



Sediment management of run-of-river hydroelectric power project in the Himalayan region using hydraulic model studies

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Abstract. Storage capacity of hydropower reservoirs is lost due to sediment deposition. The problem is severe in projects located on rivers with high sediment concentration during the flood season. Removing the sediment deposition hydraulically by drawdown flushing is one of the most effective methods for restoring the storage capacity. Effectiveness of the flushing depends on various factors, as most of them are site specific. Physical/mathematical models can be effectively used to simulate the flushing operation, and based on the results of the simulation, the layout design and operation schedule of such projects can be modified for better sediment management. This paper presents the drawdown flushing studies of the reservoir of a Himalayan River Hydroelectric Project called Kotlibhel in Uttarakhand, India. For the hydraulic model studies, a 1:100 scale geometrically similar model was constructed. Simulation studies in the model indicated that drawdown flushing for duration of 12 h with a discharge of 500 m³/s or more is effective in removing the annual sediment deposition in the reservoir. The model studies show that the sedimentation problem of the reservoir can be effectively managed through hydraulic flushing.

Keywords. Run-of-the-river hydroelectric project; reservoir sedimentation; hydraulic flushing; physical model.

1. Introduction

Rate of storage capacity reduction of worldwide reservoirs due to sediment deposition is reported to be about 1% per year. For example, average storage loss rate of reservoirs in China is more than 2% [1, 2]. In India, measurements of reservoir sedimentation indicate average annual loss rate of 0.78% [3, 4]. Most of India's hydropower potential exists in the Himalayan and northeastern region, where, due to the fragile geology of the hills and steep slope of the valley, the rivers carry a lot of sediment during monsoon. Hence, the storage capacity of reservoirs in these regions is lost rapidly due to sediment deposition. Such projects are required to be designed on different criteria from the conventional reservoir projects. They are required to be designed for sediment management rather than water storage. The sediment deposition in the reservoirs can be controlled by different methods [5, 6]: (i) reducing the sediment reaching the reservoir by catchment area treatment or diverting sediment concentrated flows; (ii) passing sediment-laden flows through the reservoir by sluicing and thereby reducing the settlement of sediment in the reservoir; and (iii) removing the already deposited sediment hydraulically by drawdown flushing or

mechanically by dredging. Sediment removal from reservoirs of run-of-river projects can be effectively carried out by lowering the reservoir level to scour the deposited sediment and flushing them through the sluice spillways.

The study by Atkinson [7] of 50 reservoirs for which flushing of sediment are being practised indicated that the favourable conditions for effective flushing operations are mainly natural. However, for successful flushing, other technical and operational conditions also have to be fulfilled [8]. Reservoirs in humid or semi-humid regions or in regions with distinct wet and dry seasons are suitable for flushing. Narrow and long gorge-type reservoirs with a higher shape factor and reservoirs with small capacity to inflow ratio are also suitable for flushing. Other technical and operational conditions are: availability of large low-level sluicing outlets and possibility of reservoir emptying for drawdown flushing. Since no standard criteria can be adopted for the design of various components of such projects, simulations with numerical and physical models are required to finalise the design and optimise the operation schedule. Numerical models can be used to predict the long-term sediment deposition pattern in reservoirs. A one-dimensional numerical model was used by Ahn and Yang [9] to simulate the reservoir sedimentation and flushing. The model was applied to simulate the Xiaolangdi reservoir

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flushing. A 3D numerical model was applied by Olsen and Haun [10] to simulate flushing of Kali Gandaki reservoir, Nepal. Application of one-dimensional numerical model for predicting reservoir sedimentation and physical model for reservoir flushing has been presented by Isaac *et al* [11]. The results of the studies were applied for planning and design of sediment management scheme of run-of-the-river projects in India [12, 13]. For the appropriate design of the hydraulic flushing system, detailed hydraulic model studies are essential. In this paper, the hydraulic model studies conducted on a physical scale model for flushing of sediment from the reservoir of a run-of-the-river hydroelectric power project is presented.

2. Project description

Kotlibhel Hydroelectric Project Stage-IA is proposed on the river Bhagirathi near village Muneth at about 3.8 km upstream of the confluence of Bhagirathi and Alaknanda rivers at Devprayag in Tehri Garhwal district of Uttarakhand, India (figure 1). The run-of-the-river project is designed as a peaking station with 195 MW power generation capacity. Catchment of the river Bhagirathi is spread over the Tethys Himalayas, the Great Himalayas and the lesser Himalayas. The region is characterised by series of high ridges and narrow and deep valleys. The gradient of the river varies considerably from that at its origin to the project site near Devprayag, where the river has a gradient of 3.5–4 m/km. The catchment area of river Bhagirathi up to the proposed dam site is 7887 km². An area of 2227 km² lies above the permanent snowline in the Himalayas. The remaining 5660 km² area is rain-fed catchment.

The project envisages construction of an 82.5-m-high (from deepest foundation level) concrete gravity dam. The

spillway consists of five spans of 11.0 m width and 18.5 m height with a breast wall. The dual-purpose spillways have been designed for passing the probable maximum flood (PMF) discharge of 13,500 m³/s at Full Reservoir Level (FRL) of El. 532.0 m. The spillway crest is at El. 490.50 m. The capacity of the reservoir at FRL is estimated to be 46.17 Mm³ with no live storage. The power intake and underground power house provided on the left bank has an installed capacity of 195 MW (3 units of 65 MW each) with a design discharge of 341.16 m³/s and water head of 63.33 m.

3. The physical model of reservoir

The 1:100 scale geometrically similar (GS) model of Kotlibhel H. E. Project stage IA reservoir was constructed by reproducing about 10.5 km reach of river from 0.5 km downstream to 10 km upstream of the proposed dam axis (figure 2). The dam, spillways and intake structures were also reproduced in the model. The discharge to the model was measured at the upstream end using a sharp-crested Rehbock weir. The river bed in the model was moulded with cement plaster. Sand/silt of required gradation was laid on the river bed and levelled according to the probable sedimentation profile before the commencement of each flushing experiment. Figure 3 shows the view of the model with all appurtenant structures. The sediment flushed from the reservoir was collected in the trap chambers provided at the downstream end of the model and volumetric measurements were carried out at the end of each experiment. The volume of sediment flushed was also computed from the measured bed levels along the cross sections.

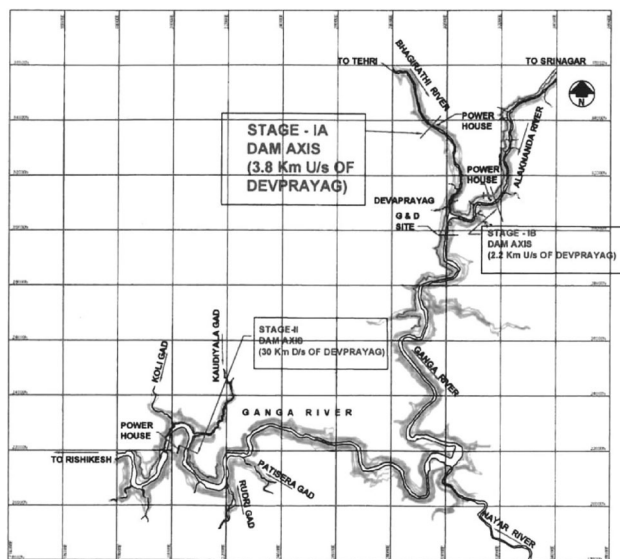


Figure 1. Location of Kotlibhel—IA H E Project.

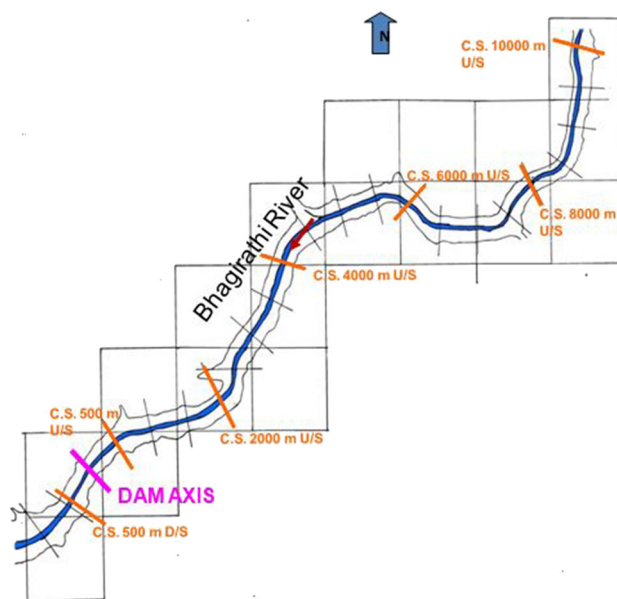


Figure 2. Plan of river in the study reach.



Figure 3. Views of the model.

Since gravitational forces are predominant in open channels, Froude's Law of similitude was applied to simulate the flow in the model. Geometrically similar scale model was selected to maintain the river slope same as in prototype. The GS scale of the model was selected 1:100 considering various parameters of model scale design: availability of space, discharge and head. It was also verified that Reynolds number is sufficiently high to maintain turbulent flow conditions for all the discharges simulated. The scale ratios for various parameters are presented in table 1.

The model calibration and proving has been carried out for hydrodynamics by comparing the water levels at dam axis. The water level was controlled at the downstream end of model according to the tail water rating curve and the water level measured at dam axis was compared with the prototype values measured at dam axis.

3.1 Simulation of sedimentation profile

Generally, long-term simulations by one-dimensional mathematical model are performed to estimate the probable sedimentation profile in reservoirs. In the present study, two sedimentation profiles, namely (i) the extreme case when the reservoir is filled up to the FRL/MDDL of El. 532 m (figure 4) and (ii) the sedimentation level near intake (El. 510 m) reaches just below the intake invert level (figure 5) were selected for simulation of drawdown flushing.

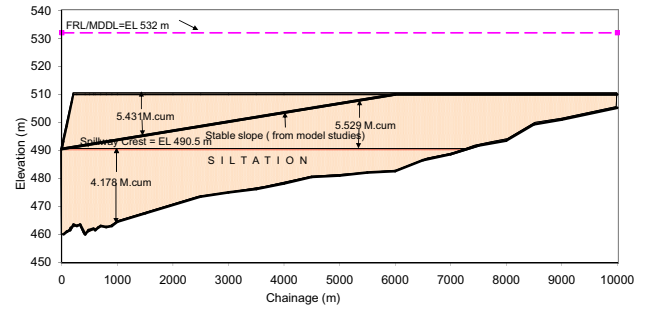


Figure 4. Sedimentation profile with deposition up to El. 532 m.

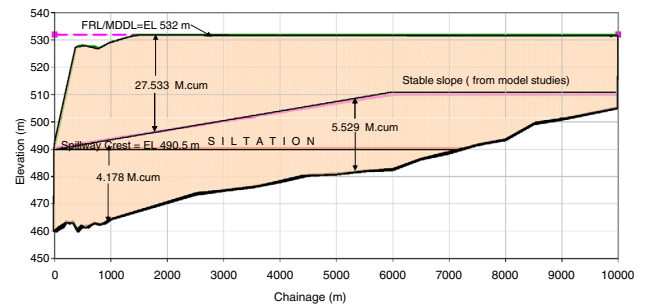


Figure 5. Sedimentation profile with deposition up to El. 510 m.

The one-dimensional model, Hydrologic Engineering Centre–River Analysis System (HEC-RAS) version 4.1 [14] developed by the U.S. Army Corps of Engineers, was applied to simulate the long-term sediment deposition in the reservoir. Figure 2 presents the plan of the reservoir reach reproduced in the physical scale model. Some representative cross sections only were marked in the figure. Cross sections were available at 30-m interval for the reach of 500 m near dam axis and 100 m interval up to the reach of 1 km. Beyond that, cross sections were available at 500 m interval. The model solves the one-dimensional energy/momentum equation to obtain the cross-section-averaged hydraulic parameters. The sediment transport potential is then computed at each cross section and the sediment continuity equation is solved for the control volume between consecutive cross sections to compute the

Table 1. Scale ratios for various model parameters.

Parameter	Scale relation	Scale ratio	Value in prototype	Value in model
Length	L_r	1:100	100 m	1 m
Depth	L_r	1:100	100 m	1 m
Area	$A_r = L_r^2$	1:10,000	10^4 m^2	1 m^2
Volume	$V_r = L_r^3$	1:1,000,000	10^6 m^3	1 m^3
Velocity	$V_r = \sqrt{L_r}$	1:10	10 m/s	1 m/s
Discharge	$Q_r = L_r^{5/2}$	1:100000	500/800/1200 m^3/s	0.005/0.008/0.012 m^3/s
Time	$T_r = \sqrt{L_r}$	1:10	1 day (24 h)	2.4 h
Manning's n	$n_r = L_r^{1/6}$	1: 2.154435	0.06	0.02785

sediment deposition level. The river plan and cross sections were used to define the reservoir topography in the model. The discharge hydrograph and measured sediment load were the other input parameters used in the model to estimate the long-term sediment deposition.

Kotlibhel H.E. Project stage-IA is located just downstream of Tehri hydro development complex, which consists of Tehri storage scheme (40 km) and Koteshwar run-of-the-river scheme (20 km). The estimated sediment inflow from the Koteshwar reservoir to the Kotlibhel stage IA is $0.415 \text{ Mm}^3/\text{year}$ and the lateral inflow from intervening catchment of 196 km^2 between Koteshwar dam and Kotlibhel stage-IA dam is computed as $0.28 \text{ Mm}^3/\text{year}$ (adopting the same sediment yield of $1438 \text{ m}^3/\text{km}^2$ as in Tehri catchment). Hence, the sediment load at Kotlibhel stage IA is estimated to be $0.695 \text{ Mm}^3/\text{year}$. The total volume of siltation in the 10-km reach of reservoir according to the sedimentation profile with deposition up to El. 532 m is 37.26 Mm^3 . Volume of the reservoir below the crest level of the spillway (El. 490.5 m) is 4.178 Mm^3 , which will be permanently locked upstream of the dam. Hence, based on the above sediment yield, the sedimentation profile may be attained in about 50 years if the reservoir is operated without any flushing during this period. Suspended sediment load measurements carried out by the project authorities at the dam site for a short period indicated that the quantity of suspended sediment at dam site during the years 2006, 2007 and 2008 was 2.58 Mm^3 , 1.07 Mm^3 and 0.7 Mm^3 , respectively; that is, a total of 4.35 Mm^3 for 3 years. Considering the measured suspended sediment load, the above profile will be attained in about 25 years.

3.2 Simulation of the bed material

Various criteria such as Shields critical shear stress [15] and Yang's incipient motion [16] were considered for the simulation of sediment transport during flushing. The bed material gradation curves at few locations along the study reach were available. The median diameter (d_{50}) of the bed material samples varied from 8 mm to 40 mm. The d_{50} of sediment according to the average gradation curve was 10 mm. The sediment size required in the model to simulate the prototype size of 10 mm based on Yang's criteria is 0.26 mm. According to Shields criteria, the sediment size required in the model is 0.20 mm. The critical value for Shields dimensionless shear stress parameter of 0.06 was selected in the analysis. Analyses were also carried out using the Yalin-Karahan modification of Shields diagram [17]. The critical shear stress of 0.045 was applied. The sediment size (d_{50}) required was about 0.105 mm. The d_{50} of the available silt material was also 0.26 mm and that is the required material size according to Yang's criteria. Hence, locally available sand, having d_{50} of 0.26 mm, d_{15} of 0.18 mm and d_{85} of 0.3 mm, was used to simulate the

bed material in the model. The above material corresponds to particle size (d_{50}) of 10 mm and 25 mm in the prototype based on Yang's incipient and modified Shields criteria, respectively.

The Manning's n is the roughness parameter to be adjusted during hydrodynamic simulation to calibrate the model. In the present study, the water-level boundary of normal depth was specified at upstream and downstream boundaries and the water level computed at dam axis using HEC-RAS [14] was compared with the prototype values measured at dam axis. The Manning's n was adjusted to match the water levels computed by model and measured in prototype at the dam axis. The Manning's n was adjusted to 0.06 to calibrate the model.

The numerical simulations for reservoir sedimentation were carried out for the entire stretch of reservoir length of 18.5 km and beyond. The HEC RAS model requires measured sediment load input at upstream boundary and at other inflow locations, if any. During simulation, the model first computes the hydrodynamic parameters. Then at each sediment computation time step, the sediment transport capacity is computed according to the specified sediment transport predictor. The incoming sediment load is compared with the transport capacity and erosion/deposition is computed according to the sediment continuity equation (Exner equation) for the control volume for the computational grid (cross section). In the present study, the measured sediment load was input at the upstream boundary. No intermediate inflow points/tributaries were modelled and hence sediment load was also input at upstream boundary only. Different sediment transport predictors were tried and, finally, simulations were carried out using the Engelund-Hansen equation, for which the parameters were matching the site conditions.

3.3 Selection of flushing discharges

The flushing discharge to be simulated on the model was selected based on the available average monthly flow during monsoon season. Accordingly, the discharges of $500 \text{ m}^3/\text{s}$ and $800 \text{ m}^3/\text{s}$ were selected for the flushing experiments. Since regulated annual peak flood discharges from the Tehri reservoir indicated higher values, additional experiments were carried out for the flushing discharge of $1200 \text{ m}^3/\text{s}$ and the sedimentation profile with siltation level up to El. 510 m.

4. Experimental studies and results

4.1 Sedimentation profile with deposition up to El. 532 m (Profile 1)

Experiments for flushing were initially conducted for the discharge of $500 \text{ m}^3/\text{s}$. The water level in the reservoir was maintained at FRL of El. 532 m at the beginning of the

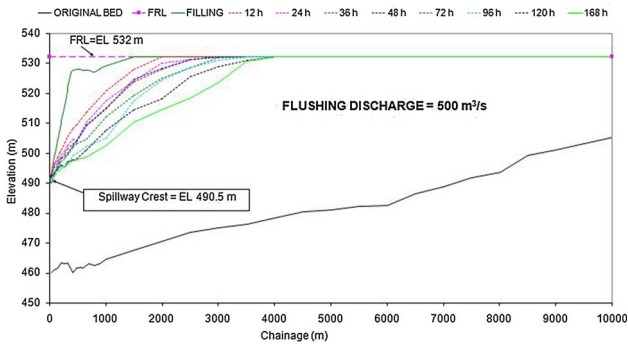


Figure 6. Longitudinal section after flushing (Profile 1 and $Q = 500 \text{ m}^3/\text{s}$).

flushing simulation. After stabilisation of flow, all the spillway gates were opened fully to drawdown the water level and establish riverine flow conditions. The flushing with the constant discharge was simulated in the model for 12 h. The discharges and durations are equivalent prototype units. After the flushing, the bed levels along each cross section in the entire reach of the reservoir were measured. The quantity of material flushed in 12-h duration through the spillway was also measured volumetrically. The experiments were repeated to simulate cumulative flushing duration of 24, 36, 48, 72, 96, 120 and 168 h. The bed levels on each cross section and volume of flushed sediment collected in the trap downstream of the dam were measured

Table 2. Quantity of sediment flushed (Profile 1) in various durations.

Flushing duration (h)	Sediment flushed (Mm^3)	
	Flushing discharge 500 (m^3/s)	Flushing discharge 800 (m^3/s)
12	1.250	1.76
24	1.990	2.85
36	2.480	3.595
48	2.925	4.175
60	–	4.73
72	4.170	5.275
96	4.820	6.07
120	5.355	6.85
144	–	7.6
168	6.565	–

volumetrically after every flushing. Figure 6 shows the longitudinal section of bed profiles for various durations. Representative cross sections after flushing for various durations; namely, cross sections at 210 m, 660 m, 1500 m, 2000 m and 3000 m, are presented in figure 7. Table 2 gives the quantities of sediment flushed out during various periods of flushing. Typical photographs of the model taken during and after the flushing operation are presented in figures 8 and 9.

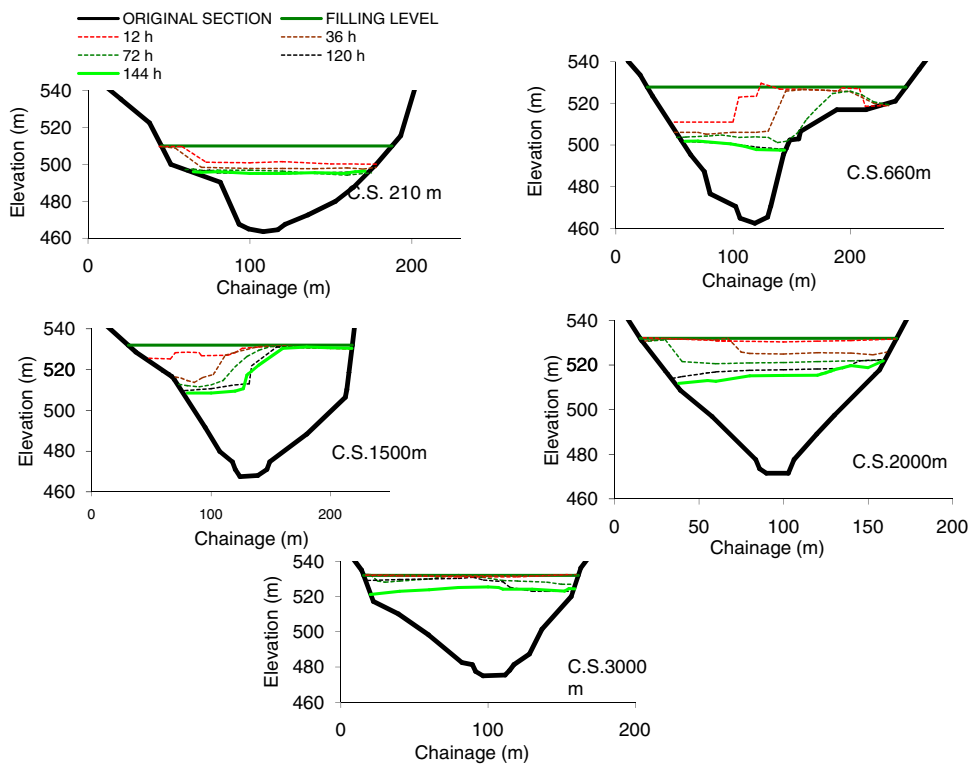


Figure 7. Typical cross sections after flushing (Profile 1 and $Q = 500 \text{ m}^3/\text{s}$).



Figure 8. View of model near dam during flushing (Profile 1 and $Q = 500 \text{ m}^3/\text{s}$).

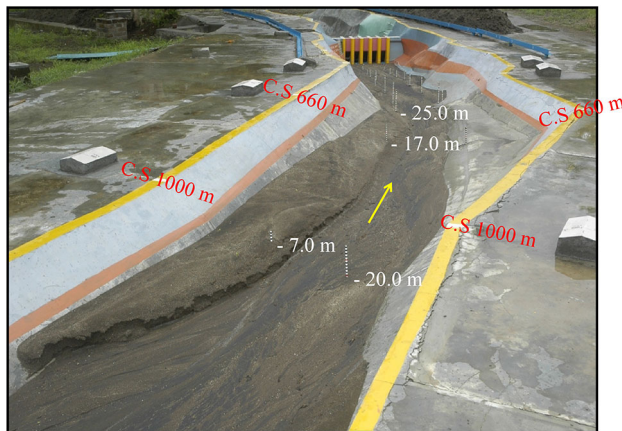


Figure 9. View of model after flushing (Profile 1 and $Q = 800 \text{ m}^3/\text{s}$).

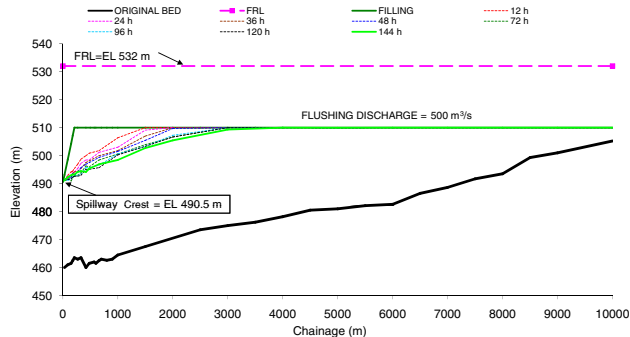


Figure 11. Longitudinal section after flushing (Profile 2 and $Q = 500 \text{ m}^3/\text{s}$).

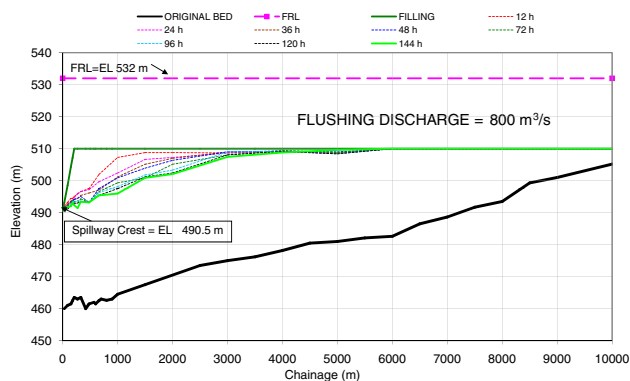


Figure 12. Longitudinal section after flushing (Profile 2 and $Q = 800 \text{ m}^3/\text{s}$).

the deepest bed level after flushing for various durations are presented in figure 10.

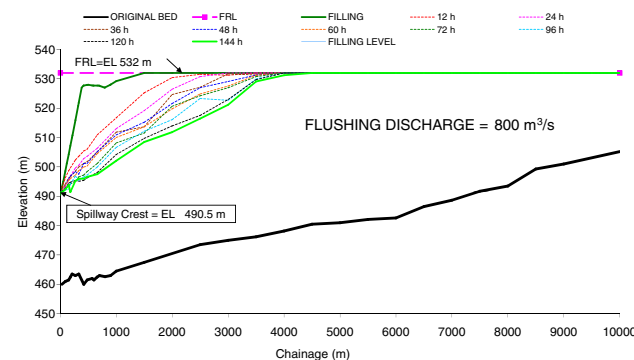


Figure 10. Longitudinal section after flushing (Profile 1 and $Q = 800 \text{ m}^3/\text{s}$).

The aforementioned set of experiments were repeated with the same initial profile and higher flushing discharge of $800 \text{ m}^3/\text{s}$ for 12, 24, 36, 48, 72, 96, 120 and 144 h of cumulative flushing durations. The longitudinal sections of

4.2 Sedimentation profile with deposition up to El. 510 m (Profile 2)

Flushing experiments were again carried out for the second sedimentation profile with deposition up to El. 510 m (Profile 2). Set of the flushing simulations similar to the first case were conducted for flushing discharge of $500 \text{ m}^3/\text{s}$, $800 \text{ m}^3/\text{s}$ and $1200 \text{ m}^3/\text{s}$ and for various flushing durations. The longitudinal sections of the deepest bed levels after flushing for different durations are presented in figures 11–13. The total quantity of sediment flushed from the reservoir in different durations for all the flushing discharges are given in table 3. Typical photographs taken after the flushing operation are presented in figures 14 and 15.

5. Discussion

The total volume of siltation in the 10-km reach of reservoir according to the sedimentation profile with deposition up to El. 532 m (profile 1) is 37.26 Mm^3 and the maximum

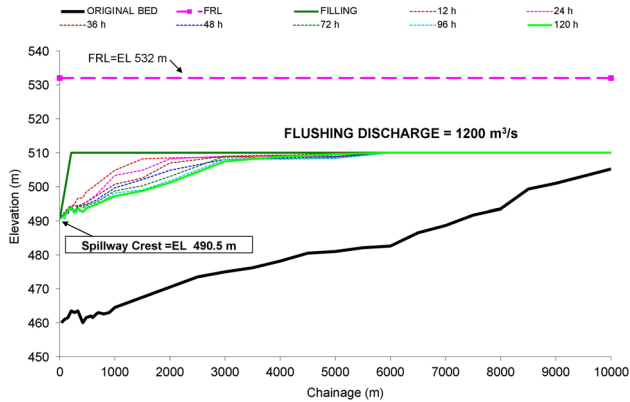


Figure 13. Longitudinal section after flushing (Profile 2 and $Q = 1200 \text{ m}^3/\text{s}$).

Table 3. Quantity of sediment flushed (Profile 2) in various durations.

Flushing duration (h)	Sediment flushed (Mm^3)		
	Flushing discharge 500 (m^3/s)	Flushing discharge 800 (m^3/s)	Flushing discharge 1200 (m^3/s)
12	0.690	0.910	1.070
24	0.930	1.210	1.500
36	1.105	1.490	1.735
48	1.250	1.665	1.965
72	1.465	1.910	2.310
96	1.615	2.120	2.580
120	1.785	2.265	2.790
144	1.940	2.435	–

thickness of deposition above the spillway crest is 41.5 m. To attain this sedimentation level, it would take about 50 years of operation without any flushing of reservoir as the incoming yearly sediment load is $0.695 \text{ Mm}^3/\text{year}$ only. It was observed from the experiments of flushing with the discharge of $500 \text{ m}^3/\text{s}$ and $800 \text{ m}^3/\text{s}$ that flushing is very effective in the initial 12-h duration. The bed levels plotted in figures 6 and 7 indicate that the effect of flushing extends to a distance of about 2000 m from the dam axis when flushing is carried out with a discharge of $500 \text{ m}^3/\text{s}$. The experiments also indicated that for all flushing conditions, effect of flushing is prominent up to a distance of about 4 km upstream from the dam axis when the flushing is carried out for longer durations. Extent of flushing width wise and length wise is clearly visible in respective cross sections, longitudinal sections and photographs taken during the flushing operation. The flushing channel extends to about the full width of the river along a stretch of about 400 m upstream from the dam axis. Beyond the reach of 400 m and up to a distance of about 1500 m, a deep flushing channel developed along the left bank. Further upstream, the flushing channel shifts from one bank to the other bank depending on the river meanders.

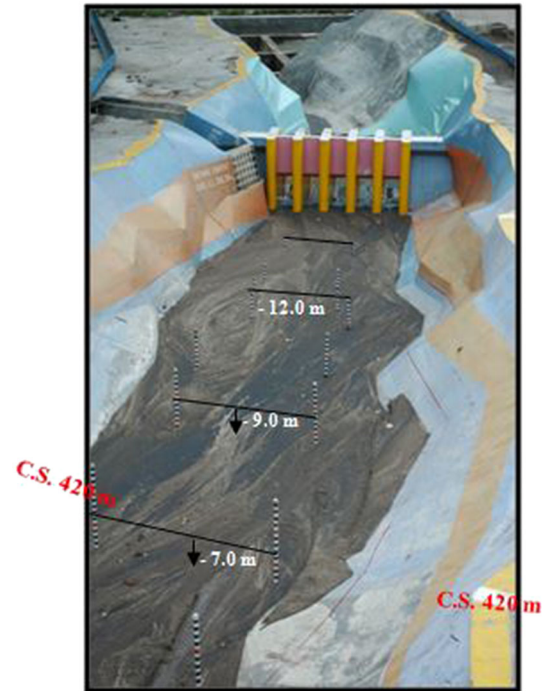


Figure 14. View of model during flushing (Profile 2 and $Q = 500 \text{ m}^3/\text{s}$).

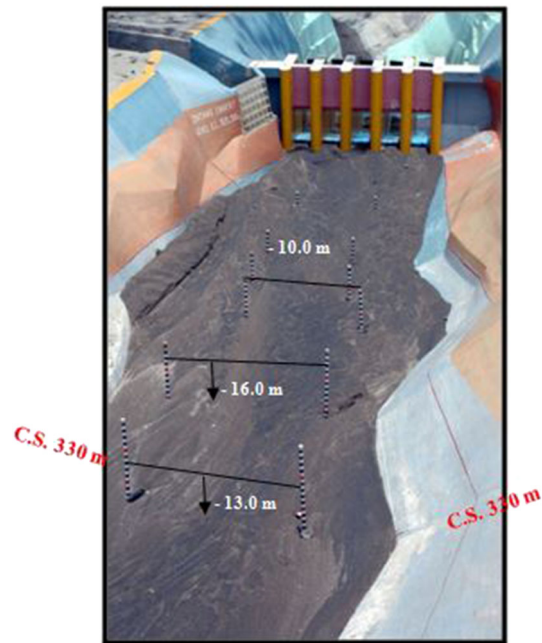


Figure 15. View of model after flushing (Profile 2 and $Q = 1200 \text{ m}^3/\text{s}$).

The quantity of sediment removed from the reservoir and the storage capacity thus restored in various durations of flushing are presented in figures 16 and 17 for profile 1 and profile 2 for different flushing discharges. It was observed that 1.25 Mm^3 of sediment was flushed out with the

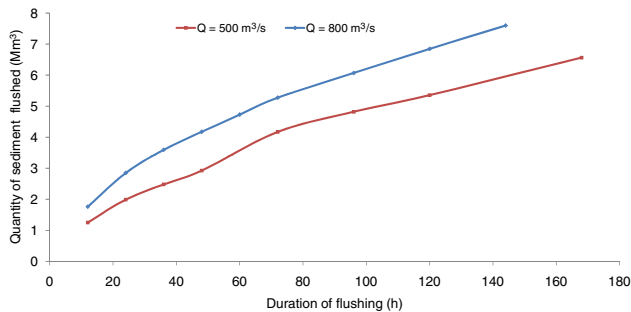


Figure 16. Quantity of sediment flushed (Profile 1).

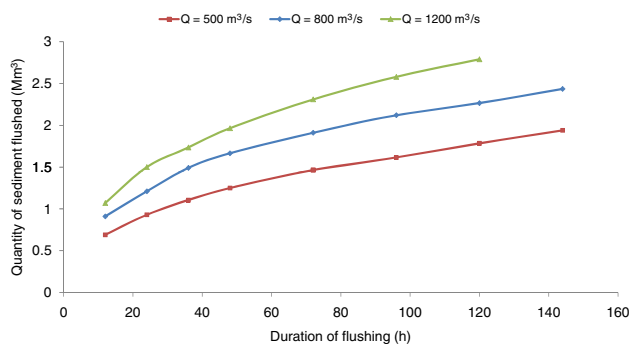


Figure 17. Quantity of sediment flushed (Profile 2).

discharge of 500 m³/s and 1.76 Mm³ with the discharge of 800 m³/s in 12-h duration. The above quantities are much higher than the annual sediment load of Bhagirathi River at the dam site (0.695 Mm³/year). Hence, an annual flushing for 12-h duration with a discharge of 500 m³/s or more is sufficient for maintaining the reservoir capacity.

The maximum thickness of deposition above the spillway crest is 19.5 m for the sedimentation profile with deposition up to El. 510 m (profile 2) and the volume of siltation in the 10-km reach of reservoir is 15.138 Mm³. Siltation above the stable slope is 5.431 Mm³. The experiments indicated that the quantity of sediment removed from the reservoir and the storage capacity thus restored in 12 h is 0.69 Mm³ with the flushing discharge of 500 m³/s. The flushing quantity increases from 0.69 Mm³ to 1.07 Mm³ as the flushing discharge increases to 1200 m³/s for the same duration of 12 h.

The quantity of sediment removed from the reservoir by flushing and the storage capacity thus restored for all the experiments presented in tables 2 and 3 indicated that maximum scour occurred in the first 12 h. Subsequently, the rate of sediment transport reduces and an equilibrium profile (stable slope) will be attained if the flushing is continued. The effect of drawdown flushing is not significant beyond a distance of 4000 m upstream from the dam. Further, if the power intake is located near to the dam within a distance of 400 m, the area can be always kept free of sediment deposition. Considering the annual incoming sediment load of Bhagirathi River and performance of flushing of reservoir achieved in the model, it can be seen

that one flushing during the monsoon month with a discharge of 500 m³/s or above is suitable to sustain the reservoir capacity.

In the present study, the model was operated according to Froude's Law of similitude. The various scale ratios for geometrically similar models were applied to convert model results to prototype values. The model scale of 1:100 was selected considering the availability of space, discharge and head. A reach of about 10.5 km of Bhagirathi River covering the reach of 0.5 km downstream and 10 km upstream of dam axis was reproduced in the present studies. Accordingly, the length of river in the model was about 105 m. While selecting the model scale, it was ensured that flow is turbulent and Reynolds number is more than 10,000 for all the discharges simulated. Model was calibrated with water levels by adjusting the roughness. Hence, there may not be much effect on the scale chosen.

The sediment size used in the model was scaled down to match the incipient motion criteria for sediment movement during flushing. However, the model has certain limitations in simulating sediment transport. The sediment size was selected based on the median size of sediment particles on the river bed. The measurements at the dam site had indicated 25.4% of coarse, 29.1% of medium and 45.5% of fine particles in the suspended sediment load. When the project becomes operational and impoundment starts, finer particles from suspended load also will settle in the reservoir. The gradation (size composition) of reservoir deposition will be different from the original river bed material and most probably the percentage of finer material will be more. Hence, the quantity of sediment removed by flushing will be more than that predicted by model simulations.

6. Conclusions

Sediment management to sustain the functional life of reservoirs is the most important aspect in various stages of planning and operation of the run-of-river hydropower projects. Hydraulic model studies can be used as an important tool during the decision making at all the stages of the projects. Simulations carried out on a hydraulic model for the drawdown flushing of the reservoir of Kotlibhel Hydroelectric Project in Uttarakhand, India, is presented in this paper. Simulations of drawdown flushing were conducted on a 1:100 scale geometrically similar model for various durations and discharges for two sedimentation profiles.

Following are the major conclusions from the present studies.

- For the sedimentation profile with deposition up to El. 532 m (profile 1) with flushing discharges of 500 m³/s and 800 m³/s, it is possible to flush out 1.25 Mm³ and 1.76 Mm³ of sediment in a flushing duration of 12 h.

- Studies for sedimentation profile with deposition up to El. 510 m (profile 2) with flushing discharges of 500 m³/s, 800 m³/s and 1200 m³/s indicated that 0.69, 0.91 and 1.07 Mm³ of sediment could be removed from the reservoir and capacity restored in a duration of 12 h.
- The quantities of sediment removed by flushing are much higher than the annual sediment load of Bhagirathi River at the dam site (0.695 Mm³/year).
- Studies indicated that prominent flushing discharge would be ~500 m³/s and flushing is not effective beyond an upstream distance of ~4000 m from the dam.
- One flushing during the flood season when the discharge is 500 m³/s or higher would be suitable to remove the annual incoming sediment load.

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