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Sediment removal from run-of-the-river hydropower reservoirs by hydraulic flushing

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ABSTRACT

The concept of sustainable development is gaining popularity and hydroelectric projects designed and operated on this concept require sediment management as prime design criteria. Drawdown flushing is being practised in such projects for sediment management. Investigations using hydraulic models are required for the projects to address the site-specific design concerns. In the present study, simulations conducted using hydraulic model for sediment removal by drawdown flushing of the reservoir of Punatsangchhu hydroelectric project, Bhutan, is presented. The experiments on 1:100 geometrically similar scale model indicated that flushing is effective in maintaining the power intake area clear of sediment deposition. Deposition from the upstream reaches could not be flushed hydraulically. Furthermore, based on wide range of experimental data from hydraulic model studies, empirical equations have been developed for predicting the quantity of sediment that can be flushed from the reservoirs. The present equations have been developed including more parameters than those used in equations already available in literature. Two equations have been developed for different riverbed slope ranges with steep slope (0.005–0.04) and moderate slope (0.001–0.005). The equations developed were validated against different sets of data and it indicated that the predictions could be made within reasonable accuracy. These equations can be effectively used for hydraulic design of sediment removal from run-of-the-river hydropower reservoirs.

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Empirical equation; hydraulic flushing; hydraulic models; one-dimensional models; run-of-the-river hydropower project; reservoir sedimentation

Notation

φ	a dimensionless parameter depending on sediment type
C_f	the volume of sediment deposition
C_f/C_v	the ratio of reservoir sediment deposition to the capacity expressed as fraction
C_v	the capacity of reservoir (in million m^3)
d_{50}, D_{50}	median size of sediment (mm)
L	the length of reservoir (m)
Q, Q_f	the flushing discharge (m^3 s^{-1})
Q_s	the sediment transport capacity (t s^{-1})
S	the river bed slope
T	the flushing duration (h)
V_s	the volume of sediment flushed (million m^3)
V_w	the volume of water (million m^3)
W, W_f	the width of flushing channel (m)

1. Introduction

The storage capacity of reservoirs all over the world is reducing at the rate of 1–2% (>2% in China) per year due to sediment deposition. Studies indicate that 80% of the useful storage capacity of hydropower reservoirs will be lost by the year 2035 (Morris and Fan 1997, White 2000, Basson 2008, Schleiss *et al.* 2014). Since suitable dam sites for new reservoir projects are limited and/or non-existent, sustainable development of water resources projects by adopting sediment management techniques is required (Schleiss *et al.* 2014, Isaac and Eldho 2016). Sediment management techniques can be grouped into three categories; viz., catchment management, prevention of deposition in reservoirs and removal of already deposited sediment. Catchment management is to prevent entry of sediment into the reservoir. Sediment deposition can be prevented by bypassing sediment, density current venting and sediment sluicing. The sediment removal techniques include; drawdown flushing, dredging, dry excavation, etc. (Yoon 1992, Lai and Shen 1996, Morris and Fan 1997, Shen 1999, Brandt 2000, White 2000, Yang 2003, Annandale 2011, Schleiss *et al.* 2014).

Sediment sluicing and drawdown flushing are widely being used for sediment removal from small and medium reservoirs and run-of-the-river projects provided with large low-level outlets. During sediment sluicing, the incoming sediment load is routed through the reservoir without allowing it to be deposited. Drawdown flushing is carried out by lowering the reservoir water level sufficiently to create riverine flow condition and already deposited sediment can be removed by retrogressive erosion. However, the effect of flushing depends on hydrological, topographical, technical and operational conditions (Yoon 1992, Lai and Shen 1996, Morris and Fan 1997, Shen 1999, Batuca and Jordan 2000, Brandt 2000, White 2000, Yang 2003, Isaac and Eldho 2016). The hydrological conditions require that sufficient water should be available for flushing and capacity to inflow ratio should be small such that reservoir can be refilled. Topographical conditions indicate that reservoirs should be elongated and narrow. In wide reservoirs, a flushing channel will be developed and retrogressive erosion will occur in the flushing channel only. Technical requirement is that sluicing outlets having sufficient capacity to effect drawdown of reservoir should be provided. Operational conditions should permit lowering of reservoir water level sufficiently to achieve riverine flow conditions.

In the Himalayan region, due to the topographical and hydrological conditions of the rivers, huge potential for hydropower development exists. However, the main challenge in development of hydropower projects on these rivers

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is designing and operating the projects with effective sediment management techniques. Many of the hydroelectric projects on the Himalayan rivers are recently being designed as run-of-the-river schemes by providing large size sluice spillways with crest very near to the riverbed for passing excess water during flood events and sediment during flushing/sluicing. In this study, the details of the simulation of hydraulic flushing of a run-of-the-river hydropower project using physical model study are presented. In addition, based on a large number of hydraulic model studies, two empirical equations derived for predicting the quantity of sediment that can be flushed is also discussed.

2. Hydraulic flushing of reservoir for sediment removal

Run-of-the-river hydropower projects in the Himalayan region are designed with the concept of sediment management by drawdown flushing of reservoir during monsoon to remove the annual sediment deposition. The hydraulic design of various components; viz., spillways, energy dissipating arrangements, intakes and water conductor systems are mostly site specific. The alignment, size and crest/invert levels of above components are highly dependent on the sediment deposition profile in the reservoir. Hence, it is essential during the investigation, planning and feasibility study stages of such hydropower projects to estimate/predict the sedimentation pattern in the reservoir, volume and location of sediment deposition that can be removed from the reservoir by flushing for optimizing the design of various hydraulic structures of the project and the reservoir operation schedule. Hydraulic model simulations are the generally accepted tool for such investigations, where the governing parameters are mostly site specific. Simulation of hydraulic flushing of sediment is generally carried out using physical scale models. Experimental models for reservoir flushing are cumbersome, costly and time-consuming. Empirical equations can be used during the project investigation and planning stages to get a preliminary estimate of the quantity of sediment that can be removed from the reservoir by flushing.

2.1. Physical and numerical modelling for flushing of sediment

Details of reservoir flushing carried out for sediment removal and physical scale model and/or numerical model simulations are reported by many investigators. The sediment management by drawdown flushing of reservoirs on Alpine River Drau has been reported by Althaus and De Cesare (2006). Emamgholizadeh and Samadi (2008) studied the feasibility of removing deposited sediment from the Dez reservoir. The details of flushing operations of reservoirs on Kurobe River and integrated management strategies of water and sediment downstream of dams in Japan have been reported (Kantoush *et al.* 2010, Sumi and Kantoush 2010). Ji *et al.* (2011) studied the possibility of replacing mechanical dredging with sediment flushing through gate operation changes at Nakdong River Estuary Barrage (NREB). Furthermore, the effects of different sediment control methods on sedimentation were quantitatively analysed using the two-dimensional numerical model CCHE2D (Ji *et al.* 2016).

Experiments conducted by various investigators on laboratory flumes to study different aspects of reservoir flushing such as effects of discharge on flushing, channel formation and geometric characteristics of flushing cone at the vicinity of bottom outlets have been reported (Talebbeydokhti and Naghshineh 2004, Emamgholizadeh *et al.* 2006, Jugovic *et al.* 2009, Kantoush and Schleiss 2009, Meshkati *et al.* 2009). Huang and Huang (2001) studied the effect of sediment scour in lowering water level of the Liujiaxia Reservoir using physical model.

Mathematical models have been successfully applied to predict the sedimentation in reservoirs and many such examples are available in literature. Brief review of important models is presented by Morris and Fan (1997), Sloff (1991), Batuca and Jordan (2000) and Annandale (1987). One dimensional numerical models are being widely applied for prediction of long term deposition pattern in reservoirs (Brandt 2000, USBR 2006, Ahn and Yang 2010, Castillo *et al.* 2014, 2015, Isaac *et al.* 2014, Isaac and Eldho 2016). Applications of 1D numerical model for prediction of long-term sedimentation profile of few reservoirs are reported in Schleiss *et al.* (2014).

Recently, due to the developments in the field of computational fluid dynamics, application of numerical models to simulate sediment flushing is being practised (Esmaeili *et al.* 2014, 2015). Ahn and Yang (2010) studied the reservoir sedimentation and flushing processes of Xiaolangdi Reservoir located on the Yellow River in China using 1D numerical model GSTARS3. Applications of the three-dimensional numerical model SSIIM, with an adaptive, non-orthogonal and unstructured grid for reservoir flushing of Kali Gandaki hydropower reservoir in Nepal and the Angostura reservoir in Costa Rica were reported (Olsen and Haun 2010, Haun and Olsen 2012a, 2012b). Gallerano and Cannata (2011) proposed a system of numerical models to simulate the flushing of reservoirs. The proposed system of models was applied to the Pieve di Cadore reservoir and its catchment area. The hydrodynamic model was further developed to simulate wave transformation phenomena, wave breaking, and near shore currents in complex geometry of coastal regions (Gallerano *et al.* 2016a, 2016b). Campisano *et al.* (2004) presented experimental and numerical investigation on the scouring effects of flushing waves on sewer sediment deposits. The 3D hydrodynamic model coupled with turbulence and sediment transport models is applied by Keshtpoor *et al.* (2015) to investigate the development of scour holes in a tidal inlet. Castillo *et al.* (2014, 2015) presented details of the analysis and numerical model simulations carried out to predict the flushing of the proposed Paute-Cardenillo Dam across the Paute river in Ecuador. Generally, empirical equations and 1D numerical model simulations are used to estimate the sedimentation in the reservoir and 2D and 3D numerical model simulations are used to estimate the flushing of sediment from reservoir.

2.2. Empirical equation for quantity of sediment flushed

Few empirical relations for estimating the sediment outflow during flushing are reported by researchers (Atkinson 1996, Lai and Shen 1996, Morris and Fan 1997, Shen 1999, Batuca and Jordan 2000, Brandt 2000). Paul and Dhillon (Batuca and Jordan 2000) developed an empirical relationship for the quantity of sediment flushed with the flushing discharge:

$$V_s = 0.048 V_w^{0.687}, \tag{1}$$

where V_s is the volume of sediment flushed (in million m^3) and V_w is the volume of water (in million m^3) used for flushing. The equation was developed from very limited data from prototype and model of reservoirs where drawdown flushing had been carried out.

Atkinson (1996) derived a criterion for assessment of the feasibility of flushing of reservoirs and verified the criteria using data of 14 reservoirs where flushing had been carried out. The concepts of sediment balance and sustainable capacity of reservoirs had been applied to derive the criteria. The sediment transport capacity of flushing flow was estimated by the Tsinghua University empirical equation:

$$Q_s = \varphi \frac{Q_f^{1.6} S^{1.2}}{W^{0.6}}, \tag{2}$$

where Q_s is the sediment transport capacity (t/s); Q_f is the flushing discharge (m^3/s); S is the slope and W is the width of channel (m) and φ is a dimensionless parameter depending on sediment type; $\varphi = 1600$ for fine loess sediments, $\varphi = 650$ for $D_{50} < 0.1$ mm, $\varphi = 300$ for $D_{50} > 0.1$ mm, and $\varphi = 180$ for low flushing discharge (<50 m^3/s). The equation was developed from the data collected from reservoirs in China.

The width of the channel is a function of the flushing discharge. From field data of reservoirs, Atkinson (1996) derived the following equation for the width of the channel:

$$W_f = 12.8 Q_f^{0.5}, \tag{3}$$

where W_f is the channel width (m) and Q_f is the flushing discharge (m^3/s). Experimental results obtained by Lai and Shen (1996) have shown that the multiplication constant in Equation (3) has a lower value of 10.91. Lower values of 5 to 7 have also been reported for reservoirs in Japan (Batuca and Jordan 2000).

Fan and Jiang (Morris and Fan 1997, Brandt 2000) developed an empirical equation similar to Equation (2) to calculate sediment outflow rate due to retrogressive erosion. The sediment outflow rate L_{wo} (kg/s) is $L_{wo} = KQ_o^{1.2}(S \times 10^4)^{1.8}$; where Q_o is the water discharge (m^3/s), S is the slope of the deposit and K is a constant of proportionality equal to 0.0035 for Sanmenxia Reservoir, China.

3. Methodology

In this study, the details of the simulation of hydraulic flushing of a reservoir using physical scale model are presented. Furthermore, based on a large number of physical model studies and experimental observations, an attempt is made to develop empirical equations for estimating the volume of sediment flushed from reservoirs. The equations are developed using known parameters of the reservoir system to predict the volume of sediment that can be flushed. Two equations have been derived for moderate and steep sloped river systems. The efficiency of the empirical equations is verified with available data and found to be satisfactory.

3.1. 1D numerical model for reservoir sedimentation

Prediction of reservoir sedimentation is a pre-requisite for simulation of reservoir flushing. The mathematical models for reservoir sedimentation simulate the water flow and sediment transport, the spatial and temporal distribution of sediment within the reservoir, armouring and sorting of sediment etc. Long-term simulation extending over many years and longer reaches of reservoirs using 2D and 3D numerical models are not practical due to the requirement of computational time and resources. Moreover, sedimentation pattern along narrow and elongated reservoirs can be predicted fairly accurately using 1D numerical models. Hence, the long-term sedimentation pattern in reservoirs of run-of-the-river projects can be predicted using one dimensional (1D) numerical model. The models solve the one-dimensional momentum and continuity equations of water flow and continuity of sediment in the river-reservoir system. In the present study, the one-dimensional numerical model HEC-RAS 4.1 (USACE 2010) was used to estimate probable sedimentation profile in the reservoir.

3.2. Experimental model for reservoir flushing

Hydraulic model simulations of reservoir flushing are essential during the planning stage of run-of-the-river power projects to optimize the various design parameters and operation schedule from sediment management considerations (Isaac *et al.* 2014, Isaac and Eldho 2016, 2017). Many 1D numerical models are not capable of simulating the highly turbulent flow conditions during the flushing. Generally, physical scale models are used to simulate the reservoir flushing. Geometrically similar (GS) scale models based on Froude's law of similitude are used to simulate hydraulic flushing of reservoir sediments. The sediment particles on the river bed are scaled using critical shear stress at incipient motion criteria. Suspended sediment is scaled based on fall velocity criteria.

In the present study, a 1:100 GS scale model of Punatsangchhu river was constructed covering a reach of about 10 km upstream and 500 m downstream of the dam for flushing simulations. The discharges and durations corresponding to prototype discharges of 600, 800, 1000 and 1200 m^3/s (6, 8, 10 and 12 l/s in model) and durations of 12 and 24 h (1.2 and 2.4 h in model) were studied in the model. At the end of simulation, the volume of sediment collected in the trap chamber and downstream of the spillways was measured. The bed levels at each cross section were also measured and volumetric computations made to estimate the quantity of sediment flushed from the reservoir.

3.3. Derivation of empirical equation

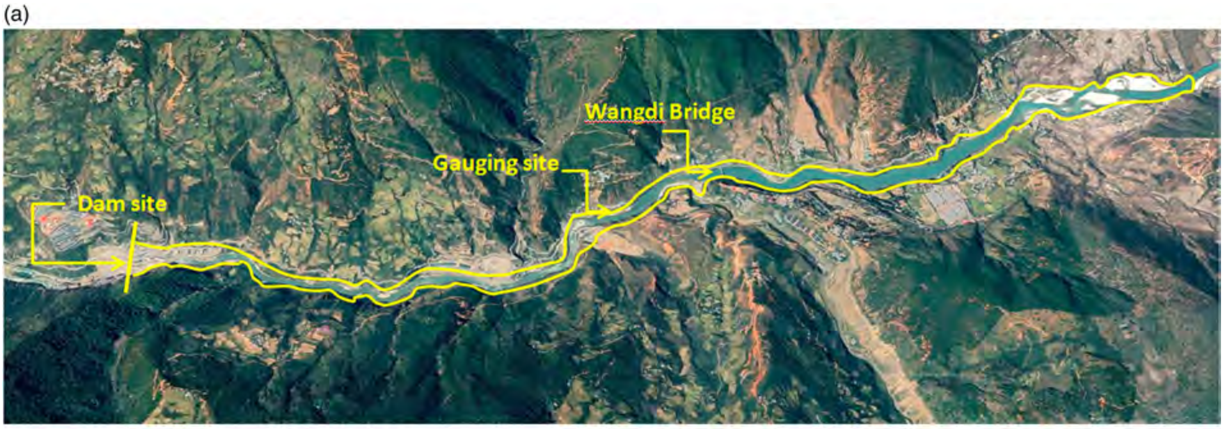
The available equations in literature for estimating the quantity of sediment that can be removed from reservoir by hydraulic flushing have been derived from limited data and based on few parameters. The flushing process depends on many parameters related to the reservoir geometry, water and sediment flow, and structural/operational parameters of the dam. In order to get a better prediction of the volume of sediment flushed, it is required to derive equations based on more parameters and data. In the present study, an attempt is made to derive empirical equations that can make fairly accurate prediction of the volume of sediment removed by hydraulic flushing of reservoir. Non-linear multiple regression analysis using the statistical analysis software 'R' has been carried out to derive a relation to predict the volume of sediment that can be flushed from the reservoirs.

4. Case study of reservoir flushing

In this study, experiments were conducted on a (scaled) model to simulate the flushing of sediment from the reservoir of the hydropower project called Punatsangchhu-I Hydro Electric power project in Bhutan. The flushing experiments were carried out for the reservoir deposition profile obtained from 1D numerical model simulation.

4.1. Characteristics of the project

Punatsangchhu hydroelectric project is proposed on Punatsangchhu river in Wangdue District of Bhutan. The dam site is located about 7 km downstream of Wangdi Bridge and 80 km from the Capital Thimpu (Figure 1(a)). Wangdi Rapid gauging site is about 500 m downstream of Wangdi Bridge. The river Punatsangchhu, which originates from the Himalayan ranges in North–West Bhutan at an elevation of about 7000 m is a tributary of the Brahmaputra river. The rivers Phochhu and Mochhu join at Punakha to form the river Punatsangchhu. The total catchment area of Punatsangchhu river upto the project site is 6390 km^2. 3115 km^2 of the catchment is snowfed and the remaining 3275 km^2 is rainfed. Monsoon and high discharge season is from June to September. The average monthly flow during the above period is about 800 m^3/s. The river flow is to be passed through the diversion tunnels during the construction period. The diversion tunnels are designed to pass the flood of 967 m^3/s which is the 25-year return period



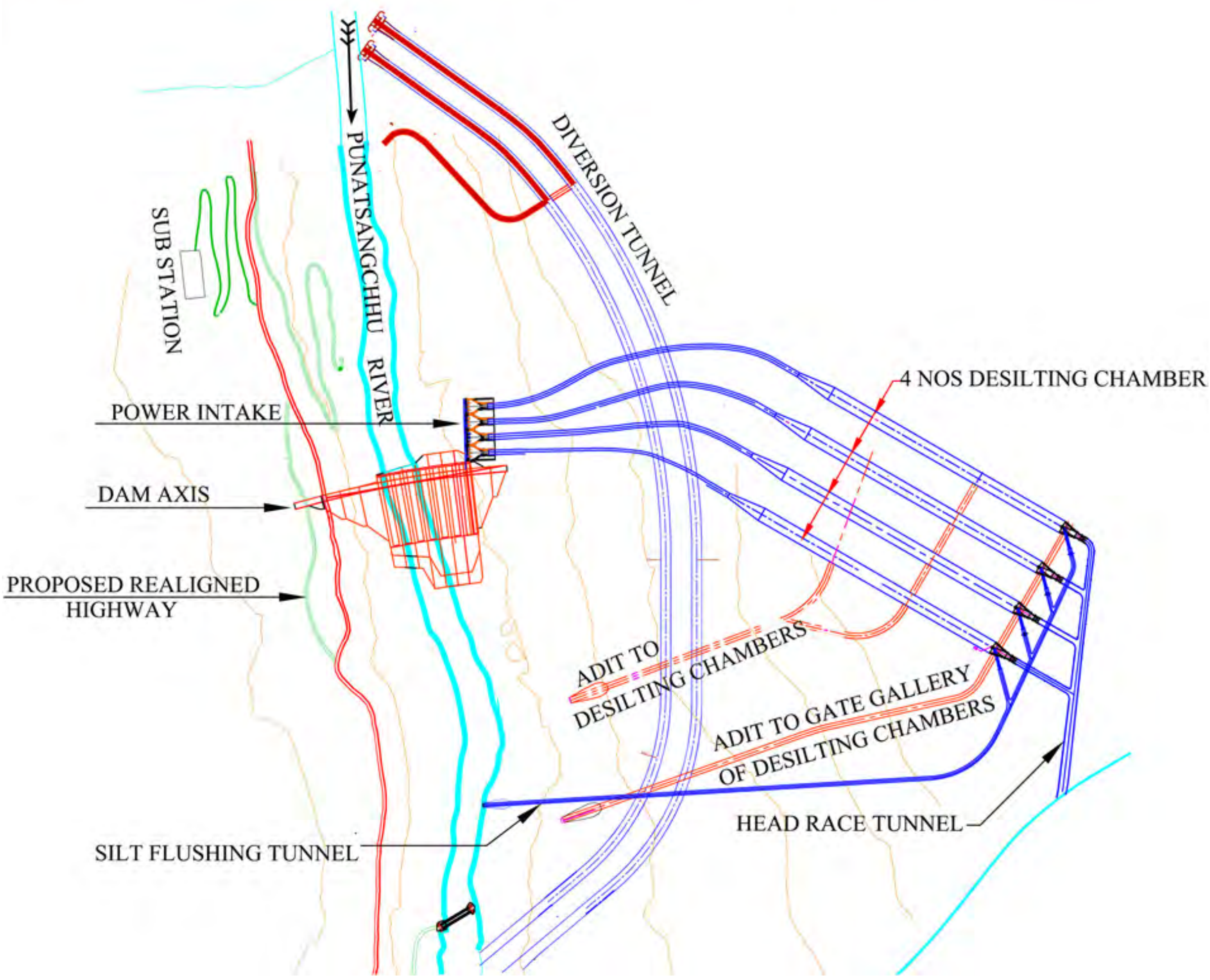


Figure 1. (a) Location map of the project. (b) General layout of the dam complex.

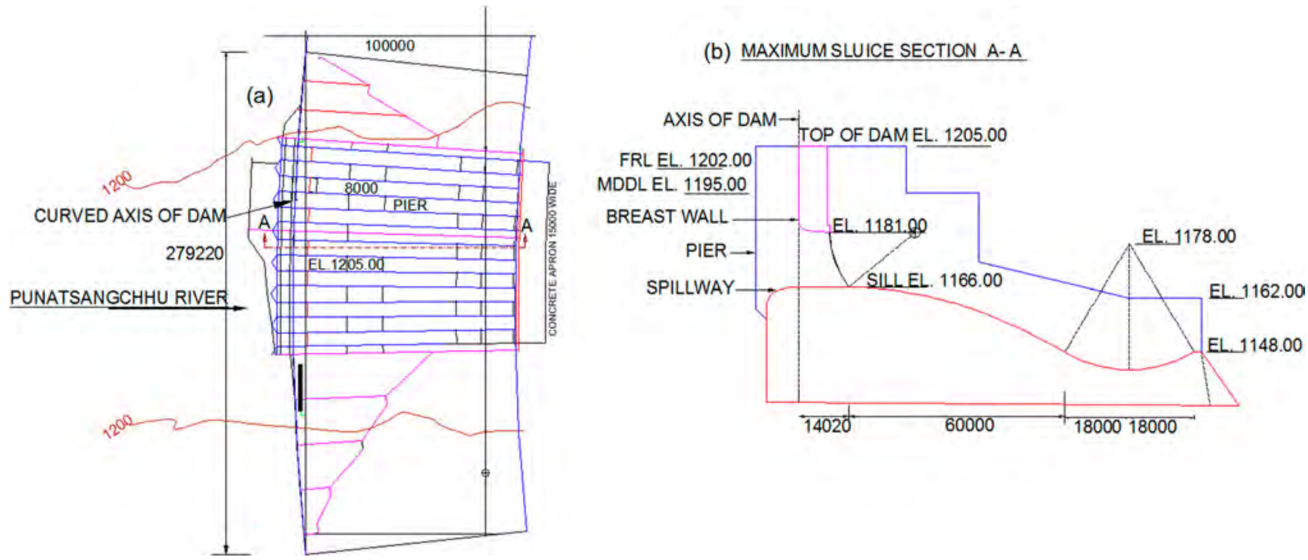


Figure 2. Plan and section of the spillway.

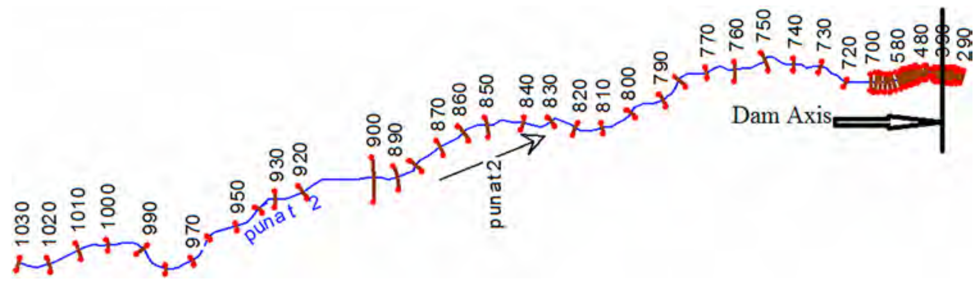


Figure 3. River schematic with cross section locations marked.

flood computed using non-monsoon peaks at Wangdi G & D site for the period 1991–2004. The project is designed for the Probable Maximum Flood (PMF) of 11,500 m^3/s and the Glacial Lake Outburst Flood (GLOF) of 4300 m^3/s.

The project envisages construction of a diversion dam across Punatsangchhu River; an intake system to draw the discharge of 462.65 m^3/s through four units; desilting chambers; a water conductor system and an underground powerhouse. The proposed power generation capacity of the project is 1200 MW utilizing the gross head of 357 m. The general layout of the dam complex is given in Figure 1(b).

Seven sluice spillways of 8 m width and 15 m height are provided to pass a design discharge of 11,500 m^3/s and GLOF discharge of 4300 m^3/s. The proposed reservoir operation level ranges from the elevation El. 1195 m to El. 1202 m; viz., the Minimum Draw Down Level (MDDL) during high flow season to the Full Reservoir Level (FRL) during lean flow season. The sluice spillway crest is at El. 1166 m. An auxiliary log spillway is also provided with crest at a higher elevation of El. 1198 m. The plan and section of the dam and spillway are given in Figure 2.

4.2. 1D numerical model for reservoir sedimentation

A one-dimensional numerical model was developed using HEC-RAS 4.1 (USACE 2010) software to estimate probable sedimentation profile in the reservoir of Punatsangchhu project. The river reaches from dam axis to 18.5 km upstream and 1.5 km downstream was modelled. The topography/bathymetry of the study area was represented in the model by the river plan and cross sections. Cross section data were available at closer interval of 35 m for about 1.5 km near the dam and at a longer interval of 500 m in the upstream reaches. The river schematic specified in 1D numerical model is given in Figure 3.

The 1D numerical model was calibrated for hydrodynamic conditions by adjusting the roughness coefficient; viz., the Manning's 'n'. Steady flow computations for observed discharges and corresponding water levels in the prototype were carried out to arrive at the value of 0.048 for the roughness coefficient.

Discharge measurements were made daily at the Wangdi rapid gauging site and the data were available for the period from July 1992 to July 2009. The above daily discharge hydrograph (Figure 4) after correcting errors and filling the gaps

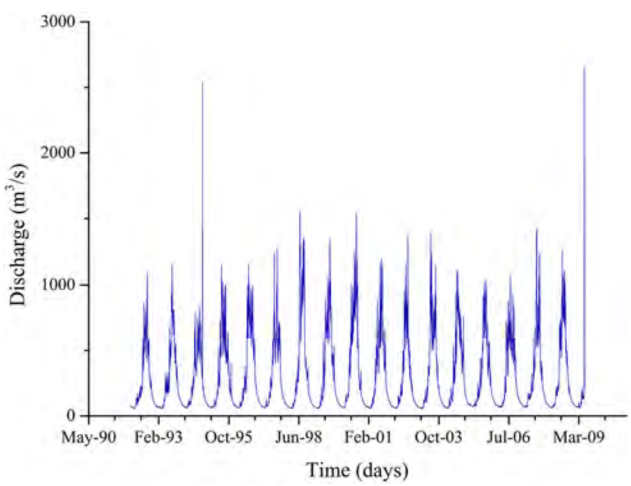


Figure 4. The daily discharge hydrograph.

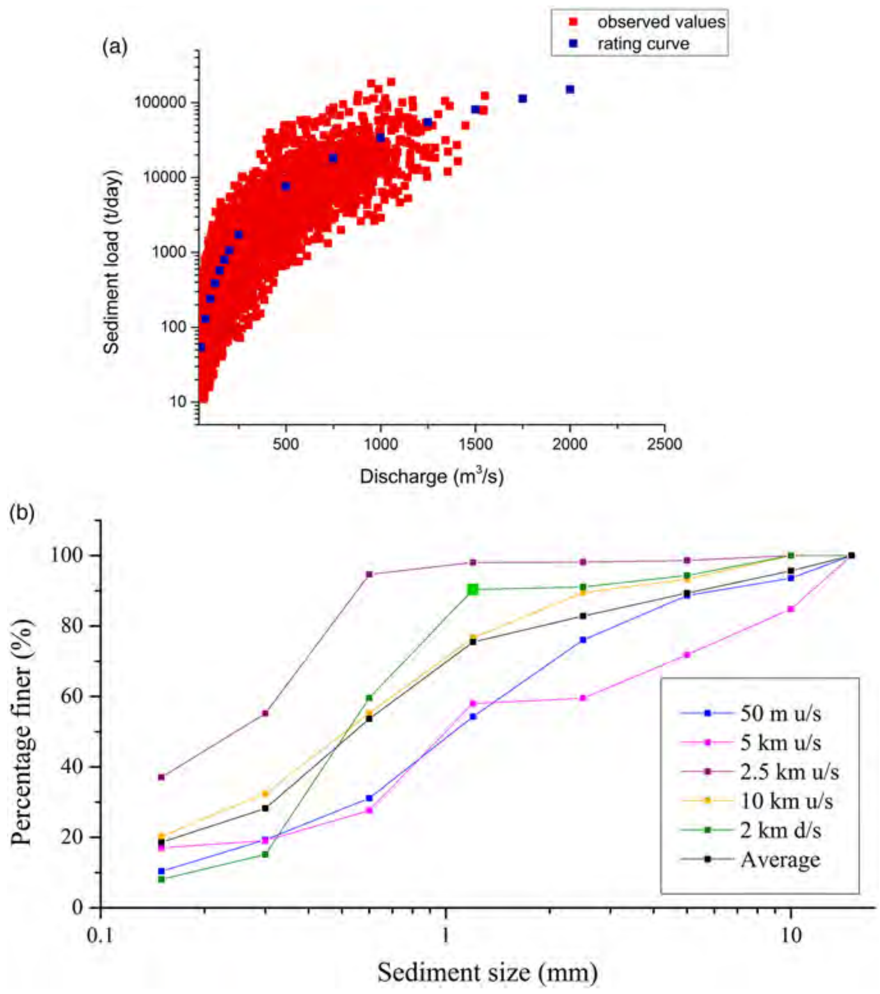


Figure 5. (a) The sediment rating curve. (b) Bed material gradation curves.

was used as the upstream boundary in the simulation runs. Suspended sediment concentration along with corresponding discharge observations was also made at the Wangdi rapid gauging site for the same period. The sediment rating curve (Figure 5(a)) developed from the above data after adjusting for unmeasured load and bed load (20% of the suspended load) was used as upstream sediment boundary condition in the simulations for reservoir sedimentation. The annual sediment load is about 0.23 Mm^3. Gradation curve of bed material from five different locations in the study reach was also used as input data for 1D model (Figure 5(b)).

Sediment transport simulations were further carried out in quasi-unsteady flow mode to predict the sedimentation levels in the reservoir. The reservoir reach from upstream end to the dam axis only was modelled. The discharge hydrograph and sediment rating curve were provided as upstream boundary and reservoir operation levels of MDDL (El.1195 m) and FRL (El. 1202 m) as downstream boundary. Exner 5 bed mixing algorithm, time-step varying with discharge and Ackers–White sediment transport model were adopted in the simulations.

The predicted sedimentation profiles for different years with the MDDL operating condition is presented in Figure 6.

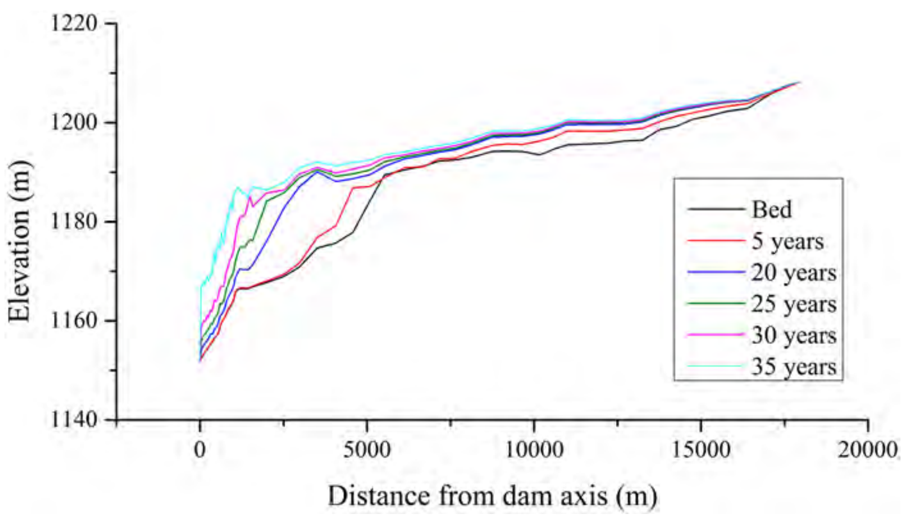


Figure 6. Longitudinal section profiles of reservoir bed after different years of reservoir operation.

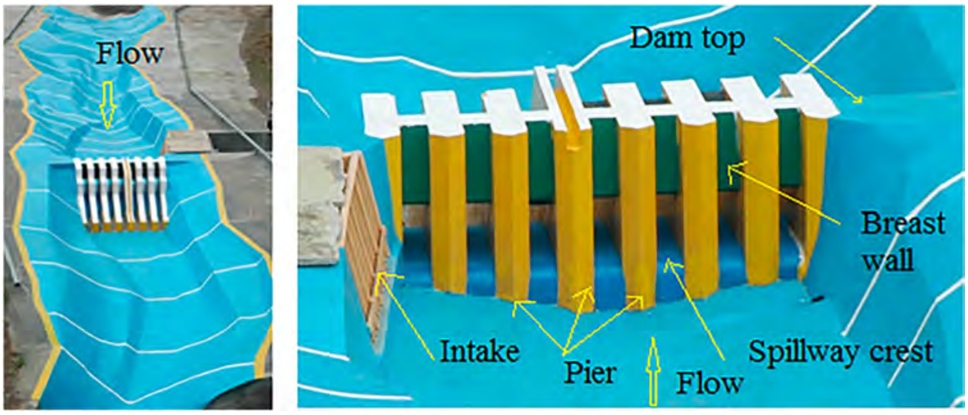


Figure 7. View of Punatsangchhu Reservoir model showing dam and spillway.

The simulations indicated that the sedimentation at the dam axis reached the spillway crest level of El.1166 m after a period of about 33 years. Run-of-the-river reservoirs are operated at MDDL during monsoon season when sediment concentration is high and at FRL during non-monsoon season. Hence, to simulate the extreme sediment deposition condition, the above profile was used as input to the simulation models for reservoir flushing. The project is planned with drawdown flushing during monsoon when the sediment concentration exceeds the design value of desilting basins. Hence, simulations were also carried out with annual flushing by lowering the water level at dam axis during annual peak flows. It was observed that during flushing, the sediment deposition from the area around 5 km is moving downstream towards the dam axis. Finally, the profile will stabilize with the sedimentation level near the dam at the spillway crest level.

4.3. Experimental model for reservoir flushing

In the present study, a 1:100 GS scale model of Punatsangchhu river was constructed for flushing simulations. The reservoir reach of about 10 km upstream and 500 m downstream was constructed (Figure 7). Since gravitational forces are predominant in open channel flows, the model was based on the principle of Froude's law of similitude. The dimensions and hydraulic parameters of model and prototype were related by the same principle. The scale ratios for important parameters are: length 1:100, depth 1:100, area 1: 10,000, volume 1:1,000,000, velocity 1:10, discharge 1:100,000, and time 1:10. The dam with spillways, gates and intake structure as per original design were reproduced in the model. Arrangements had been provided for measurement of inflow discharge (measured at the upstream end of model using standing wave flume), discharge through intake (measured by V-notch), water levels (pointer gauge) and bed levels (measured along each cross-section using pointer gauge). A trap chamber was provided to collect the sediment flushed out.

The model was filled with fine sand according to the sedimentation profile computed from the 1D numerical model to reproduce the initial condition for flushing simulations. Shields critical shear stress and Yang's incipient motion criteria were considered for the simulation of sediment size in

Figure 8. View of Punatsangchhu Reservoir model during flushing.

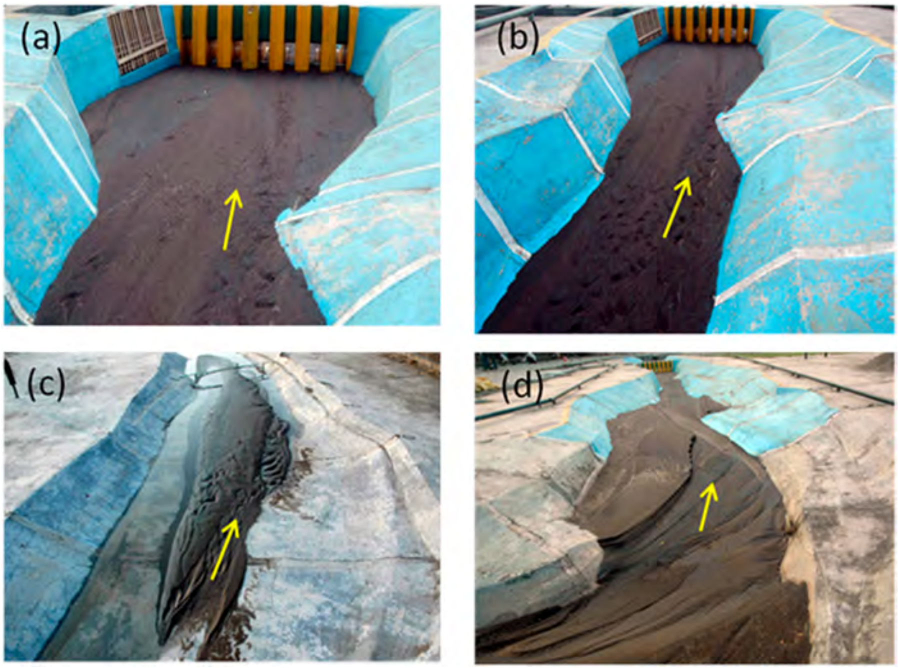


Figure 9. View of Punatsangchhu Reservoir model after flushing with 1000 $m^3 s^{-1}$ for 24 h.

the model. The median diameter (d_{50}) of the bed material samples varied from 0.3 to 1 mm. The d_{50} of sediment according to the average gradation curve was 0.8 mm. The sediment size required in the model to simulate the prototype size of 0.8 mm based on Yang's criteria is 0.14 mm. According to Shields criteria, the sediment size required in the model is 0.10 mm. Since fine sand to simulate the d_{50} of bed material was not available, the locally available sand having d_{50} of 0.24–0.26 mm was used in the experiments. Experience from similar projects indicated that the results of the model studies would be on the conservative side. The actual quantity of sediment removed by flushing on prototype will be more than that predicted by model. Effect and quantum of flushing of reservoir were studied in the model for different flushing discharges and durations. The annual peak discharges during the monsoon months varies from 600 to 1200 m^3/s. Flushing is not feasible beyond 24 h duration since power generation is stopped during flushing. Hence, the discharges and durations corresponding to prototype discharges of 600, 800, 1000 and 1200 m^3/s (6, 8, 10 and 12 l/s in model) and durations of 12 and 24 h (1.2 and 2.4 h in model) were studied in the model. The reservoir water level was kept at FRL at the start of the experiment and all the gates were opened fully to draw down the water level and to achieve free flow condition. Flushing was simulated for the specified duration and at the end of experiments, the volume of sediment collected in the trap chamber and downstream of the spillways was measured. The bed levels at each cross section were also measured and volumetric computations made to estimate the quantity of sediment flushed from the reservoir. The same procedure of experimentation was followed for each set of experiments. Figure 8 shows the reservoir model with the water level maintained at FRL and during the flushing operation.

The sediment deposition levels in the model after 24 h flushing with the discharge of 1000 m^3/s are presented in Figure 9. The longitudinal profile of the reservoir after flushing for 12 h is presented in Figure 10, and Figure 11 shows the longitudinal profile after 24 h flushing. Typical cross sections for 24 h flushing with the discharge of 1000 m^3/s are presented in Figure 12. The volume of sediment flushed out of the reservoir are given in Table 1 and presented in Figure 13 for all the experiments with different flushing discharge and duration combinations.

4.4. Discussion on experimental model results

The sediment deposition profile derived from the 1D numerical model had been used in the flushing model as initial condition. The profile represented the sedimentation pattern after 33 years of reservoir operation. The Punatsangchhu river has three

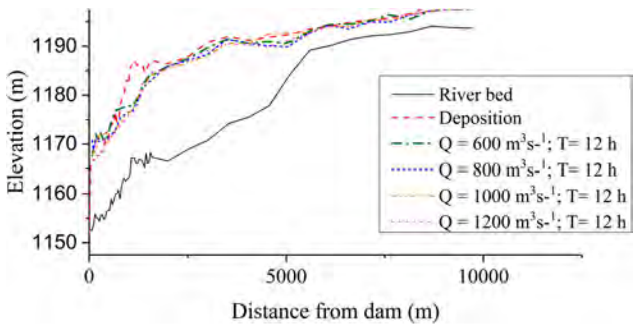


Figure 10. Longitudinal section of Punatsangchhu Reservoir after flushing for 12 h.

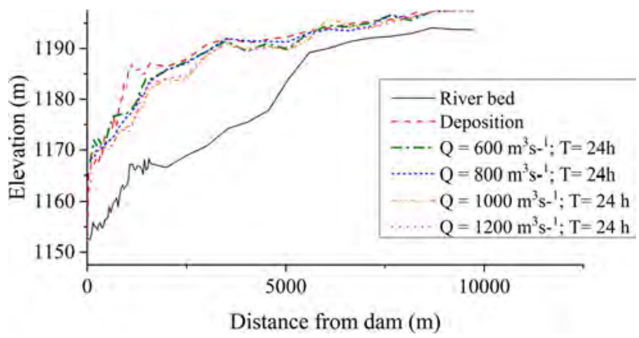


Figure 11. Longitudinal section of Punatsangchhu Reservoir after flushing for 24 h.

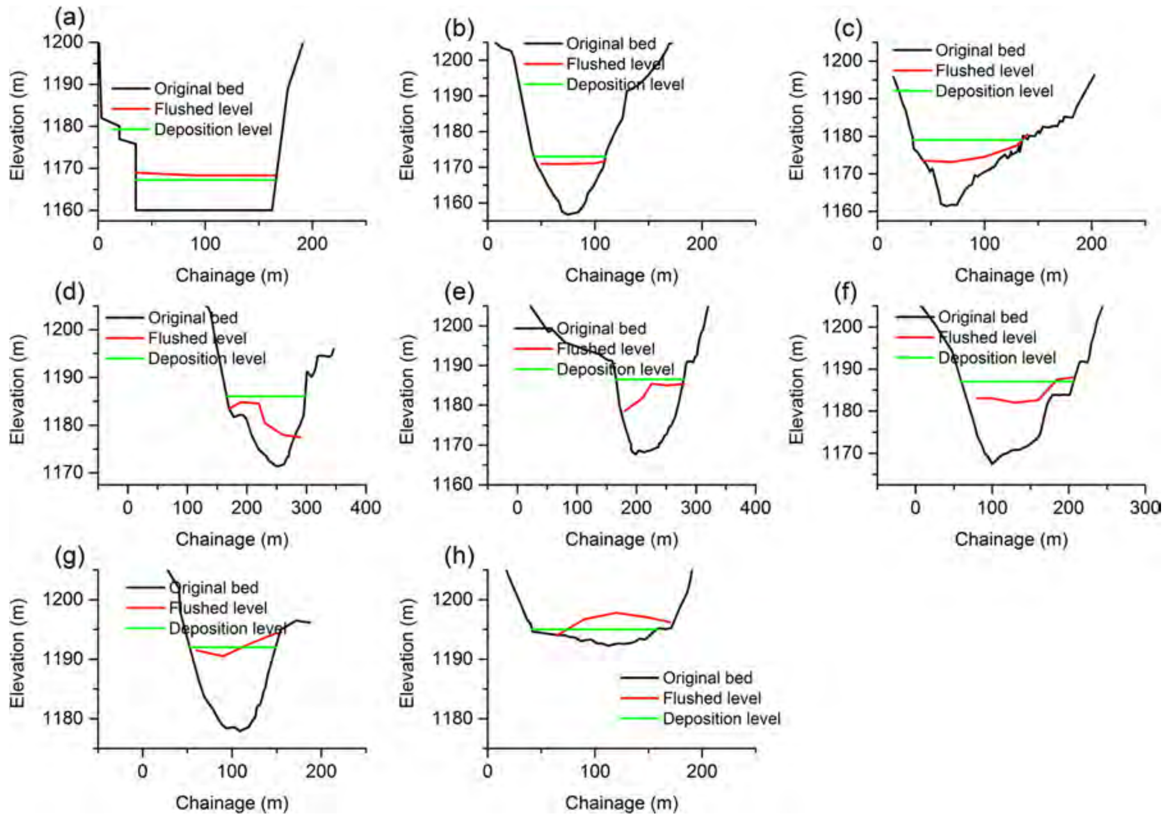


Figure 12. Typical cross-sections after flushing for 24 h with discharge of 1000 $m^3 s^{-1}$.

Table 1. Volume of sediment flushed in 12 and 24 h with various discharges.

Discharge	Quantity of sediment flushed			
	12 h		24 h	
($m^3 s^{-1}$)	Volume (m^3)	Percentage (%)	Volume (m^3)	Percentage (%)
600	169,901	1.89	226,535	2.52
800	254,852	2.84	382,277	4.26
1000	297,327	3.31	410,594	4.59
1200	297,327	3.31	417,673	4.66

distinct bed slopes in the reservoir reach. The downstream most reach of about 1 km near the dam has very steep bed slope (0.013). The river in the reach from 1.5 to 4.5 km is wider and has a flatter bed slope of 0.0034. The Wangdi rapid exists in the reach between 5 and 5.5 km upstream from the dam. The river reaches further upstream of 6 km has a very mild slope

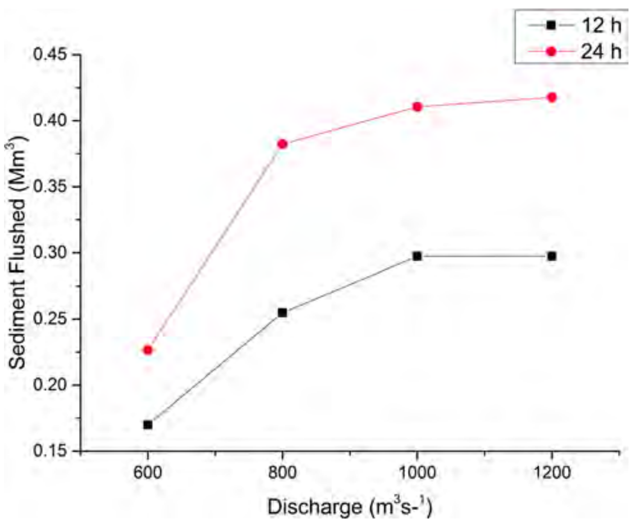


Figure 13. Volume of sediment flushed with different discharges for case study.

of about 0.001. Due to the typical site conditions (river bed slopes), most of the incoming sediment gets deposited along the upstream reaches of the reservoir during the initial period of reservoir operation. The 1D numerical model for reservoir sedimentation indicated this phenomenon. The results of simulation further indicated that most of the sediment deposition occurs along the pool reach (between 1.5 and 4.5 km) downstream of Wangdi Rapid (Figure 6).

The simulations of reservoir flushing indicated that for all the discharge and duration combinations, sediment deposition from the delta front (1.5–4.5 km) in the middle reaches was transported downstream and was flushed out of the reservoir (Figures 10 and 11). The sediment trapped between the river bed and spillway crest level could not be flushed. Due to the very steep bed slope in the downstream reach near the dam and intake, sedimentation is not rising above the spillway crest level and deposition level always remains below the intake invert level.

Observations in the model indicated the development of a flushing channel along the wider middle reaches. The flushing channel was shifting from bank to bank and bars were observed to form along bends (Figures 9 and 12). It was also observed that the sediment deposited along the further upstream reach (about 5.6 km to 7.5 km upstream of dam axis) is not getting flushed even with the higher discharge of 1200 m^3/s. Since the river bed is quite flat and wider in the upstream reaches, sediment deposition from those sections was also not eroded during flushing. Hence, alternative methods of mechanical removal may be necessary to remove the sediment deposition from the above areas where hydraulic flushing is not effective.

The quantity of sediment flushed increased with discharge and duration. However, there was only a marginal increase in the quantity of sediment flushed when the flushing discharge increased from 1000 to 1200 m^3/s. The quantity of sediment flushed varies from 0.17 Mm^3 for 12 h flushing and discharge of 600 m^3/s to 0.42 Mm^3 for 24 h flushing and discharge of 1200 m^3/s. The flushing simulations were carried out on a deposition profile of about 33 years when 72% of the storage capacity is filled with sediment deposition. The flushing simulations had indicated that the annual sediment deposition could be removed by flushing for 24 h duration and discharge of 600 m^3/s; and in 12 h duration if flushing is carried out with higher discharges.

5. Derivation of empirical equations for volume of sediment flushed

5.1. Data used

Hydraulic model studies for drawdown flushing of several run-of-the-river hydropower reservoirs in the Himalayan region were carried out on scale models at Central Water and Power Research Station (CWPRS), Pune, India (CWPRS 2001a, 2001b, 2002, 2004, 2005, 2006, 2008a, 2008b, 2010, 2011a, 2011b, 2014, 2015, 2016). The experimental data from these studies have been utilized to develop empirical equations to estimate/predict the volume of sediment flushed from the reservoirs.

Here, the data corresponding to the experimental studies carried out at CWPRS for reservoir flushing of 13 run-of-the-river hydropower projects in the Himalayan region are considered. The experiments were conducted on geometrically similar scale models of reservoirs as reported in previous sections. The scale of the models varied from 1: 60–1:100. The scale of Chamera – II, Parbati – II and Dhauliganga model was 1:70, The Devsari model was constructed to a scale of 1:60 and the scale of all the other models was 1:100. The height of the dams varied from 26 m in the case of TLDP – III to 116 for Subansiri. However, the heights of most of the dams are in the range of 30–60 m. The reservoirs of Teesta V, Tala, Sewa – II, Kotlibhel IA, II, Subansiri, Punatsangchhu – I and TLDP – III were flushed when sediment deposition was about 70% of the reservoir capacity and TLDP – IV, Kotlibhel – IA and Devsari was flushed when sediment deposition was about 30%. In few cases, the reservoir flushing operation was carried out with extreme deposition and others when the deposition reached spillway crest level or invert level of intake. In all the cases, flushing was carried out with the discharges in the range of average monthly discharge during the monsoon season. The flushing was generally carried out for the duration corresponding to 12, 24 and 36 h in prototype. The details of the data points are given in Tables 2 and 3.

The bed slope of the rivers in these cases varied from 0.0012 to 0.05 and length of reservoir varied from less than 3 km to more than 30 km. For smaller reservoirs, the entire reservoir reach was modelled and for longer reservoirs, l0 km reach of reservoir only was simulated.

The analysis of data from earlier studies and the results of the present studies indicated that the riverbed slope is the most important parameter governing the sediment flushing. It was also observed that the flushing discharge and flushing duration are the other important parameters. Based on the riverbed slope and reservoir capacity; the reservoir projects have been grouped into three categories as:

- 'Very steep': Reservoirs on high gradient (>2%) streams – Very steep bed slope >4% (0.04); stream type 'A' and low storage capacity (<5 Mm^3)
- 'Steep': Steep bed slope 0.5% – 4% (0.005–0.04); stream type 'C' or 'D' and low storage capacity (<10 Mm^3)
- 'Moderate': Reservoirs on low gradient (<2%) streams – Moderate bed slope 0.1% to 0.5% (0.001–0.005); stream type 'C' or 'D', and medium storage capacity (>10 Mm^3)

The stream types 'A', 'C' and 'D' are according to the Rosgen (1994) stream classification system. The present analysis considers the 'steep' and 'moderate' categories only. The details of the projects and the range of important parameters of the data are given in Tables 2 and 3 respectively.

The quantity of sediment flushed depends on various parameters of reservoir geometry, flushing discharge, duration and sediment properties. Scatter plot matrix for 'steep' and 'moderate' category were analysed to observe the variation of the volume of sediment flushed with important parameters and the relation between various parameters. Given a set of variables $X_1, X_2, \dots, X_k$, the scatter plot matrix contains all the pair wise scatter plots of the variables on a single page in a matrix format. That is, if there are k variables, the scatter plot matrix will have k rows and k columns and the ith row and jth column of this matrix is a plot of X_i versus X_j.

The analysis of data indicated that the river bed slope (S) is the most important parameter governing the sediment flushing. The shear stress that depends on the slope is the governing factor for sediment movement during flushing. It was also observed that the flushing discharge (Q) and flushing duration (T) are the other important parameters. Analysis of data indicated that for each of the project investigated; the quantity of sediment flushed increased with the flushing discharge and duration. However, for each discharge, the flushing becomes ineffective after certain duration. The duration of effective flushing generally decreases with an increase in discharge. Similarly, the quantity of sediment flushed stabilizes beyond a certain discharge; generally, the discharge corresponding to the bankfull flow.

The sediment size is another important parameter. The Shield's parameter for critical shear stress for sediment movement is inversely proportional to the sediment size. Hence, the flushing quantity should decrease with an increase in sediment size. In the present analysis, not much data was available with sediment size variability. The quantity of sediment flushed depends on the capacity to inflow ratio of the reservoir. Reservoirs with small capacity-inflow ratio are suitable for flushing. The quantity of sediment flushed was more than 70% of the deposited sediment for 'very steep' category. In some of the case studies, the reservoir flushing operation was carried out when the deposition level reached the spillway crest level or the invert level of intake. In other cases, the flushing operation was carried out when the deposition level reached equilibrium state. In the case of steep and moderate category, the sediment deposition was of delta type. The quantity of sediment flushed depends on the location of delta front with respect to the dam axis and the capacity already occupied by the sediment deposition. If flushing is carried out when the delta front is away from the flushing outlet, the sediment from the delta front will move towards the dam and deposit in the reservoir itself up to the spillway crest level. Hence, the percentage of reservoir capacity filled

Table 2. Details and range of data used for developing empirical equation for 'steep'.

Sl. No.	Project details	Model scale	No. of data points	Slope	Flushing discharge $m^3 s^{-1}$	Flushing duration h	Sediment size (d_{50}) mm	Length of reservoir m	Height of dam m	Capacity at FRL Mm^3	Sediment deposition %
1.	Devsari	1:60	7	0.00667	200–700	12–24	0.26	4800	35	12.46	33.06
2.	Chamera – II	1:70	12	0.00857	300–500	12–36	0.26–0.53	3500	39	2.25	58.98
3.	Teesta V	1:100	12	0.009	1000–2000	12–216	0.53	2500	47	13.52	72.86
4.	Tala	1:100	6	0.0274	300–500	12–36	0.26	2920	89	9.8	77.24
5.	Sewa -II	1:100	12	0.017	50–200	24–72	0.26	2310	40	5.45	77.43

with sediment is an important parameter to optimize the flushing schedule.

5.2. Derivation of empirical equation

Depending on the importance of the parameter and ease of availability during the planning stages of projects, the following parameters; viz., river bed slope (S); flushing discharge (Q_f); flushing duration (T); sediment size (d_{50}); length of reservoir (L); capacity-inflow ratio; and percentage of capacity filled with sediment was selected for developing the empirical equation for predicting quantity of sediment flushing.

Non-linear multiple regression analysis has been carried out to derive a relation to predict the volume of sediment that can be flushed from the reservoirs; using known parameters of reservoir geometry and flushing flow. The regression analysis has been carried out to derive the best-fit equation including the selected parameters using the statistical analysis software 'R'. Separate equations have been derived for the steep and moderate slope categories. The data sets from the earlier experiments have been used for deriving the equations and the data from the present studies have been used for validating the equations.

A total of 37 data sets from 5 reservoir model investigations as detailed in Table 2 have been used to derive the equation for 'steep' category.

The derived equation for 'steep' slope (0.005–0.04) category (hereafter called as Isaac and Eldho Equation for steep slope) is:

$$V_s = 0.11 \; S^{0.0886} Q^{0.5818} \; T^{0.6442} (C_v/V_w)^{-0.1319} (C_f/C_v)^{4.5724} d_{50}^{-0.3171}, \tag{4}$$

where, V_s is the volume of sediment flushed (in million m^3); S is the river bed slope; Q is the flushing discharge (m^3/s); T is the flushing duration (h); C_v is the capacity of reservoir (in million m^3); V_w is the volume of water (in million m^3) used for flushing; C_f/C_v is the ratio of reservoir sediment deposition to the capacity expressed as fraction; C_f is the volume of sediment deposition; d_{50} is the sediment size (mm); L is the length of reservoir (m).

The multiple R-squared value of fitted equation is 0.9962 and adjusted R-squared is 0.9955; which indicates good agreement with the observed values and the fitted equation. The equation was validated using separate set of data (12 data sets). Figure 14 presents the plot of observed data against the predicted values. Results indicate that the predicted values are within 30% error limit.

Similarly, the derived equation for 'moderate' slope (0.001–0.005) (hereafter called as Isaac and Eldho Equation for moderate slope) is

$$V_s = 9.604 \; S^{1.788} Q^{1.334} \; T^{1.429} (C_v/V_w)^{0.919} (C_f/C_v)^{0.959} d_{50}^{3.678} L^{0.154}. \tag{5}$$

The multiple R-squared value of fitted equation is 0.955and adjusted R-squared is 0.952; which indicates good agreement with the observed values and the fitted equation. The data used for derivation of the equation included 104 data sets from 8 reservoir models. The equation was validated using the data from the present set of experiments (8 data sets). Figure 15 presents the plot of observed data against the predicted values. Results indicate that the predicted values are within 40% error limit. The scatter in this case may be due to the large difference in

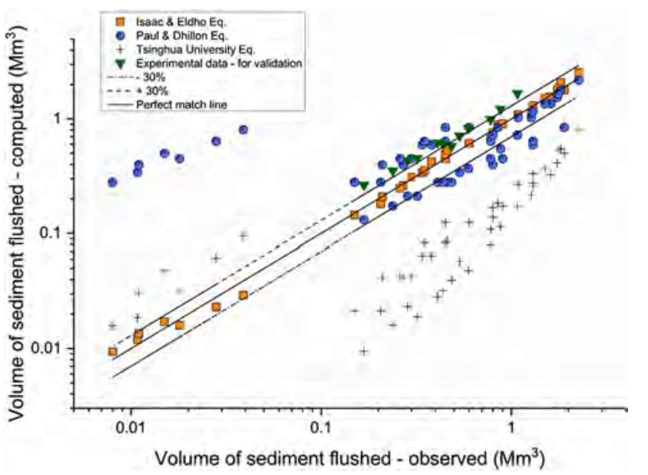


Figure 14. Comparison of observed and predicted values of the volume of sediment flushed ('steep').

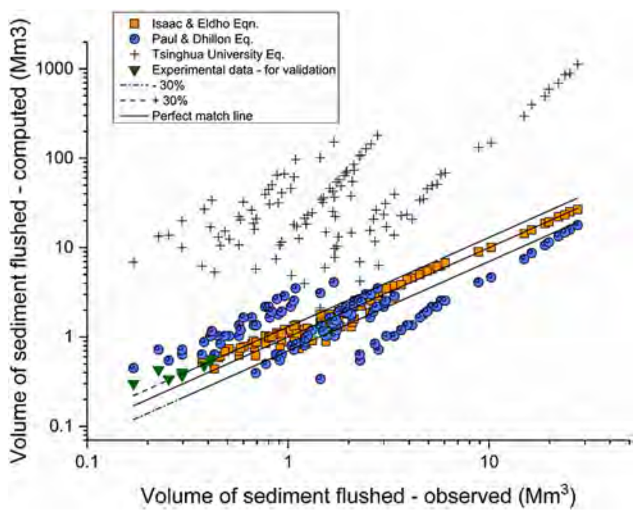


Figure 15. Comparison of observed and predicted values of the volume of sediment flushed ('moderate').

Table 3. Details and range of data used for developing empirical equation for 'moderate'.

Sl. No.	Project details	No. of data points	Slope	Flushing discharge $m^3 s^{-1}$	Flushing duration h	Sediment size (d_{50}) mm	Length of reservoir m	Height of dam m	Capacity at FRL Mm^3	Sediment deposition %
1.	Kotlibhel – II	15	0.00129	700–3000	12–36	0.26	29,000	57	78.58	71.3
2.	Subansiri Lower	12	0.001833	6000–7500	12–216	0.21	10,000	116	316.16	75.7
3.	Dhaulasidh	12	0.002	1000–4000	12–36	0.26	6500	48	95.87	14.22
4.	Punatsangchhu-I	8	0.0032	600–1200	12–24	0.23	14,500	54	12.5	71.84
5.	Teests Low Dam Project (TLDP) – III	15	0.002273	1000–5000	12–36	0.26	5500	26	18.36	66.23
6.	Teests Low Dam Project (TLDP) – IV	12	0.0025	1000–2500	12–36	0.26	3500	32.5	36.63	37.6
7.	Kotlibhel – IA	23	0.00452	500–1200	12–144	0.26	10,000	82.5	46.17	32.8
8.	Kotlibhel – IB	15	0.00246	400–2000	12–36	0.26	10,000	68.5	57.41	95.84

bed slopes existing along different reaches of the reservoir considered for validation.

5.3. Discussion on empirical equations

The values predicted for the volume of sediment flushed with the flushing discharge using Paul and Dhillon equation (Equation (1)) is also presented in Figures 14 and 15. Figures 14 and 15 indicate that there can be more than one equation to predict the volume of sediment flushed using volume of water used. Three distinct set of curves can be fitted for 'moderate' category. The prediction is better for 'steep' category. However, in this case, also three distinct equations are possible. Equation (1) considers only the flushing discharge for predicting the sediment discharge. The variation of the predicted values can be due to the omission of other important parameters.

Similarly, the flushing quantity predicted using Tsinghua University equation (Equation (2)) is also presented in Figures 14 and 15. However, in the available data and the present set of experiments, the outflow rate of sediment discharge was not measured. The total volume of sediment that was flushed from the reservoir was measured at the end of each experiment. The plotted values are the average rate of sediment discharge computed from the total volume of flushed sediment. Equation (2) was developed for the equilibrium sediment outflow rate in wide reservoirs when the drawdown flushing is fully established and the flushing channel width and the sediment outflow rate stabilize. In the present analysis, the width of channel was predicted using Equation (3) and the coefficient of 10.91 reported by Lai and Shen 1996. Since the data used in the present analysis corresponds to steep and narrow reservoirs, Equation (3) over predicts the width of flushing channel. Figures 14 and 15 indicate multiple sets of curves for a different type of reservoirs. The dimensionless erodibility coefficient (φ) was selected as 1 for 'steep' and 300 for 'moderate' category. Few other equations are also available in literature (Morris and Fan 1997, Batuca and Jordan 2000, Brandt 2000). However, they have not been compared here mostly due to non-availability of data at the planning stage of projects. Comparison of Fan and Jiang equation shows more or less similar results as for Equation (2). Hence, the same has not been plotted in Figures 14 and 15.

The present set of equations is developed based on the data of the physical model studies for reservoir flushing of hydropower projects in the Himalayan region. Equation (1) also has been developed for the same region. However, the prediction using the above equation is not good since it is based on only one parameter of volume of water used for flushing. Equation (2) has been developed based on Chinese reservoirs, which are wider than the flushing channel, and for the sediment discharge rate at equilibrium state. The present equations are developed for predicting the quantity of sediment that can be flushed from reservoirs of run-of-the-river projects in the Himalayan region. The reservoirs are narrow and gorge type and the flushing channel extends to the entire reservoir width. The river bed slope is steep and ranges from 0.05–0.001.

The presently developed equations (Eqs 4 and 5) are more accurate and since the parameters are readily available, they can be used effectively during the planning and investigation stages of projects to get preliminary estimates of the quantity of sediment that can be removed by flushing. It will be useful for analysing the project feasibility. Since the percentage of water storage capacity already occupied by sediment deposition is included as one of the variables in the equation, the present equations are very much useful during the planning and design of hydropower projects. Various alternative flushing schedules at different sediment deposition levels can be analysed and flushing schedule can be optimized.

6. Conclusions

In the present study, hydraulic model simulations were carried out for flushing of sediment from the reservoir of Punatsangchhu hydroelectric project in Bhutan. The 1D numerical model simulations carried out to predict the long term deposition pattern in the reservoir indicated that the sedimentation level at dam site reaches the spillway crest level in about 33 years of reservoir operation. It was also indicated that due to the typical river bed slope pattern existing along the reservoir reach, sediment deposition levels are high in the middle and upper reaches and the delta front advances to about 1.5 km from the dam axis. The experiments for hydraulic flushing was conducted on a 1:100 geometrically similar scale model of 10 km reach of reservoir with the sedimentation profile computed by 1D numerical model as initial condition. The experiments indicated that flushing is effective in maintaining the power intake area clear of sediment deposition. If flushing is carried out every year with discharges more than 800 m^3/s for 12 h, the annual sediment deposition can be flushed out. However, due to the typical flatter bed slopes in the upstream reaches, sediment deposition from the upstream reaches could not be flushed hydraulically. Alternative methods may be required to remove the deposition from the upstream reaches.

An alternative to hydraulic model studies is to use empirical equations to get a preliminary assessment of the volume of sediment that can be removed by flushing. Few empirical relations available in literature have been crosschecked using the data available from the earlier experimental studies carried out at CWPRS, (Central Water Power Research Station) Pune, India. It was observed that the equations are not good enough to predict the flushing quantity; due to the limited amount of data and parameters used for developing these equations. In the present study, attempts have been made to develop empirical equations for predicting the quantity of sediment that can be flushed from reservoirs using wide range of experimental data and including more parameters. Non-linear multiple regression analyses have been carried out between the important parameters of reservoirs and the measured quantity of sediment that was flushed. Two separate equations (called as Isaac and Eldho Equations) have been developed for different river bed slope ranges; 'steep' (slope 0.005–0.04) and 'moderate' (slope 0.001–0.005). The equations were developed using data from 104 data sets of 8 different experimental studies for 'moderate' and 37 data sets of 5 different experimental studies for 'steep' slope. The analysis indicated very good correlation between the measured and the computed values with multiple regression coefficients greater than 0.95. The equations were validated against different sets of data and it indicated that the predictions could be made within 30–40% error limit. Hence, these equations can be used during the planning and feasibility study stages; to make a preliminary assessment of the volume of sediment that can be removed by hydraulic flushing from reservoirs of run-of-the-river hydropower projects. The equations are very much useful during the project feasibility study stages, to analyse alternative proposals and designs and to optimize the flushing schedule.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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