated than the amount of water. (See Table 2.). The amount of bed load is around 2.43 million tons. The characteristic values of yearly runoff and sediment load are shown in Figure 4.

Table 2. Mean Monthly and Annual Runoff & Suspended Sediment Distribution.

Month	1	2	3	4	5	6	7	8	9	10	11	12	Annual

Flow (m^3/s)	54	57	63	71	113	304	529	615	460	193	75	61	218
Runoff ($10^9 m^3$)	0.1	0.1	0.2	0.2	0.3	0.8	1.4	1.6	1.2	0.5	0.2	0.2	6.9
Percentage (%)	2.1	2.0	2.5	2.7	4.4	11.5	20.7	24.0	17.4	7.6	2.9	2.4	100
Sediment Concentration (mg/l)	44.7	49.2	62.6	76.0	326.8	1374.9	2,605.3	3,387.7	2475.4	654.7	73.5	58.1	2,013
Monthly Sediment ($10^6 t$)	0.0	0.0	0.0	0.0	0.1	1.1	3.7	5.6	3.0	0.3	0.0	0.0	13.8
Percentage (%)	0	0	0.1	0.1	0.7	7.8	26.8	40.4	21.4	2.5	0.1	0.1	100

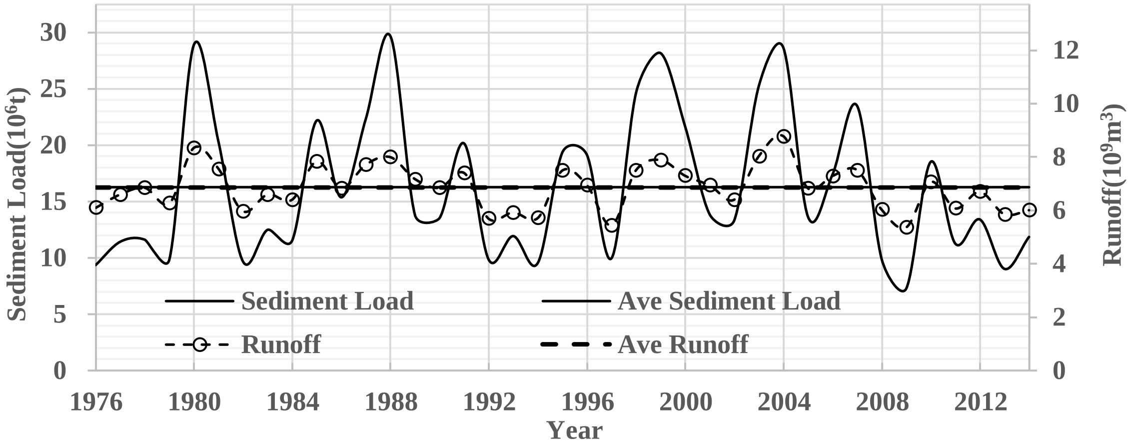

Figure 4. Annual runoff and sediment load variation of UAHEP.

2.2 *Particle Size Distribution (PSD)*

Suspended sediment particle size data are given in Figure 5, along with the curve selected for modelling. The d50 size is 0.057mm. Measured material data near the dam site are also shown in Figure 5, based on bulk sampling of sediment deposits at the following location (542490 Easting, 3069902 Northing). The PSD of the bed load was assumed to be the same as the bulk sample.

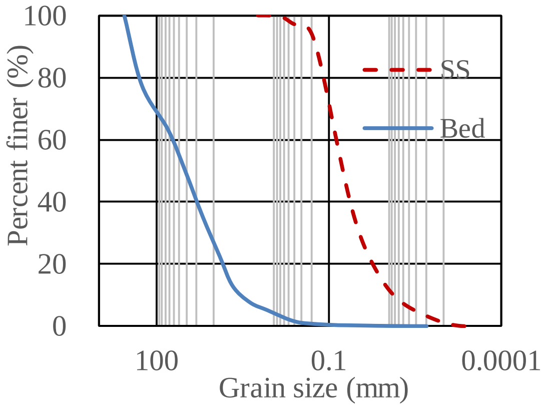

Figure 5. Gradation curve of suspend sediment and bed material.

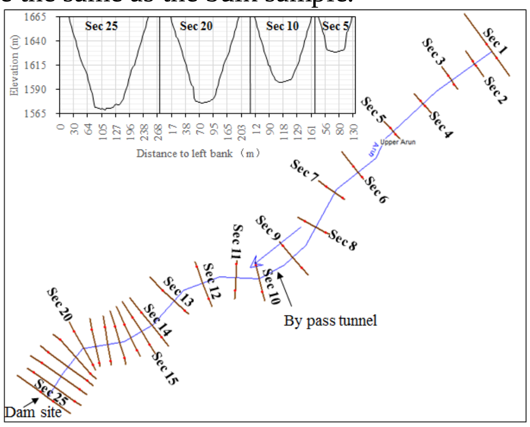

Figure 6. Section distribution of UAHEPUA Reservoir.

3 METHODS AND CONDITIONS

3.1 *Simulation methods*

In this paper, the "Sedimentation and River Hydraulics-1D" (SRH-1D, V4.0.1) model (Blai & Jianchun, 2018) is applied to studying the movement law of flow and sediment in reservoir and analyze the effectiveness of sediment management of UAHEP. SRH-1D is a hydraulic and sediment transport numerical model developed to simulate flows in rivers and channels with or without movable boundaries. It is developed by the Technical Service Center of the United States Bureau of Reclamation (USBR).

3.2 *Calculation Conditions and Parameters*

(1) Simulation Period
The available 39 years of daily inflow data for the period 1976 to 2014 has been repeated, resulting in a simulation period totalling 78 years, or 683,256 hrs.
(2) Upstream Boundary
Inflowing sediment load was computed by the rating equation and the time-discharge series of daily water inflows, years 1976-2014. This load has been distributed by size class and the PSD curve given in Figure 5.
(3) Downstream Boundary
Time-stage, is generated hourly by the operating rules as determined by reservoir simulations.
(4) Lateral Flow
Discharge of water and sediment by the SBT are determined by the operation rule. The suspended sediment concentration of diverted flow is assumed to be the same as the average concentration at the cross-section, where the intake of the SBT is located.
(5) Channel Geometry
The initial channel geometry is defined by field measured XSEC, and the XSEC locations are shown in Figure 6. Calculations are performed from dam site to the upstream limit of the reservoir tail along the geometry defined by 25 cross-sections along the 2.42 km-long reach, with average spacing of ~100 m. XSEC are simulated as being non-erodible (Tomkin et al, 2003).
(6) Transport Equation
The Meyer-Peter Muller equation (Meyer-Peter & Müller, 1948, Wong & Parker, 2006) is selected for sediment transport based on sensitivity analysis of different equations. The result of the equation is the most reasonable one.
(7) Erosion width
The equation for flush channel bottom width, as below, is used to control the rate and erosion width of the flushing channel.

$$W=aQ^b \tag{1}$$

4 RESULTS ANALYSIS

4.1 *Cumulative Deposition and Development Process*

During the power generation period, water level in front of dam obviously rises from natural level, the river flow characteristics is changed from the natural conditions, and the sediment transportability is reduced, thus causing silting in reservoir. The daily variation process of deposition in reservoir is shown in Figure 7. In the early stage of reservoir operation, although the sediment deposition in reservoir fluctuates during the year due to intermittent sediment flushing and desilting, the whole sediment deposition tends to be cumulative. After 3 years of reservoir operation, a relative equilibrium state of sediment scouring and silting is reached, and there is a certain variation in the cumulative deposition of a year, only due to the siltation in power generation period and intermittent shutdown for sediments flushing.

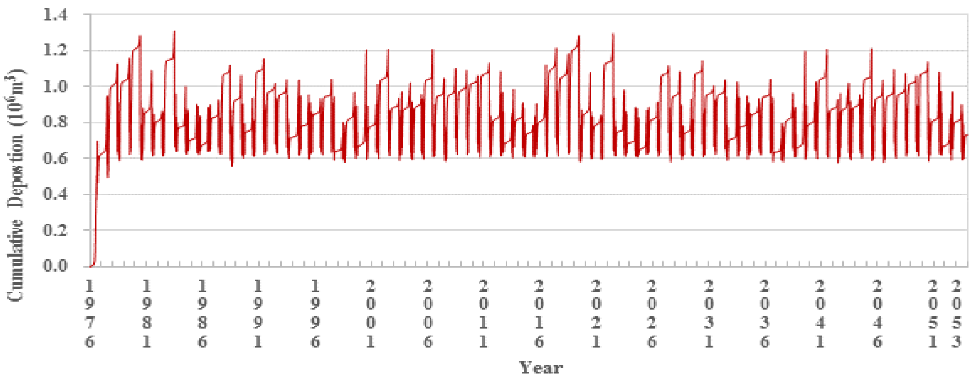

Figure 7. Daily cumulative deposition variation of reservoir area.

Figure 8 show the maximum and minimum cumulative deposition in each year. After 3 years of reservoir operation, although the difference of maximum cumulative deposition varies greatly from year to year, with an variation ranging of 0.81 million m³ to 1.31 million m³, however the difference of minimum cumulative deposition is very small; after scouring at the end of flood season, the variation is in the range between 0.56 million m³ and 0.64 million m³.The sediment deposited during the power generation period can be flushed out of the reservoir, applying the operation rule of sediment management during the year, and the scouring and silting can be basically balanced during the year.

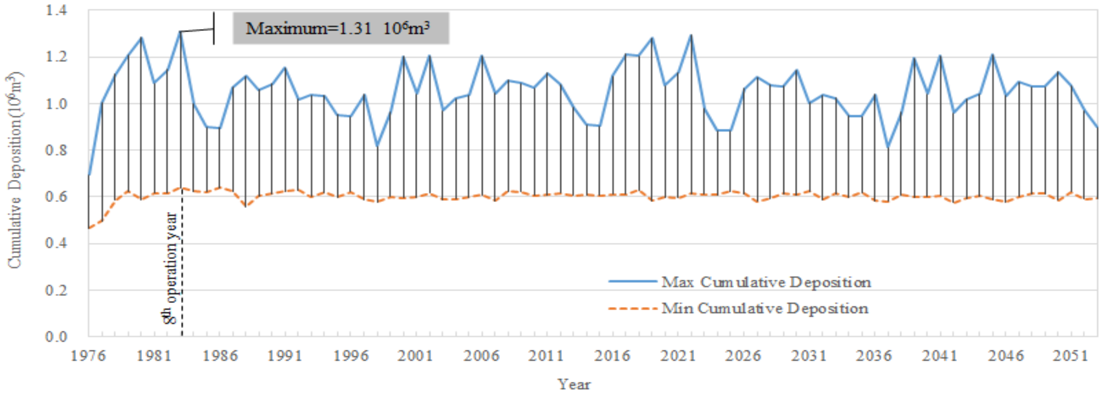

Figure 8. Cumulative deposition variation range of each year in reservoir.

4.2 *Deposition Morphology*

The longitudinal profiles of sediment deposition in the reservoir at the end of each operational year (31th, Dec) are shown in Figure 9. As the ratio of reservoir capacity to annual sediment load volume at FSL is very small, the sediment deposits quickly reach the dam. During the 78 years of reservoir operation, the talweg changes a little at the end of each year, but varies within one year due to the process of sediment accumulation and followed by sediment flushing. Taking the year 1983, which has the largest deposition, as an example, the variation in the longitudinal talweg profile at different dates is shown in Figure 10; details are presented as follows:

− At the end of July in the previous year (July 30, 1983), the reservoir returns to FSL after sediment flushing and desilting, and the sediment is deposited about 2km from the dam and gradually advance toward the dam site.

− Deposition in the reservoir reaches a maximum on July 6, 2039, and the longitudinal profile of the deposits exhibits a delta siltation pattern, as expected.

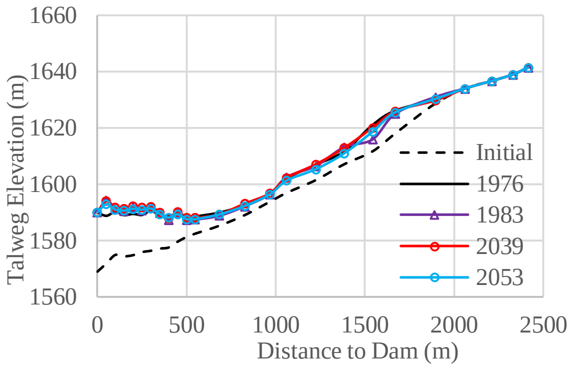

Figure 9. Variation of deposition longitudinal profile.

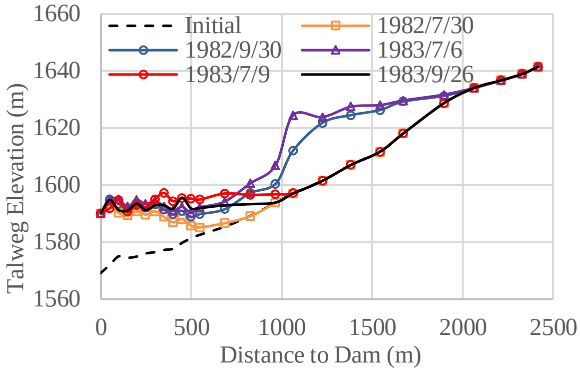

Figure 10. Variation of deposition longitudinal profile in 8th year (1983).

− During this monsoon there are 6 sediment flushing events, the sediment deposited in the reservoir earlier in the monsoon is washed out of the reservoir, and by the end of the last flushing on September 26, 1983, the longitudinal profile has basically returned to the state at the end of the flood season of the previous year.

4.3 *Regulating Reservoir Capacity Variation*

The remaining percentage of the regulating reservoir capacity is shown in Figure 11. It can be concluded as follows:

− The development of sediment deposition is rapid and the regulating reservoir capacity in the initial stage of reservoir operation is gradually reduced with the increase of sediment deposition;

− The storage capacity of the main river channel can be kept well as the intermittent shutdown for sediment flushing, and only little cumulative deposition on both sides of the main channel will affect the regulating reservoir capacity;

− After operating the reservoir for about 3 years, the scouring and silting will be basically balanced in the year, and the average remaining percentage of the regulating reservoir capacity at the end of the year (31th, Dec) is about 81.4%, with a maximum remaining ratio of 86.4% and a minimum remaining ratio of 73.9%.

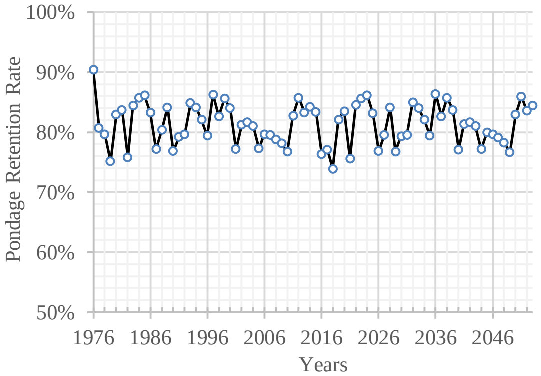

Figure 11. Remaining percentage of regulating reservoir capacity at the end of each year.

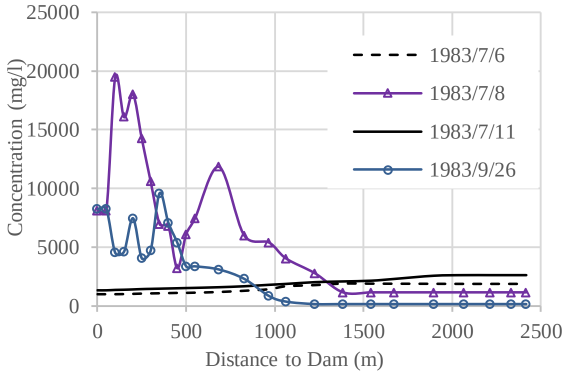

Figure 12. Concentration Variation along the Chanel in Different Stages in the 64th Operation Year

4.4 ***Sediment Concentration and Gradation in Front of Dam***

The sediment management strategy of a joint operation of the SBT and flushing & desilting, applying intermittent shutdown to maintain the long-term life of the reservoir, is adopted; with this strategy, the reservoir capacity retention and sediment passing through the turbine is regulated. Taking the year 1983 with the largest deposition as an example, as shown in Figure 12, the variations of sediment concentration in different operation stages are presented below:

− On July 6, 1983, the deposition in the reservoir area reaches the maximum, and the daily inflow sediment concentration reaches 1.86kg/m³; then followed by the gradual deposition along the channel, the sediment concentration in front of the dam decreases to 0.99kg/m³;

− On July 8, 1983, the reservoir is shut down for sediment flushing, and the daily inflow sediment concentration reaches 1.14kg/m³; the sediment concentration in the process of scouring increases along the channel, and up to 8.10kg/m³ in the front of dam;

− On July 11, 1983, the reservoir water level reaches El.1,637m, the inflow sediment concentration is 2.62kg/m³; sediment deposits along the channel, and outflow sediment concentration is reduced to 1.30kg/m³.

In order to analyse the effect of reservoir area sediment deposition on the sediment passing through the turbine, the daily discharge and grouped sediment load of dam site section during power generation are counted (excluding the period of shutdown for sediment flushing & desilting). The monthly average sediment concentration and gradation results for 78-years long series are shown in Table 3. and Figure 13. Meanwhile, analysis of sediment abrasion of the units showed the effectiveness of the joint operation of reservoir and the SBT in reducing the suspended sediment load on the turbines.

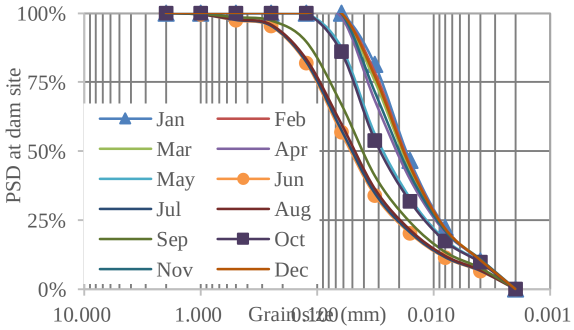

Figure 13 Monthly average suspended load particle gradation for 78 operation years.

Table 3. Monthly Average Sediment Concentration and Gradation in Front of Dam for 78 Years.

Month	SC (kg/m³)	D_{50} mm	Month	SC (kg/m³)	D_{50} (mm)
Jan	0.012	0.018	Jul	1.783	0.052
Feb	0.014	0.018	Aug	2.011	0.050
Mar	0.019	0.019	Sep	1.183	0.043
Apr	0.028	0.022	Oct	0.274	0.029
May	0.161	0.028	Nov	0.024	0.021
Jun	0.903	0.054	Dec	0.017	0.019

5 CONCLUSIONS

Due to the characteristics of "high utilized water head, small reservoir storage, high sediment content and particle hardness", the Sedimentation and River Hydraulics-1D was applied to studying the movement law of flow and sediment in reservoir and analyze the effectiveness of sediment management of UAHEP. The following conclusions are drawn:

(1) The sediment management strategy of "bypass sediment at the end of reservoir, replacing desander with reservoir, flushing intermittently" can effectively solve the serious sediment issue of UAHEP, which can provide a good reference for other similar projects located on sandy rivers.

(2) The ability of maintaining the long-term live storage capacity by reservoir flushing has been confirmed, particular focusing on the potential long-term accumulation of bed material. After 3 years of reservoir operation, although there is a certain variation in the cumulative deposition of a year, sediment basically will reach a relative equilibrium state, the sediment deposited during the power generation period can be flushed out of the reservoir, applying the operation rule of sediment management during the year.

(3) The storage capacity of the main river channel can still be kept well as the intermittent shutdown for sediment flushing, and only little cumulative deposition on both sides of the main channel will affect the regulating reservoir capacity. After nearly 3 years of reservoir operation, the average yearly remaining percentage of the regulating reservoir capacity at the end of each year will reach about 81.4%, with a maximum remaining ratio of 86.4% and a minimum remaining ratio of 73.9%.

(4) The joint operation of reservoir and the SBT can effectively reduce the suspended sediment load on the turbines.

ACKNOWLEDGMENTS

This work was supported by the National Key R&D Program of China (2016YFC0402309, 2018YFC1508002) , National Natural Science Foundation of China (Grant No. 51779014), the Three Gorges Follow-up Project (Grant No. 17900100000016J032-2), the Special fund for basic scientific research business of central public research institutes (Grant No. CKSF2019470/HL).

REFERENCES

Blair, G, & Jianchun, V.H. 2018. *SRH-1D 4.0 User's Manual*. US Department of Interior, Bureau of Reclamation, Technical Service Center, Sedimentation and River Hydraulics Group.

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.

Han, Q.W. 2003. *Reservoir Sedimentation*. Beijing: China Science Publishing.

Meyer-Peter, E. & Müller, R. 1948. Formula for bed-load transport. *Proc. of the Int. Assoc. for Hydraulic Research*. 2nd Meeting, Stockholm.

Tomkin, J. H., Brandon, M. T., Pazzaglia, F. J., Barbour, J. R. and Willet, S.D. 2003. Quantitative Testing of Bedrock Incision Models for the Clearwater River, NW Washington State. *Journal of Geophysical Research*, 108:2308.

Wong, M. & Parker, G. 2006. Reanalysis and Correction of Bed Load Relation of Meyer-Peter and Muller Using Their Own Database. *J. Hydraulic Engineering, ASCE*. 132(11): 1159-1168.

Xavier, I.V. 2011. Development of Lower Arun Hydropower Project in Nepal. *Express Water Resources & Hydropower Information*, 32:35-39.