MODELING FOR SEDIMENT MANAGEMENT OF GULPUR HPP RESERVOIR ON POONCH RIVER

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ABSTRACT: *Sediment deposition in a reservoir decreases storage capacity and effects many other parameters of the reservoir adversely. It reduces benefits and useful life of a hydro power project that have huge socio-economic impacts. Flushing is one of the techniques to remove sediments from reservoirs. This study investigates sediment accumulation, transportation and flushing using both the physical and numerical modeling. Gulpur Hydro Power Project (HPP) on Poonch River in Pakistan was chosen for this purpose. The geometry, cross-sections and other physical attributes of the Poonch River were prepared and hydraulic structures were placed on the basis of topographic survey using AutoCAD. Physical model of scale 1:40 was developed at Nandipur Research Station in Pakistan. After base test the model was used to get data for various scenarios of sediment flows. HEC-RAS was used for numerical simulations. Delta profile and flushing were simulated. Delta modeling was made for hourly time step for 20 years of sediment deposition with average discharge conditions, whereas, suitable flushing durations were predicted for various flushing discharges to de-silt yearly deposited sediments. Simulation showed that life of the un-sluiced Gulpur HPP is about 14-15 years. To enhance the life of project, annually 4-5 days are required for flushing with 250 m^3/s discharge.*

Keywords: Sedimentation, Flushing, hydropower, Reservoir, HEC-RAS, modeling

1 INTRODUCTION

Sedimentation is one of the most complex aspects in the reservoir operation, engineering, planning and management. Sedimentation has multidimensional influences on water resources. Loss of capacity of a reservoir has direct impacts on its functionality hence it should attract maximum attention from sustainability point of view [1]. From operational and physical perspective of the issue, sedimentation is gradually reducing the storage capacity of reservoirs all over the world. The average annual storage loss is about 1 percent [2]. Severity of the situation can be net estimated from the fact that if current sedimentation rate continues, it is predicted that around 300 to 400 new dams would be required to be constructed every year to sustain total storage [3]. There are various ways to sustain the storage capacity of a reservoir like catchment management, dredging, sediment flushing, routing/sluicing and bypassing of sediments that can be used individually or in grouping [4]. In area of flushing, Atkins [5] develops a procedural model which determines the features of a reservoir to be effective in flushing at full drawdown; whereas, assessment of reservoir sedimentation has been done using numerical simulation for previous two decades.

The importance of the sediment flushing can be seen from another aspect that national grids of poor countries are facing severe electric power shortages which have forced them for maximizing the utility of available water resource by putting hydropower projects in cascade manner on rivers. Like many other countries worldwide, almost on all rivers of Pakistan, hydropower projects are being placed in a cascade sequence. Most of the cascade hydropower projects are run-of-river schemes i.e. do not have seasonal storages, hence have very limited reservoir capacities which are prone to filling-up in very small span of life if adequate flushing mechanism is not provided. However, while providing the flushing mechanism, it needs to be optimized as in most of the cases water used for flushing will not be available for power generation hence overall generation capacity of the project will be compromised.

In flushing, the velocity of flow in a reservoir is increased near the bed of the river which mobilizes and transports the deposited sediments through bottom outlets [6]. There are two approaches for flushing i.e. complete draw down and partial drawdown [7]. Partial draw down flushing can be used to increase live storage capacity and trace the sediment in a further satisfactory location aimed to full drawdown flushing [8]. In complete drawdown technique, reservoir water is spilled afore the flood season under normal conditions of flow in the reservoir. For flushing; outlets placed near the original river bed level with adequate hydraulic capacity to accomplish complete draw down [9]. The parameters of flow and sediment need to be optimized separately for each type of flushing. In present study complete draw down flushing has been investigated.

Longitudinal slope of reservoir, reservoir length, shape of reservoir, sediment size, flushing discharge, flushing duration, bed width, size of flushing outlet, capacity inflow ratio of the reservoir, flushing outlet sill height are among the parameters that affects the sediment flushing in a reservoir [10]. Whereas, sediment balance ratio (SBR), drawdown ratio (DDR), long-term capacity ratio (LTCR), top width ratio (TWR) and flushing width ratio (FWR) are various indicators to assess the feasibility of flushing sediments from a reservoir.

Flushing is considered successful when SBR >1, LTCR approaches 1, FWR >1, DDR = 0.7, and TWR = 1 to 2 [11].Out of six, the most essential indicators are LTCR and SBR that are fulfilled for successfully flushed reservoir but LTCR criteria is never met for unsuccessfully flushed reservoirs [12] [13].

The goal of current study is to examine the reservoir sedimentation aspects with the help of physical model and numerical simulation for a river which may encounter a flash flood pattern with a large sediment concentration transported through it. Gulpur HPP on Poonch River was used to deal with a real life problem. In case of Gulpur reservoir, which has smaller storage volume compared to the annual inflow and water depth is also relatively smaller; so, without sediment management, Gulpur reservoir will be filled with sediment within 14-15 years. Under this situation more sediment will pass through the turbines compromising their performance and integrity. Therefore, for the sustainability of the project a proper desiltation is required. For this purpose the sediment flushing method has been chosen being the most economical method for desilting. However, there is a need to explore adequate parameters to flush the sediment through reservoir, so that the life of the reservoir is enhanced.

2 MATERIALS AND METHODS

2.1 Description of HEC-RAS and Governing Equations

Several methods are being used to evaluate the reservoir sediment management including HEC-RAS. The HEC-RAS was developed at Hydrologic Engineering Center (HEC) by U.S. Army Corps of Engineers and is a widely tested model. It has the capacity to act as a tool for reproduction of one dimensional steady and unsteady flow in a variety of hydraulically possible cases and sediment transport mobile bed modeling over moderate periods. This software is available as an open source.

The assessment of general sedimentation pattern in the reservoir, considering long time scales (several years) and changes in storage capacity for trapping the sediment, is performed with one dimensional HEC-RAS numerical model for simulation of long-term reservoir sedimentation.

For performing the sediment transport analysis, HEC-RAS works by using sediment continuity equation shown below (which is also called as Exner equation,[14] and sediment is routed from a cross section to the next one. Particles' Entrainment depends on the bed shear stress [14].

$$\left(1-\lambda_p\right)B\,\frac{\partial\eta}{\partial t}=-\frac{\partial Q_s}{\partial x} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(1)}$$

"Where η is bed elevation, B is the width of the control volume, Q_s is transported sediment load, λ_p is bed porosity, x is a distance, t is the time".

Each cross section is made up of a sediment control volume that extends half way upstream and halfway downstream from a particular cross section. The transport capacity is calculated for each control volume and is compared to the available sediment supply. Generally, when the supply of sediment is greater than the transport capacity, deposition occurs as a vertical change of the bed elevation and if the supply is smaller than the transport capacity, erosion occurs. Sediment boundary conditions are applied in similar way as that of flow boundary conditions.

Grain size distributions from bed samples can be associated with each cross section. Sediment transport is then calculated for each size division of particle separately before adding together to a total transported load. The amount of transported material for specific hydraulic conditions can be solved in many ways, and the user can choose from established transport functions. Most of the functions were developed for sand or coarser particles and only a few treat finer particles. Using standard supply-driven transport equations for finer cohesive sediments would force the model to extrapolate outside the derived range of the function. The finer fractions would then represent an almost unlimited source that only requires a small flow increase to be entrained [14]. Bed erosion of finer particles would have to use other transport functions to account for the cohesive characteristics. HEC-RAS offers transport functions for cohesive materials like silt and clay. There are two methods available in HEC-RAS for dealing silt and clay particles: using the standard transport equations, or implementing the Krone [15] and Partheniades [16] approach.

Moreover, HEC-RAS includes three algorithms to simulate bed sorting and armouring that divide the bed into active and inactive layers. The algorithms as well as sediment fall velocity can be chosen by the user. The sorting method decides how specific grain fractions are eroded and the fall velocity determines whether a particle will be held in suspension or be deposited.

The 2-D models require a significant amount of additional data of specific nature and time to set up and run. The 1-D model can satisfactorily serve the purpose if suitable data is available. Keeping in view the nature and extent of data available for this study, use of 1-D model was preferred; however, it has a limitation that it cannot simulate meander development or compute a lateral distribution of sediment load across a cross section. Further, the sediment transport results are strongly dependent on selected transport function.

HEC-RAS requires two boundary equations, Manning's equation and a sediment transport function which may deal with variation of sediment concentration in different layers of flow depth wise (sorting). This will involve some additional parameters to be estimated for roughness (Manning's n) and sediment transport. The input data for HEC-RAS includes geometry of river, hydraulic data like discharge hydrographs and sediment data.

2.2 Geometry and parameter of the model

As described above HEC-RAS needs data for categories like Quasi-unsteady flow data; Geometric data; bed gradation curve and inline structure data. The geometry file for HEC-RAS contains information on cross-sections, hydraulic structures, river banks and other physical attributes of the river.

The model was built for 11.46 km river length with 41 cross-sections and the dam site is situated at halfway between Section No. 10 & 11 (Fig. 1). River reach under study is a mountain stream with vegetation in channel, banks are steep with trees and brush on banks submerged. Choosing the value roughness coefficient say Manning's n is a challenging task for such a river reach [17].

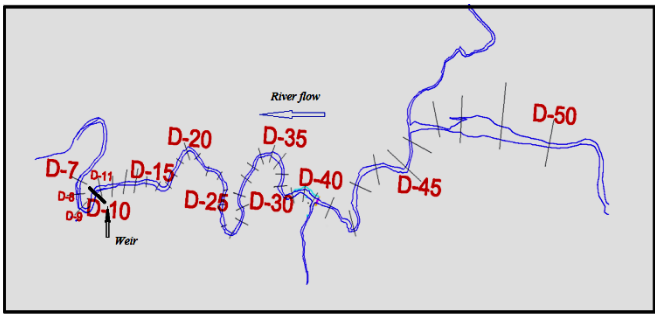

Fig. 1: Schematic Diagram showing the Cross Sections Locations used for the delta modeling.

2.3 Boundary conditions and transport function

Quasi-Unsteady flow boundary conditions: Monthly flow hydrograph was taken as upstream flow boundary condition and stage time relationship as downstream flow boundary condition.

Sediment data: Bed gradation, maximum scour depth, sediment transport function, sorting method and fall velocity method were taken as "initial conditions and transport parameters" whereas; sediment rating curve as "sediment boundary condition".

Bed load transport capacity is estimated by different transport functions such as Ackers-White [18], Engelund-Hansen, Meyer-Peter & Muller-MPM and Yang. The results of HEC-RAS simulations by using various transport functions were compared and Ackers-White formula was found the most appropriate for this study. It has intensively been adopted for cases having more sand fraction than finer materials. This was also used for sediment simulation and management of Mangla dam in 2015 [19]. Geomorphological conditions of Poonch River resembles with that of Mangla Dam. Moreover, Wallingford [20] also considered it appropriate to use in case of total load transport capacity of sand-sized fraction. The measured sediment data shows different fractions in various sediment layers in water so adoption of sorting was necessary in present study for which Thomas (Ex-5) [21] was preferred. Theoretical deposition and erosion estimated by solving sediment continuity needs modifications to bring it close to the real values. Various approaches were used for this transformation. Van Rijn approach [22] was selected to deal with fall velocity.

3 PROJECT AREA AND SPECIFICATIONS

The Gulpur Hydropower Project (HPP) is a run-of-river scheme located on Poonch River about 25 km upstream of very famous Mangla Reservoir in Pakistan. The Gulpur HPP has a 66 m high dam with a crest level at 533.5 masl having 205 m length. The weir structure is provided with 6 ogee type spillways with free overflow having crest level at 503.3 masl and a width of 11.5 m each. The design flood of the weir is 17208 m^3/s that corresponds to 500 years frequency flood. The Project with 57.45 m head has installed capacity of 102 MW and will generate 465 GWh of energy per annum. The maximum water level in the reservoir is 532.2 masl whereas; normal operating level is 532 masl which creates 10 km long reservoir upstream of the weir structure.

3.4 Catchment data

Poonch River is one of the three main tributaries of Jhelum River, (Neelum, Kunhar and Poonch). It rises in Pir Panjal mountain range at an elevation of about 4320 masl and has its confluence with Jhelum River in Mangla reservoir at an elevation of about 366 masl. Near the city of Poonch it enters a comparatively wide valley; from there onwards the average slope of the river is about 6 meters per kilometer. The total catchments area of the Poonch River (i.e. upto Mangla Reservoir) is 4196 km2; whereas, the catchment area up to the proposed dam site is about 3,648 km2. Mean weighted elevation of the catchment is about 2380 masl. Gulpur Reservoir Catchment is shown in Fig.2.

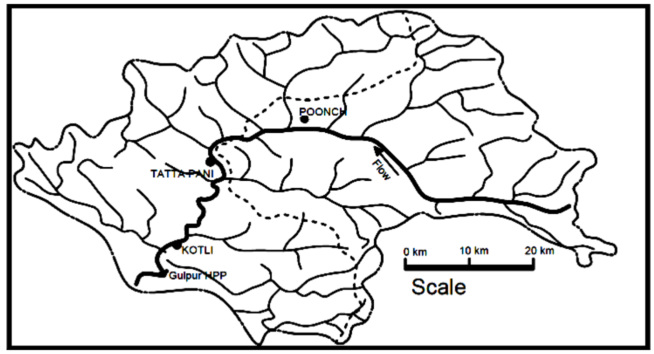

Fig.2: Gulpur Reservoir Catchment

3.5 Hydrology and sediment data

Daily flow series was developed from the daily mean flow data of the Gulpur HPP for the period of 1960 to 2014. The average mean annual flood in the recorded period is 125.4 m^3/s. A minimum of 9 m^3/s was observed in January 1966 and maximum monthly value of 830 m^3/s in September 1992. Average annual discharges from year 1960-2014 are shown in Fig.3:

Two series of water discharges each of 20 years period have been considered. The first series (Series 1 in Fig.3) extends from 1962 to 1982 and is representative of the average inflows into the reservoir. The second series starts in 1988 which includes some of the highest discharges in the record, as the 1992 event (Series 2 in Fig. 3).

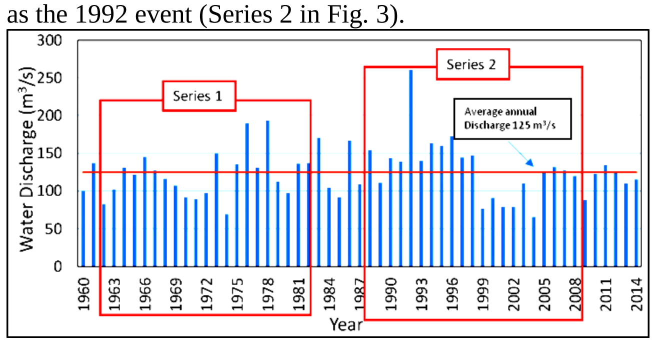

Fig. 3. Water Discharge Series Used For Numerical Simulations

The average monthly values show two annual peaks of discharge, a minor one in March-April (of the order of 180 m^3/s) related to the snowmelt period, and a larger one in July-August (with an average value of 264 m^3/s).The monthly variation of flow within an average year is shown in Fig. 4.

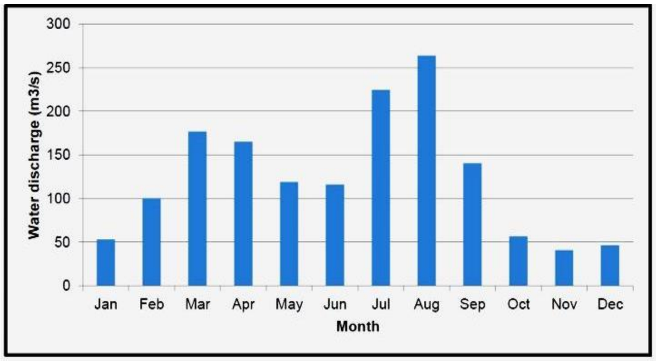

Fig.4: Ave. Monthly Water Discharges from 1960-2014

Sediment concentration data measured by Water and Power Development Authority (WAPDA) at gauging station near Rehman Bridge was analyzed. A sediment rating curve was prepared by correlation between river discharge and sediment load for the period of 1960-2014 as per USBR guidelines procedures. The resultant models to estimate the daily suspended load using daily flows is shown below in equation 2 through 4:

$Q_s = 6.048 \times 10^{-3} Q_w^{2.95}$ for $Q_w < 153 m^3/s$ ………… (2)

$Q_s = 2.5056 \times 10^{-1} Q_w^{2.22}$ for $153 < Q_w < 530 m^3/s$…….(3)

$Q_s = 94.0032 Q_w^{1.276}$ for $Q_w > 530 m^3/s$ …………... (4)

Whereas; (Q_s) Suspended sediment discharge (tons/day), (Q_w) is the River discharge (m^3/s).

The annual suspended sediment load is calculated for the existing flow series, from 1960 to 2014, as shown in Fig. 5.

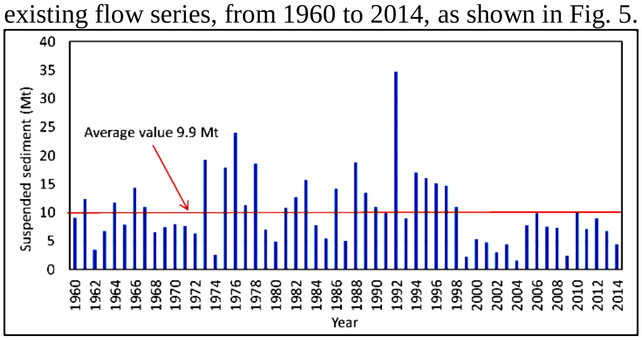

Fig. 5: Annual Suspended Sediments from 1960-2014

It is estimated that mean annual suspended sediment load is about 9.9 million tons. Keeping in view the guidelines of USBR given in design of small dam [23], the characteristics of suspended sediment concentration and streambed material of Poonch River, the quantity of bed load has been taken as 20% of the suspended sediment load.

The average percentages for each fraction are calculated from the suspended field data and an additional 20% is added to the sand fraction that corresponds to the material transported as bed load. The percentages considered in this study are 23% of clay, 50% of silt and 27% of sand, based on recorded data.

Since a large amount of sediment inflow encounters in Poonch River so an arrangement is essential for effective and timely flushing of the sediment flows for the proper operation of the power plant. The representative sizes and proportions for each fraction of sediment used in model, as a base case, are presented in Table 1.

Table 1. Sizes and %age of fractions in sediment inflow (Assumed as base case for modeling)

Class no	Description	Representative diameter	%age in all sediment
1	Clay	0.003 mm	23%
2	Silt 1	0.01 mm	25%
3	Silt 2	0.035 mm	25%
4	Sand 1	0.1 mm	12.27%
5	Sand 2	0.3 mm	12.27%
6	Sand 3	1 mm	2.01%
7	Gravel 1	3 mm	0.45%

It is assumed that the sizes larger than medium gravel will be removed upstream from the reservoir by sediment mining (except variation 3) see Table. 2. It is advised to remove the large sediment in a controlled manner using check dams.

To assess the sensitivity of the results to the sediment values, three additional scenarios were considered based on sizes and %ages of fractions in sediment inflow as shown in Table 2.

- Variation 1: It considers an increased total sediment inflow by considering bed load as 40% of the suspended load.
- Variation 2: This variation considers the observed suspended flow only, i.e. without the addition of the estimated 20% of bedload. The proportion of fine sediment (silt and clay) flowing into the reservoir (i.e. 89%) is thus higher than the base case (i.e. 73%) and the coarse material in suspended load comes out to be 11 % only.
- Variation 3: It considers two more fractions of coarse material (Gravel 2 with d=10 mm and Gravel 3 with d=30 mm) but maintaining the total amount of sediment. The added 20% of unmeasured bedload is split equally between sand (10%) and gravel (10%).
- Variation 4: It considers that the proportion of sand is double (i.e. 54%) while maintaining the same total amount of sediment. The percentage of clay is thus reduced to 14.4% and silt to 31.6%.

Table 2. Sizes and %ages of Fractions in Sediment Inflow (Assumed For the Variation Scenarios)

Class No.	Description	Representative diameter (mm)	Percentage in all sediment (%)			
			Base case & variation 1	**Variation 2**	**Variation 3**	**Variation 4**
1	Clay	0.003	23	27	23	14.4
2	Silt 1	0.01	25	31	25.6	15.8
3	Silt 2	0.035	25	31	25.6	15.8
4	Sand 1	0.1	12.27	5	8.1	24.5
5	Sand 2	0.3	12.27	5	8.0	24.5
6	Sand 3	1	2.01	0.82	1.2	4.02
7	Gravel 1	3	0.45	0.18	4.4	0.9
8	Gravel 2	10	-	-	2.9	-
9	Gravel 3	30	-	-	1.2	-

3.6 Operation policy

For the modeling of deposition pattern in the reservoir, water level in the reservoir was considered constant at 532 masl called Normal Operation Level.

3.7 Definition of modeling scenarios

Table 3 describes the scenarios considered to model the deposition pattern in the reservoir, considering no sediment management options in the reservoir.

Table 3. Description of Tests

Test	Description	Discharge	Sediment inflow	n
1	Base case	Series 1	Base case	0.03
2	High water flow series	Series 2	Base case	0.03
3	Increased sediment inflow	Series 1	Variation 1	0.03
4	Observed inflow only	Series 1	Variation 2	0.03
5	Increased gravel fractions	Series 1	Variation 3	0.03
6	Increased roughness	Series 1	Base case	0.05
7	Double sand	Series 1	Variation 4	0.03
8	Double sand and high flows	Series 2	Variation 4	0.03

4 PHYSICAL MODELING OF GULPUR HPP

The physical model was built with geometric scale ratio of 1:40 at Nandipur Research Institute, Gujranwala, Pakistan. The river bed elevation of 480 masl at just upstream of the dam in Prototype corresponds to bed elevation of 230 masl in the Model. The scale ratios shown in Table 4 were generated according to Froude's model law [24].

Table 4. Scale ratios of Physical Model

Dimension	Ratio	Scale Relation
Length	L_r	**1: 40**
Time	$T_r = L_r^{1/2}$	**1: 6.32**
Velocity	$V_r = L_r^{1/2}$	**1: 6.32**
Discharge	$Q_r = L_r^{5/2}$	**1: 10119**
Pressure	$P_r = L_r^{1/6}$	**1: 1.85**

Discharge measuring arrangements (flume) have been provided at two different locations one upstream and one downstream of the model. At both the locations a suppressed sharp crested weir was installed at the end of the discharge measuring flume.

4.4 Condition for selecting Model particle size

The weight and electrostatic force or viscosity among particle are in relation with particle size and affect the selection of the particle size for the model. As the particle size reduces from silt to clay, its influence on the electrostatic force among particles increases. Therefore, clay particles exhibit different behaviour in movement than that of sand or gravel. While the weight of sand and gravel particles is the determinant factor of particle movement, the electrostatic force is a decisive in case of clay particles as they are clumped together and move in chunks instead of moving independently. While selecting the model particles, the minimum particle size should not be smaller than silt size. Accordingly, the minimum particle diameter has been set to be about 0.2 mm for this test. For the application of similitude law by particle size, refer to Table 5.

Table 5. Application of Froude number by particle size.

Larger than 2~3mm	Froude model law
0.2~2mm	Froude model law with small inaccuracies
Smaller than 0.2mm	Froude model law cannot be used (owing to cohesive binding force become dominant)

4.5 Flushing Test

In this research, mainly the influence range of the flushing operation was studied in order to develop an optimal flushing operation plan. Overall experiment procedure is as follows.

4.6 Sediment deposition before Testing

Sediment delta at upstream of the dam was built to EL. 230.75 (Prototype El. 510.0 masl) with slope gradient of 1:500 for the worst possible conditions. A constant flow rate of 0.02609 m^3/s was used corresponding to the prototype river flow of 264 m^3/s (average flow rate of August) until achievement of equilibrium in riverbed profile. Fig 6 shows the riverbed sedimentation.

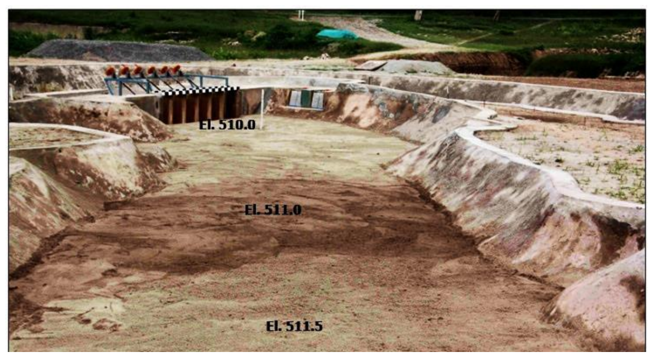

Fig. 6. Riverbed Sediment Profile (Model)

Model was filled up with water to elevation of 231.3 masl (corresponding to 532 masl of the Prototype) very slowly without disturbing the sediment bed moulded in the model.

Fig. 7a. Riverbed Sediment Profile upstream after flushing

After maintaining the reservoir level at of 231.3 masl with the incoming constant flow of 0.02609 m^3/s (i.e. 264 m^3/s for Prototype) all the 6 gates of spillway were fully opened within 5 minutes on model.

The reservoir level was lowered down gradually and attained 505.6 masl at the end when the sediment flushing started. The model was continuously run for duration of 4 hours on model equal to 1- day prototype.

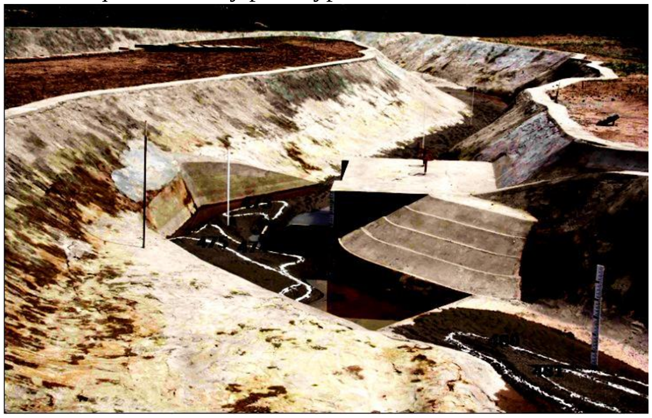

Fig. 7b. Riverbed Sediment Profile downstream after flushing

The bed configuration upstream and downstream of spillway was observed on next day after the model got dried. The model observations (visual and recorded photographically) are shown in Fig. 7a and Fig. 7b.

4.7 Testing for Flushing with Physical Model

4.7.1 Calibration and Sensitivity Analysis

Numerical simulations based on Gulpur HPP physical model were carried out using HEC-RAS 5.0. The calibration of calculated data by the HEC-RAS model was performed using the measured bed change values in physical model. The manning's roughness coefficient of flow resistance and constant of Ackers and white were considered as the calibration parameters of the model in such a way that the change of this coefficient makes the error between calculated bed level changes and those of observed bed levels minimum. Sensitivity analysis was performed to get guidance for calibration of the model. Selection of appropriate manning's roughness coefficient and sediment parameters was checked through such sensitivity analysis.

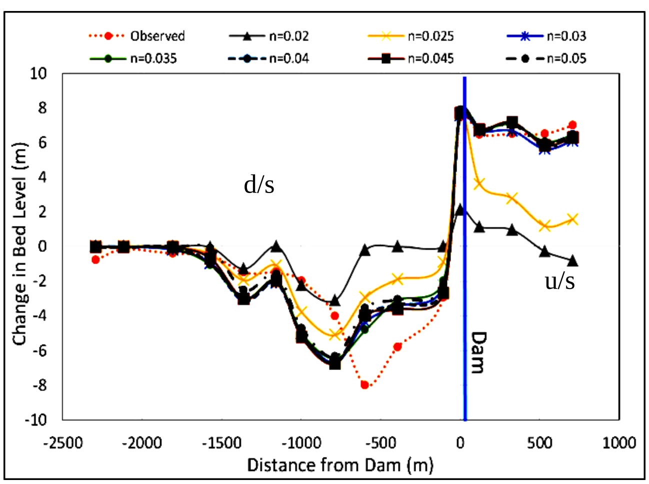

Fig. 8. Change in river bed level for different values of "n"

HEC-RAS Model was run for Manning's values of 0.02, 0.025, 0.03, 0.035, 0.04, 0.045 and 0.05. The results of

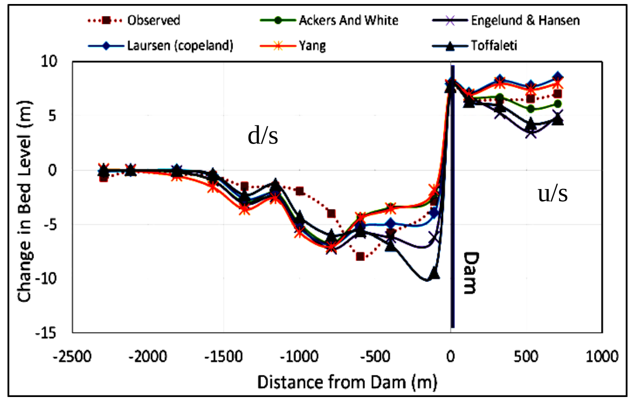

Fig. 9. Change in river bed level for different sediment transport functions.

change in bed elevation are shown in Fig. 8. Change in bed elevation for 'n' values of 0.03, 0.035 and 0.04 closely resembles with that of observed in the physical model. Statistical analysis was performed (Table 6) which supports 'n' value of 0.03. Similar analysis was made with various sediment transport functions and the results of change in bed elevation are shown in Fig. 9. Statistical analysis was performed to further refinement of the results. The trending line in Fig. 9 as well as statistical analysis (Table 6) supports to select Acker's and White sediment Transport function.

4.7.2 Validation of Numerical Model:

Two tests were performed for validation of the model by considering manning co-efficient of 0.03 and Acker's and White as sediment transport function. First test was performed with 3 gates of spillway fully opened within 5 minute and the second test was performed with 1 gate fully opened within 5 minute. Results are shown in fig 10 & 11

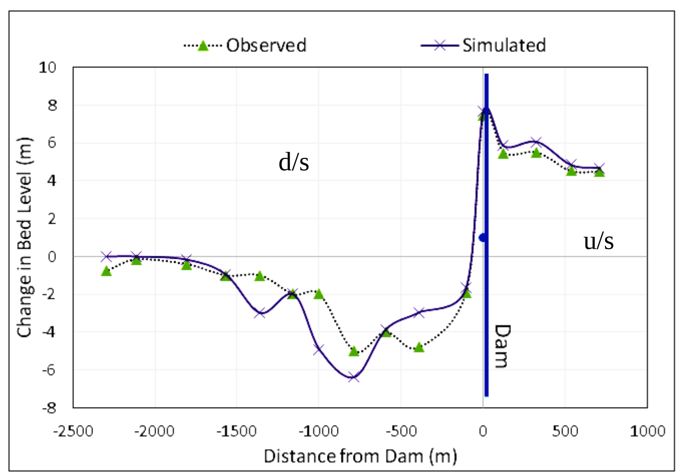

Fig. 10. Change in river bed level under 3 gate opening condition

respectively. Bed configuration upstream and downstream of spillway was observed. The observed reverbed sediment profile was compared with that of observed one with HEC-RAS. The observed and HEC-RAS generated reverbed sediment profiles closely resembles with each other.

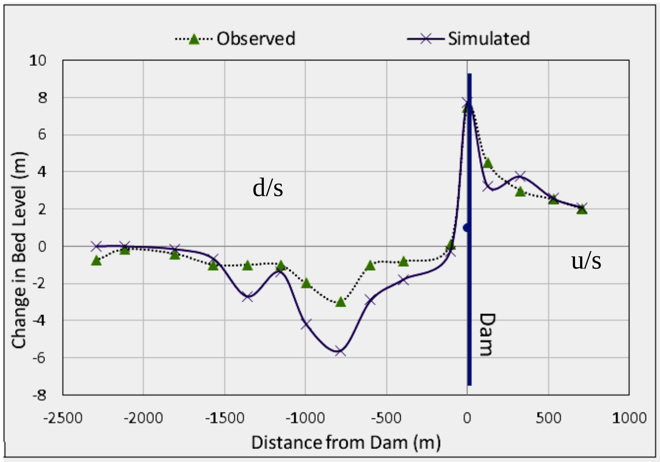

Fig. 11. Change in river bed level under 1 gate opening condition

The goodness-of-fit measures employed to evaluate different simulations representing different choices of parameter are Nash-Sutcliffe coefficient and Root Mean Square Error (RMSE). The parameters [25] as given below at equation (5) and (6) were used to test the model accuracy:

Nash-Sutcliff Efficiency $=1-\frac{\sum_{i=1}^{n}(O_i-C_i)^2}{\sum_{i=1}^{n}(O_i-\bar{O})^2} \to (5)$

Mean Square Error $=\frac{1}{N}\sum_{i=1}^{n}(C_i-O_i)^2 \quad \to (6)$

Where;

$$\bar{O}_i=\frac{1}{N}\sum(Yb_o)_j \qquad \to (7)$$

and
N = Length of record
(C_i) = Computed bed level change
(O_i) = Observed bed level change
$(\bar{O}_i)$= Mean observed bed level change

5 DEPOSITION PATTERN IN THE RESERVOIR WITH NO SEDIMENT MANAGEMENT OPTIONS

5.1 Results and simulations

5.1.1 Base case scenario

The results of the base case scenario (Test 1, Fig. 12) show that sedimentation will increase gradually in the reservoir that will be completely filled-up in approximately 15 years. The deposited sediment at the dam reaches the level of intake (519 m) in 14 years. The numerical results show that after 4 years, the delta rises near to operating level at chainage 5000 m and beyond from the dam.

Table 6. Statistical Analysis

Calibration

Selection of Manning Co-efficient "n"

'n'	0.02	0.025	0.03	0.035	0.04	0.045	0.05
Nash-Sutcliffe Efficiency	-250.75	-102.42	0.02	-0.44	-0.54	-0.96	-1.17
Root Mean Square Error	6.24	4.00	0.39	0.47	0.49	0.55	0.58

Selection of Sediment Transport Function

	Ackers And White	Engelund & Hansen	Laursen (copeland)	Yang	Toffaleti
Nash-Sutcliffe Efficiency	0.02	-18.41	-8.26	-4.42	-12.82
Root Mean Square Error	0.39	1.73	1.20	0.92	1.46

Validation

Flushing Test

	3 gate opening condition	1 gate opening condition
Nash-Sutcliffe Efficiency	0.90	0.89
Root Mean Square Error	0.35	0.65

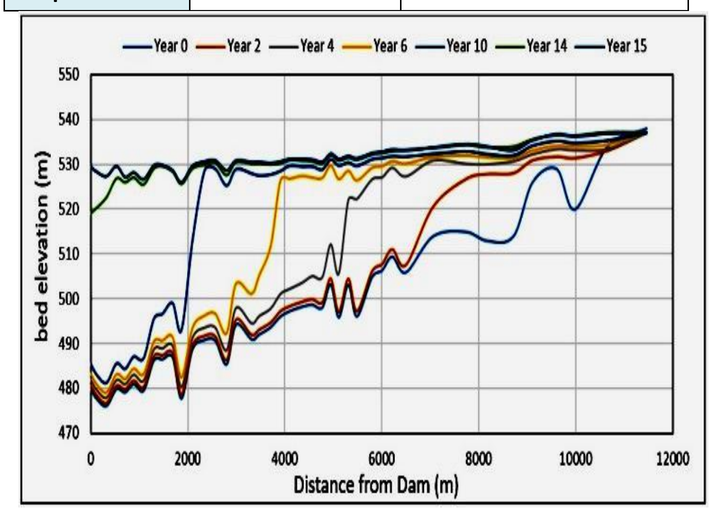

Fig.12. Longitudinal Bed Profiles along the Reservoir for the Base Case Scenario (Test 1)

5.1.3 Influence of high flood series

Test 2 considers a flow series with the 1992 large flood event (Fig. 13). The impact of 1992 flood event (4 years from the origin of the flow series) is that the filling of the reservoir is slightly quicker than previous and after 10 years; the bed level near the dam reaches 529.5 m against the base case scenario where this level was achieved in 15 years.

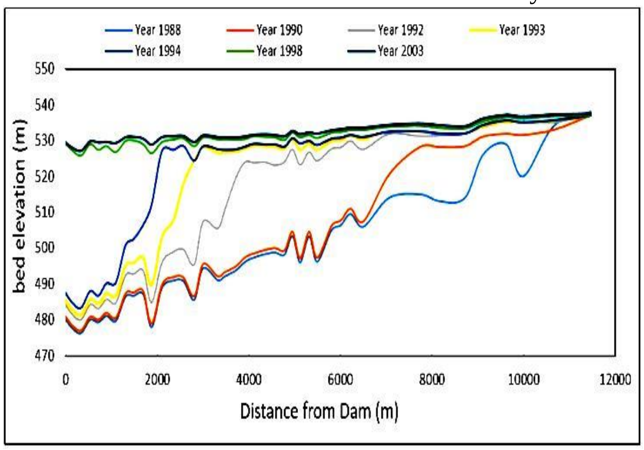

Fig.13. Longitudinal Bed Profiles Along the Reservoir for the Flow Series with a Large Event (Test 2)

5.1.4 Influence of gravel not being extracted upstream

Test 5 (Fig. 14) analyses the case when gravel is not extracted by sediment mining upstream of the reservoir and is allowed to reach the reservoir. Gravel sizes up to d=30 mm were taken into account for this simulation. The evolution of the longitudinal bed profile is show below. The model results show that the bed level in the upstream end of the reservoir rises significantly. This can cause severe problems with flooding upstream of the reservoir. The results indicate that gravel extraction, preferably in a controlled manner, with one or more check dams upstream of the reservoir, is necessary to prevent the bed level rising in the upper end of the reservoir.

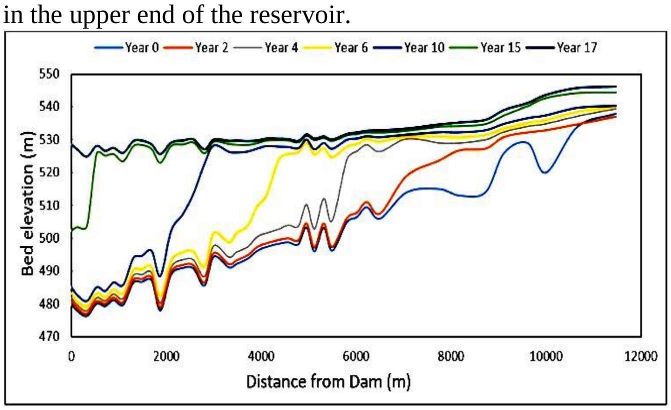

Fig. 14. Longitudinal Bed Profiles along the Reservoir (Test 5)

5.1.5 Influence of increased sand proportion

There are considerable uncertainties related not only to the estimation of unmeasured bed load but also to the suspended load and its composition.

As the amount of sand is higher, the proportion of the trapped sediment can be expected to be higher as well as and the deposition pattern to be different. Sand is less easily transported and thus deposits earlier. This can be seen from the model results presented in Fig. 15 for Test 1 and Test 7 cases. A steeper delta slop can be observed which indicates a potential problem at the upstream end of the reservoir if flushing does not start when required to keep the overall level of deposits in the reservoir low. In terms of general progress of the rate of sediment deposits towards the dam, however, there is no significant difference. This can be explained by the fact that while trapping efficiency of sand is higher (Test 7), the deposition density is also higher than that of silt and clay (by about 50%) and therefore, the deposited material occupies less volume.

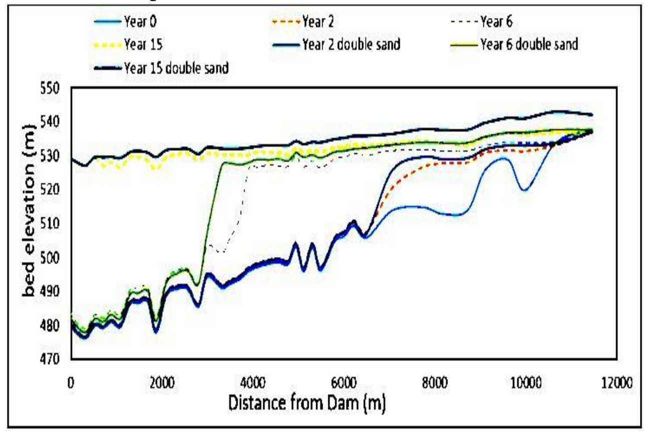

Fig 15. Comparison of Longitudinal Profiles for Test 1 and Test 7

A comparison between the high flow series with base case sand amount (Test 2) and high flow series with double sand amount (Test 8) is presented in Fig. 16. In terms of the deposition pattern, it still holds that the model predicts a steeper delta slope in the double sand case. However, in this case there is some difference in the rate of progress after the extremely high flows (which occur in year 5 of high flow series, i.e. Series in Fig. 3.

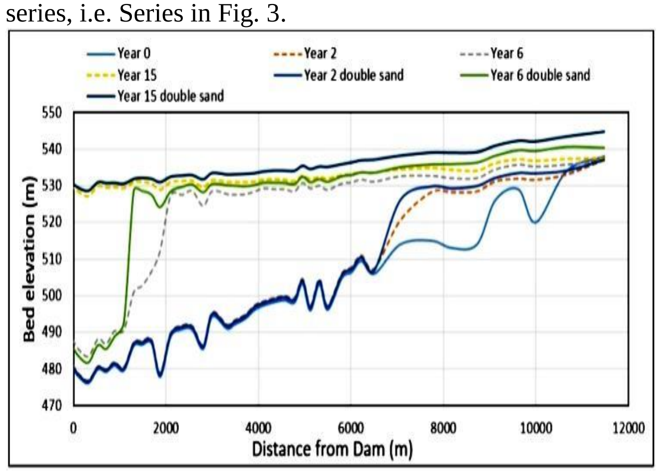

Fig.16. Comparison of longitudinal profiles for Test 2 and Test 8

A comparison of bed levels at dam with the level of intakes for all performed test is shown in Fig. 17. This sensitivity analysis shows that depending on hydrological conditions (Test 2) and sediment inflow and composition (Tests 3 and 4) the level of sediment deposits can reach the intake level several years earlier or later compared to what is predicted in the base case (Test 1) where it is 14 years. An impact of a single event (Test 2 in year 4) is evident. These variations have to be taken into account for planning purposes.

Sensitivity of this parameter to Manning coefficient (Test 6) is small.

In Test 3 scenario, with increased amount of sediments particularly sand, the model predicts that the sediment reaches the intake level in about 9 years. Similarly, in Test 4, with lower sediment inflow particularly sand, it takes 18 years and in Test 5 &6, it reaches in about 16 years.

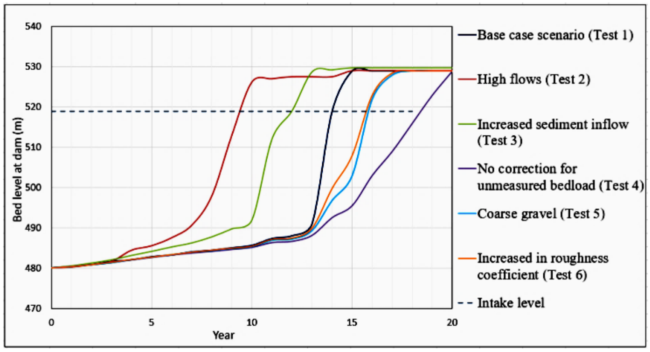

Fig. 17. A comparison of bed levels at dam with the level of intakes (Tests 1-6)

6 DEPOSITION PATTERN IN THE RESERVOIR WITH FLUSHING

The Gulpur HPP has relatively smaller reservoir with high sediment deposition rate, therefore for its technical viability, a successful flushing of the deposited sediment is required.

Depending on the size of reservoir, water and sediment inflow characteristics and operation rules, flushing can be performed in different ways. The proposed Gulpur reservoir is of run-of-river type and after the water level drawdown required for flushing, it can refill within a day or so. Water discharges are irregular but with two annual flood seasons, a smaller one in March/April with an average daily peak around 500 m^3/s and a bigger one in July/August with an average daily peak of around 1300 m^3/s. These are the periods when most of the sediments are expected to arrive and deposit in the reservoir.

Given these parameters, the most suitable time for flushing would be on the falling limb of the second flood period. In that period, water discharges will be high enough to ensure an efficient flushing operation that would be able to remove recently deposited sediments (giving no time to possible consolidation). From Fig. 18 it can be seen that a suitable timing is before calendar day 222 (10th of August).

Due to high concentration of sediment, it has been proposed that the power plant will not operate when water discharges are higher than 1,000 m^3/s. Sluicing and flushing can also be performed during these periods getting additional benefit of available water discharge being high. In the observed period of 55 years (between 1960 and 2014) there were 60 events where water discharge was higher than 1,000 m^3/s. There duration was seldom longer than one day.

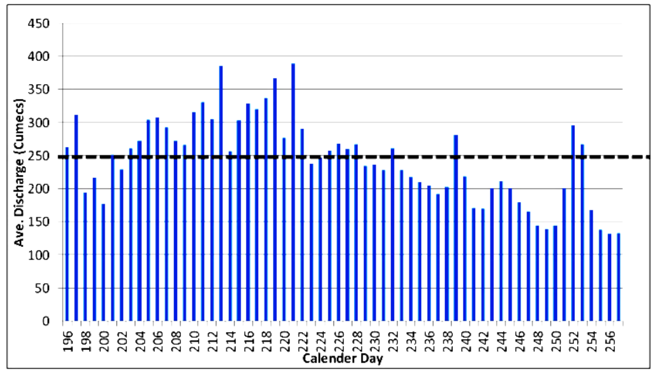

Fig 18. Average Discharges During Second Flood Period between 15th of July (196) and 15th of September (257)

To check the flushing performance of the reservoir, flushing scenario is modeled using HEC-RAS 5.0 model. The geometry of the model for the simulation of flushing scenarios was the same as that for deposition except that four additional cross sections were added downstream of the dam to simulate potential deposition in this area.

For flushing operation modeling, a quasi-unsteady file was prepared in the HEC-RAS. The constant daily flushing discharges of 250, 500, 800, 1000 m^3/s, as boundary condition, were used for the complete flushing duration and resultant durations for yearly sediment flushing were determined. The normal depth was also considered in the model. Bed material gradation curve at the dam site was used as an initial condition. Transport function of Ackers-white (1973) along with Van Rijn'sfall velocity method was used. By using long term historical data, sediment rating curve was prepared for the dam site, which was used as sediment boundary condition. Further, fraction of the gravel, sand silt and clay was allocated.

According to Sayah [26] and Castillo [27], a suitable flow for reservoir flushing is that when it has the order of double of the mean annual flow. The Poonch River has mean annual flow of 125 m^3/s (Fig. 3), hence a discharge of 250m^3/s would be a recommended one for reservoir flushing. Mean daily flow hydrograph for the Gulpur dam site has been shown in Figure 16 along with the flushing discharge of 250 m^3/s constant line. It depicts that 3rd of August is the suitable flushing time when the flows are highest. However, some variation in flushing time may be there every year based on the availability of suitable discharge.

First flushing was performed after 7 years using complete drawdown flushing approach and it was observed that it takes 5 days to flush the deposited sediments at a flushing discharge of 250 m^3/s. After further sediment deposition every year, it takes 4 days to flush it on 8th year, 4 days for 9th year flushing; thereafter, a dynamic equilibrium condition in the reservoir bed is achieved requiring 4 days flushing every year. Bed profile after 7th, 8th and 9th years flushing is shown in Fig. 19.

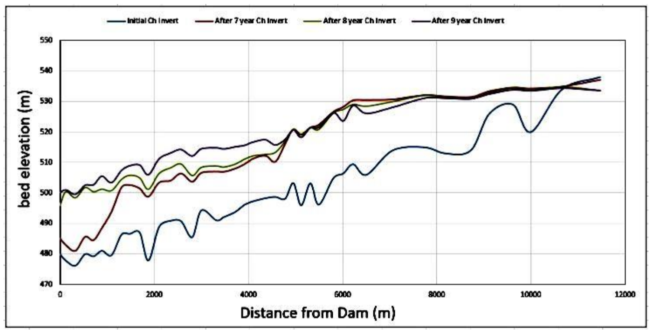

Fig. 19: Bed profile after 7th, 8th and 9th years flushing

To flush the sediments, the reservoir was emptied, continuously flushed and refilled in a sequential order. A sediments aggradation was attained on the upstream of the dam site by flushing operation because of the reason that sill level of flushing gates is at 503 masl with corresponding original bed level at 480 masl thus creating a dead storage that was silted permanently. Moreover, bed profile degradation was increased on the downstream side of the dam from 1st to 7th year of operation. It is due to the fact that the height of the dam up to sill level of flushing sluices acted as a barrier in the transport of bed load and much of the suspended load, and hence relatively silt free water caused scouring on downstream side. This scouring on the downstream of the dam site was checked once the bed level rose up to the flushing gates sill level. Then, instead of degradation on downstream side of the dam, aggradation started after an equilibrium condition was achieved.

Before starting flushing, the reservoir should be emptied at around 3rd August every year using average flow; however, this date will be refined based on the actual temporal distribution every year. After emptying, certain days are required for continuous flushing at riverine flow condition, after flushing operation, it should be refilled. To achieve drawdown, the flushing gates will be opened and a riverine flow will be obtained. For the Gulpur dam the emptying time is 5 Hours and the time required to refill the reservoir with different discharges is shown in Fig. 20.

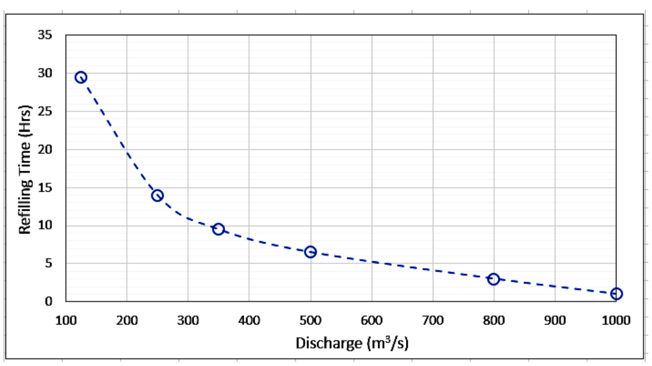

Fig. 20: Time required refilling the reservoir with different discharges

After achieving the equilibrium, one year (i.e. 10th year) delta deposited was taken as input to the HEC-RAS flushing model (Fig. 21). It takes 4 days for emptying, flushing and refilling of the reservoir.

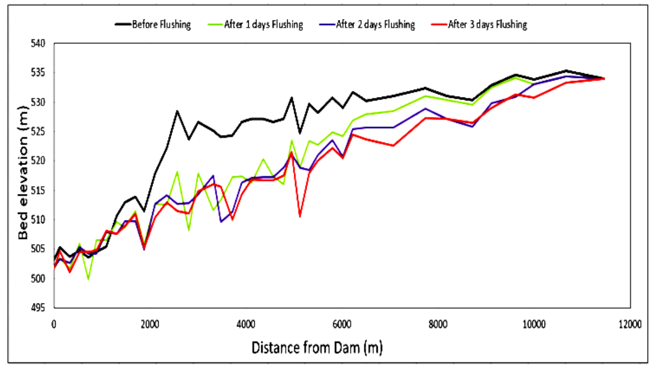

Fig. 21: Bed profile of 1 year deposition after equilibrium

The model was run for different discharges ranging from 125 to 1000 m^3/s and corresponding flushing durations were determined as shown in Fig. 22. It was observed that the flushing durations required are from 2 to 6 days corresponding to various discharges.

The value of five flushing indicator have been computed for the Gulpur HPP reservoir and are reported in Table 7 along with input data required for these calculations. The parameters are computed for a flushing discharge of 250 m^3/s with a flushing duration of 3 days. The output values shows that Gulpur HPP reservoir fulfills all the criteria, hence the flushing efficiency of the reservoir would be around 90 to 100%.

Table 7. Input and output Data for Flushing Analysis

Input Data for Flushing Analysis				
S. No	**Parameter**	**Symbol**	**Value**	**Units**
1	Original Storage Capacity	Co	43.44	Mm^3
2	Reservoir Length	L	9,000	m
3	Elevation of top water level at dam	El_{max}	532.5	m
4	River Bed Level at Dam site	El_{min}	503	m
5	Water surface elevation at dam during flushing	El_f	506	m
6	Representative bottom width	W_{bot}	133.81	m
7	Representative side slope	SS_{res}	1.631	
8	Representative side slope for sediment	SS_s	1.628	
9	Mean annual water inflow	V_{in}	3942	Mm^3
10	Mean annual sediment inflow	M_{in}	10,567,412.59	Tons
11	Tsinghua University factor for sediment type	ψ	300	
12	Sediment load factor (if different China)		3	

13	Capacity - Inflow ratio	C_o/V_{in}	0.01	
14	Capacity – Watershed ratio	C_0/w	11787.28	m^3/Km^2
15	Trap Efficiency	TE	57	%
16	Flushing Discharge	Q_f	250	Cumecs
17	Flushing Duration	T_f	3	Days
Output Flushing Parameter				
S. No	**Parameter**	**Symbol**	**Value**	**Criteria**
1	Sediment Balance Ratio	SBR	1.38	> 1*
2	Long Term Capacity Ratio	LTCR	0.845	> 0.5*
3	Drawdown Ratio	DDR	0.898	> 0.7*
4	Flushing Width Ratio	FWR	1.51	> 1*
5	Top Width Ratio	TWR	1.015	(1 to 2)*

7 CONCLUSIONS

Gulpur hydropower scheme is proposed on the Poonch River close to the town of Kotli in Pakistan. The discharge regime of the river is highly variable and so is the sediment inflow. The sediment inflow (suspended and bed load) was estimated to be, on average, 11.9 Mt per year. The annual amount however, varies between 2.5 and 38 Mt.

Reservoir sedimentation simulations were performed with HEC-RAS 5.0, 1D reservoir model that makes predictions over periods of several years. The numerical results provide a good understanding of the general deposition issues in the reservoir as well as the impacts of several management scenarios. The numerical model validation on the physical model results showed reasonable agreement, indicating its potential to simulate reservoir flushing.

The numerical results show that in average hydrologic conditions the reservoir fills completely within 15 years and in about 10 years the level of deposited sediment near the weir rises to the level of intake. However, in case of more severe hydrological conditions or increased amount of sand in the bed load this can happen several years earlier. It was observed that the initial storage capacity of the Gulpur Reservoir was 43.44 MCM, which after attaining equilibrium after 9th year, reduced to 16.15 MCM.

Due to unpredictable behaviour of the river flow regime, a combination of flushing at high discharges (1,000 m^3/s) and in absence of this, by the mid-August discharges (of the order of 250 m^3/s or more) can prevent reservoir bed levels from rising close to the intake level as well as keeping the sediment inflow into the intakes low. From the model results it appears that about three days per year plus the time required to refill the reservoir will be required for flushing.

The trap efficiency determined from the model is 57% which agrees well with 52% value from empirical curve.

Numerical values obtained for five number of flushing indicator for the Gulpur HPP reservoir are well satisfied, hence flushing efficiency of the reservoir to flush the sediment would be 90 to 100%.

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