Sustainable sediment management in a reservoir through flushing using HEC-RAS model: case study of Thakot Hydropower Project (D-3) on the Indus river

Kashif Hussain IWA and Muhammad Shahab

ABSTRACT

To increase the life of small storage reservoirs, sediment flushing is found to be a very useful technique throughout the world. A sediment flushing study of the Thakot D-3 Hydropower Project reservoir after construction of the Dasu dam on the Indus river is presented in this paper. HEC-RAS 5.0.6 numerical model has been employed to check the sediment removal during flushing and to assess the model's applicability and limitations. Dasu reservoir sediment discharge data of 20 years were used to evaluate the sediment load with different transport functions under no-flushing (FSL 656 m asl) and flushing conditions. Without flushing, the river bed would be raised 56.1 m at the dam site and the low-level spillway and power intake would be filled in 2–5 years' time. It was observed that reservoir sediment flushing is economically realistic for this dam and the HEC-RAS sediment simulation model is encouraged for reservoir flushing modeling. If the Thakot D-3 HPP is commissioned a number of years after Dasu, a coarser sediment load will also be reached in the reservoir which could pose a serious challenge for the Thakot D-3 reservoir life. It is recommended that without construction of the Bhasha-Diamer storage dam, sedimentation not only is a complicated issue for Dasu HPP and Thakot D-3 HPP, but will also have drastic impacts on other downstream run-of-river energy projects.

Key words | Dasu dam, HEC-RAS, Indus river, sediment flushing, Thakot D-3 dam

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INTRODUCTION

Sediment transport analysis or deposition assessment, the processes of sedimentation and evaluation of river bed erosion have become a very essential scientific area (Michalec 2014; Dutta & Sen 2016; Mohammad *et al.* 2016; Dysarz *et al.* 2017). A huge accumulation of sediments is decreasing reservoir water storage capacity throughout the world (Alemu 2016). Recently, sediment deposition in large storage dams of Pakistan like Chashma, Tarbela and Mangla have attracted the attention of Government, the public, engineers, water management policy makers and hydrologists to work out a solid technique to reduce the serious sedimentation impacts and existing water storage capacity problems in the country's reservoirs. Warsak dam reservoir constructed on Kabul River in Khyber Pakhtunkhwa (KP), Pakistan, has filled with an accumulation of sediment after just 30 years of operation and its water storage capacity is almost exhausted (Sabir *et al.* 2013). Accumulation of sediment in a reservoir is a general phenomenon because suspended load and bed load particles of sediment get stored, subsequent to being isolated from their origin (Dutta 2016). These serious issues affect not only water availability for agriculture, water supply, and the ecosystem, but also hydropower production in which a crisis is already faced (Javed & Tingsanchali 2016). A continuity of sediment transport through natural rivers was interrupted by hydraulic structures like dams, causing an accumulation of sediment within the reservoir (Kondolf *et al.* 2014; Esmaeili *et al.* 2017). A reservoir

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sediment flushing and sluicing technique plays a vital role in the removal or reduction of sediment and restoration of storage capacity (Liu *et al.* 2004). A large dam/reservoir is often designed at the upstream reach to control the sediment discharge efficiently and to enhance the storage life of the downstream reservoir. Irrigation, water supply and hydropower production are a very significant operation and closely based on the reservoir storage capacity. Construction of the proposed Diamer Basha dam upstream, acting potentially as a massive sediment trap, has been considered in certain scenarios (Tate & Farquharson 2000), located about 74 km upstream of the Dasu dam site. According to statistics of the world's large reservoirs, storage capacity reduced by 5% from 1901 to 2010 (Wisser *et al.* 2013; Huang *et al.* 2018). Sediment deposition within reservoirs has various ecological and engineering effects (Morris & Fan 1998) including morphological changes (de Araújo *et al.* 2006) and interference with the outlet works or hydropower intakes (Graf *et al.* 2010). Calculation of sediment deposition and flushing into reservoirs with a range of numerical models has been reported in previous publications. The HEC-RAS 5.0.6 numerical sediment transport simulation model was selected for this study. The main objective of this paper is to evaluate the reservoir capacity and significant impact of accumulated sediment on hydraulic structure outlets without and with flashing after the construction of Dasu dam.

Study area

The Thakot D-3 Hydropower Project is proposed in the Upper Indus River Basin (UIRB), just 6 km upstream of Besham city, 66 km downstream of the Dasu dam site, located in Kohistan District in Khyber Pakhtunkhwa Province of Pakistan, as illustrated in Figure 1. The Indus is one of the longest transboundary rivers of Asia. It originates from the Tibetan Platea's frozen desert in the domain of Manasarovar Lake in the Tibet valley of China. It passes through Ngari, Spituk, Ghorg, Skardu, Bunji, Chilas, Basha, Sazin, Dasu, Patan, Besham, Thakot, Tarbela, Kalabagh, Chashma, Taunsa, Guddu, Sukkur, Kotri and finally drains into the Arabian Sea near Keti Bandar at 23° 58.969′N latitude and 67° 25.331′E longitude. The catchment area of the Indus basin up to Thakot Dam (D-3) is 163,152 km^2, while the catchment area of the Indus river up to Dasu dam is 158,800 km^2. The Indus is one of the dirtiest rivers due to producing the largest amount of sediment in the region. The entry of a large amount of sediment into Dasu reservoir was already investigated in the engineering and design report for Dasu. The main source of the bulk amount of sediment inflow into the river is erosion from the very steep, barren side-slopes of glaciers (Rashid *et al.* 2014). Thakot D-3 is a small storage run-of-river hydropower project with installed capacity 2,222 MW. The area of the reservoir is 6.28 km^2 and its length is 22 km. The total height of the dam is 100 m above the foundation level. It has two types of spillway, i.e., the high-level spillway and the low-level spillway. The high-level spillway has seven gates (16.5 m wide and 22 m high) and the low-level spillway has three gates (12 m wide and 10 m high). The climate of the study area is hot in summer and very cold in winter. The average annual temperature in the basin between Dasu and D-3 is about 21.4 °C (6 °C–37 °C). January is the coldest and July is the warmest month of the year. The Indus basin has an annual precipitation at Besham Qila of about 1,082 mm with two peaks. The first peak occurs in March (169 mm) because of the Western Disturbances (WDs) system and the second peak happens in July (117 mm) due to the summer monsoon (1970–2017).

AVAILABLE DATA

The data used for the research include river cross-section, sediment inflow and hydrological data from a gauging station near to the proposed Thakot D-3 dam sites or outflow from the upstream dam that has been taken from a different source. The sediment inflow and river discharge data for Thakot D-3 dam are collected at Besham hydrometric station, which is located just 6 km downstream of Thakot D-3 dam and 72 km downstream of Dasu dam (Figure 1) and maintained by the Surface Water Hydrology Project (SWHP), WAPDA. It provides essential information on river inflow and sediment concentrations. Average annual river flow and sediment inflow at Besham Qila gauging station from 1962 to 2016 were measured at 2,421 m^3/s and 226 MST. The Upper Indus river lies between the Himalayan and Karakoram ranges; glacier and snowmelt water contribute a major portion of the annual flow reaching

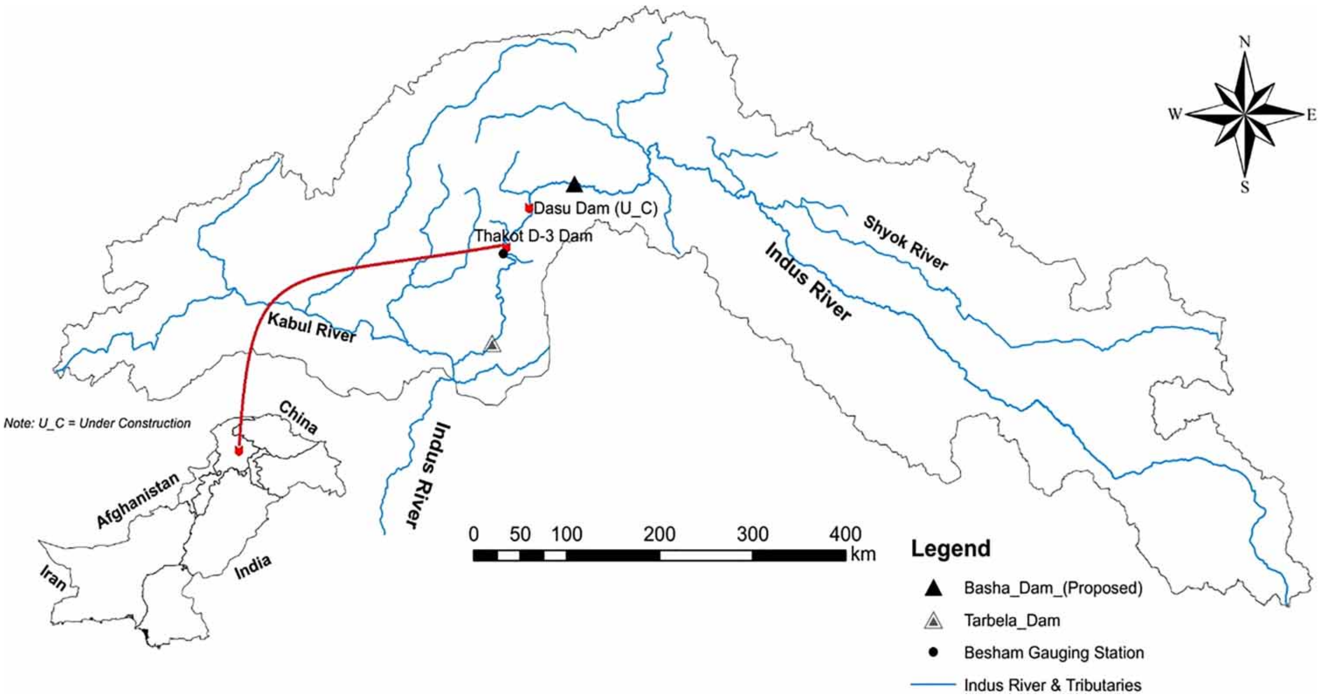

Figure 1 | Location of Thakot D-3 and Dasu dams.

Dasu and Thakot reservoirs. Annual average sediment inflow of 214.49 million tons per year (MT/yr) was predicted at the Dasu reservoir at the design stage. However, the average annual natural sediment inflow to the Dasu and Thakot D-3 reservoirs from 1962 to 2016 have been worked out at the dam site with a sediment rating curve. Therefore, Dasu reservoir sediment and hydrological outflow data have been collected from the Detailed Engineering Design Report (DHC-2013). Dongai Gah, Spat Gah, Kayal Khar, Palas river, and Duber river are among the most important perennial tributaries draining into the Indus river between Dasu and Thakot D-3 dams. River discharge and sediment flow data for these tributaries were collected from those already published in feasibility, detail engineering design and Surface Water Hydrology Project (SWHP) reports, extended and added into data information already available. Monthly water discharge at Besham station and Thakot D-3 under pre- and post-Dasu conditions is shown in Figure 2.

The data collected from Besham gauging station were used in assessment of natural river flow availability and sediment concentration at the proposed Thakot D-3 project site under pre-Dasu conditions, while data contained in the Dasu dam report and data information from intervening catchments were used as inflow data for the proposed D-3 reservoir for the sediment management and flushing study. Data for maximum and minimum water level, original river bed level and width of reservoir at the dam site were also collected. Salient features of the proposed reservoirs are listed in Table 1.

Based on annual sediment inflow it has been established that the sediment loads are high and the Thakot D-3 reservoir is relatively small. With no upstream reservoirs in place all sediments arriving in the Thakot D-3 reservoir would be retained. Under such conditions the lifetime of the Thakot D-3 reservoir would only be 0.81 years and then it would be full of sediment. However, for small reservoirs such as the Thakot D-3 reservoir there is an adequate supply of water available for flushing out the sediment during times of high flows and floods.

METHODOLOGY

Description of HEC-RAS

A one-dimensional numerical model is particularly useful for long-term sediment transport assessment of a long river

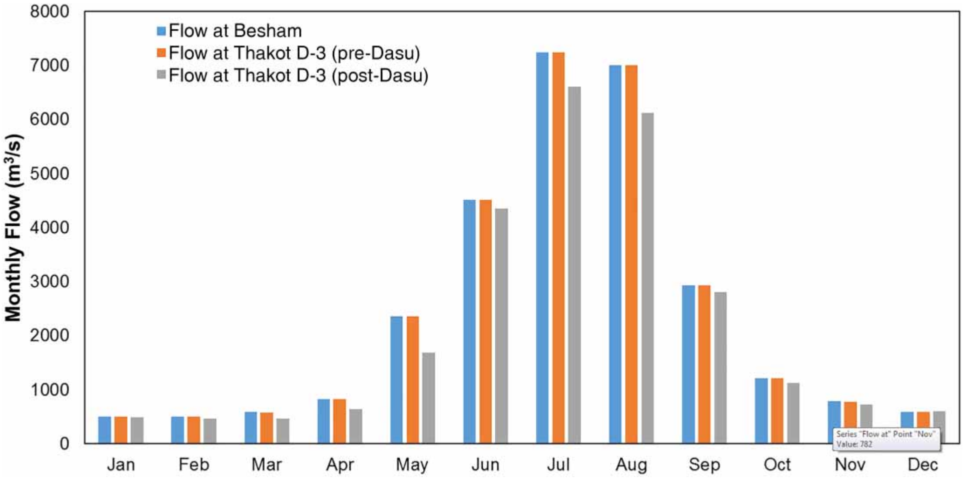

Figure 2 | Monthly water discharge available at Thakot D-3 reservoir and at Besham gauging station.

reach because numerical solutions are progressively more stable and require the least limit/time of the computer. HEC-RAS 5.0.6 was developed by the Hydrologic Engineering Centre (HEC) in November 2018 (Brunner 2018) and is well-known software used worldwide and freely available for 1-D and 2-D simulation with GIS compatibility. It is designed to perform 1-D steady hydraulic and sediment transport/mobile bed computations and 2-D unsteady flow hydraulics through natural rivers. A new unsteady sediment transport capability has also been incorporated in HEC-RAS (Boyd & Gibson 2016), including mixed flow regimes, operational rules, and inline and lateral structures, which have been effectively used in many reservoirs of the world for sediment flushing. Sediment transport computation depends on estimations of one-dimensional mobile material from the riverbed causing scour or deposition over a specific time period of modeling (Rehman *et al.* 2015). The sediment transport simulation and various other important function results are given in the graphical user interface (GUI) (Habib-ur-Rehman *et al.* 2018). The essential principle of assessing sediment transport capacity inside HEC-RAS is by simulation of sediment capacity in a particular case related with each cross-section as a control volume and for all grain sizes (Rehman *et al.* 2015). Geometric data (cross-section) are used as a key element for these function and boundary condition initial requirements within HEC-RAS for sediment flushing. Detail of the sediment transport calculation methods and equations used in this study can be found in Brunner (2018). The existing HEC-RAS has several sediment boundary conditions and is structured with a time series of gate opening on quasi-unsteady hydraulics to handle sediment analysis computations. The basic input data to the model were prepared in four blocks: Geometry (cross-section), Hydrology (flow series), Hydraulic (water level during flushing) and Sediment are elaborated as follows.

Table 1 | Salient feature of proposed Thakot D-3 and Dasu reservoirs

Sr	Parameter	Unit	Thakot D-3 reservoir	Dasu reservoir
1	Initial capacity	Mm^3	179	1,396
2	Coordinates	N E	34° 57′ 40″ 72° 54′ 18″	35° 18′ 54″ 73° 11′ 25″
3	Design flow	m^3/s	3,400	2,600
4	Installed capacity	MW	2,222	4,500
5	Generation units	no	6	12
6	Length	km	22	72
7	Normal operating level	m asl	656	950
8	Minimum operating Level	m asl	650	900
9	Dam height	m	100	242
10	Annual water discharge	Mm^3	76,318	70,389
11	Annual sediment inflow	Mm^3	205	200
12	Sand	%	20	38.2
13	Silt	%	69	53.3
14	Clay	%	11	8.5

River cross-sections

River cross-section is basic and very important geometry data required in HEC-RAS of representative locations throughout a river reach for hydraulic, sediment transport or flushing and water quality study. The spacing between these cross-sections is a function of river size and slope and it follows the same criteria for all cross-sections in both cases, gated and non-gated spillways. Reach length and Manning's roughness coefficients between upstream and downstream cross-sections are also required in the model. Cross-section and river center-line data of Thakot D-3 dam and reservoir were extracted from International Sedimentation Research Institute Pakistan (ISRIP) Report No. 286. These cross-sections covered a reach of the Indus river that was 28.4 km long up to the dam site and 6 km between the D-3 dam and Besham Qila gauging station, while within the reach the river water surface fell by 70.4 m. Elsewhere the spacing of the cross-sections was generally 200 m to 250 m.

Quasi-unsteady flow and boundary conditions

Quasi-unsteady hydraulics deal with sediment transport study and are structured only as time series of gate opening in the new version of HEC-RAS. A continuous hydrograph in case of quasi-unsteady flow is an approximation to a series of steady flows, which are directly connected with corresponding flow durations. This speculation for sediment transport computations in the HEC-RAS model with quasi-flow and changes of cross-sections is suitable particularly for flows in reservoirs (Mohammad *et al.* 2016). The boundary conditions at the upstream and downstream are mandatory; daily discharge data from Dasu and intervening catchments were used as the upstream boundary condition (Figure 3) and a stage series on a daily basis was used as the downstream boundary condition.

Therefore, a computational time step is a basic requirement for the model, and was entered according to every record. A stage series was developed just upstream of the Thakot D-3 dam during flushing when all outlet devices are fully open. The details on the dimensions and the procedure of determination of the discharge capacity curve were collected from Thakot D-3 Feasibility Report chapter 11. This discharge rate curve was incorporated in the HEC-RAS model as a control definition for the outlets to determine the reservoir water level at the dam that matches the respective daily discharge. The model simulates the sedimentation processes for the available time series of 20 years outflow from Dasu reservoir. It was also assumed that all discharges and sediment influxes coming from the intermediate catchments enter the Thakot D-3 reservoir at its upstream end and were added to the outflow of Dasu HPP. The sediment loads entering the Thakot D-3 reservoir, presented in Figure 4, were given as upper boundary conditions.

A bulk amount of sediment deposited into the low capacity reservoir gradually reduces the live and dead storage capacity and construction benefits of the reservoir, i.e., power and flood mitigations (Rashid *et al.* 2014). Rashid *et al.* (2014) found that the Ackers–White equation is better for sediment simulation for Tarbela reservoir.

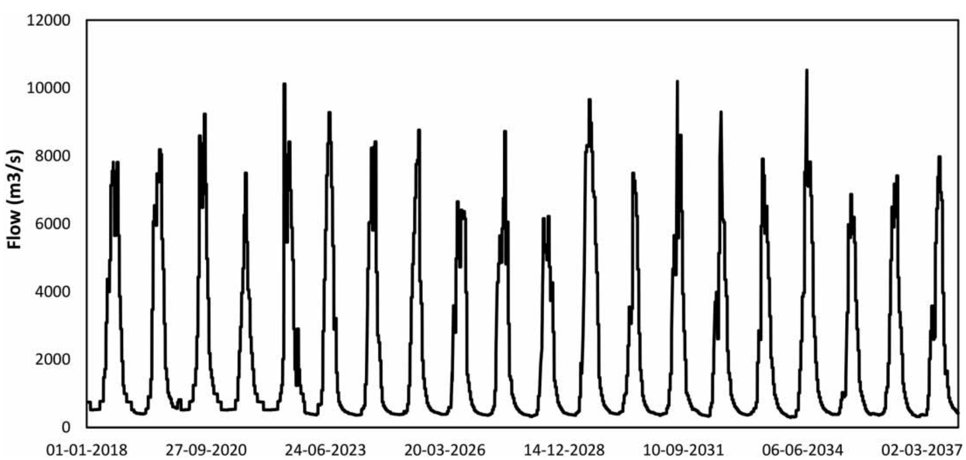

Figure 3 | Water inflows to Thakot D-3 reservoir in different years.

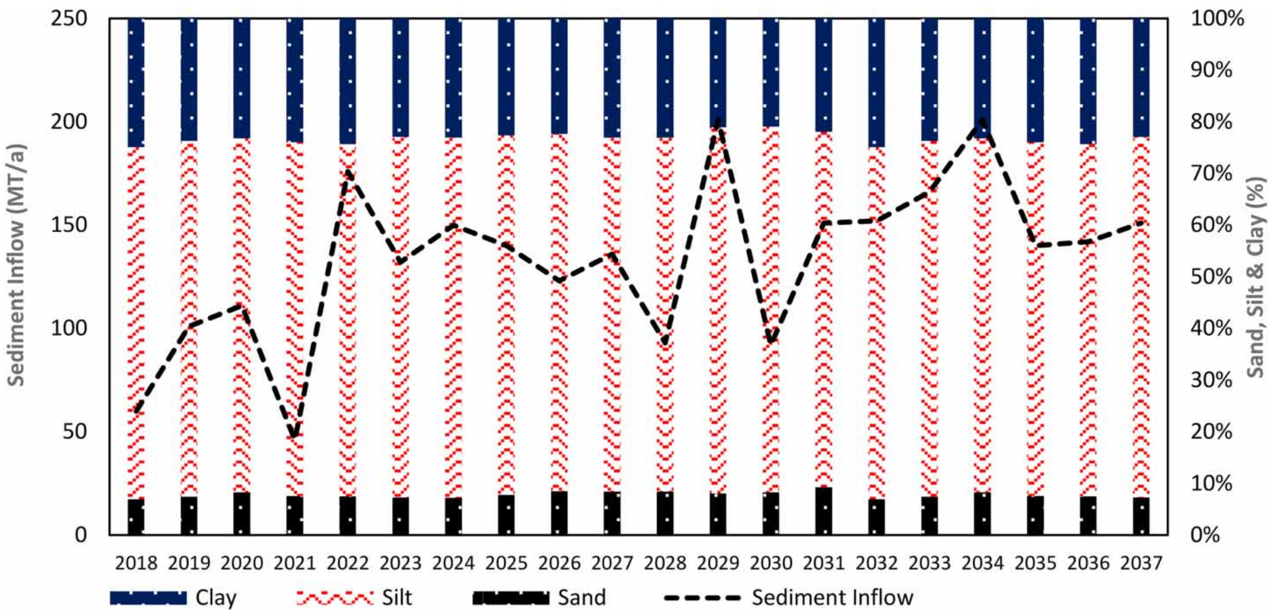

Figure 4 | Prognosis of annual sediment loads.

Rehman *et al.* (2015) found that the Ackers–White method gives better results for a Dasu reservoir sediment flushing study. The Ackers–White formula is the most appropriate technique for sediment simulation and management of Gulpur HPP reservoir (Iqbal *et al.* 2016). The Ackers–White equation was also used for sediment load estimation for the proposed Basha dam (Javed & Tingsanchali 2016). The Ackers–White formula was selected for the model for the sediment management and flushing study of the proposed Thakot D-3 reservoir.

Sediment flushing operation technique

Reservoir sediment management is imperatively essential for protecting reservoir storage capacity and decreasing the long-term maintenance costs (Annandale *et al.* 2016). Sediment flushing from the reservoir may be the most economic strategy as compared with other techniques (dredging, bypass channel and lateral erosion etc.). Flushing is generally based on two categories, free flow flushing (empty the reservoir to the level of the flushing outlet) and pressure flushing (with less drawdown of the reservoir) which is less efficient (Morris & Fan 1998). Therefore, the free flow flushing technique has been used in many case studies and is based on drawdown, sufficient capacity of flushing outlet structures, frequency of flushing and flushing duration, which are considered important input parameters for reservoir sediment flushing and management study. The technical possibility of free flow flushing is checked for different discharge rates, reservoir drawdown levels and flushing periods for various scenarios. Characteristics of the different investigated flushing scenarios are listed in Table 2.

In the do-nothing scenario there is no interruption of power production and the water level of the reservoir is maintained at full supply level (656 m). Therefore, Thakot D-3 reservoir storage capacity is very small and the rated design flow is 3,400 m^3/s, while from June to August river discharge is higher than the rated flow and is considered spill from the high-level spillway and sediment materials gradually deposit in the reservoir until an equilibrium is reached.

Table 2 | Description of scenarios

Scenario (#)	Water level during flushing (m asl)	Average flushing discharge (m^3/s)	Duration of flushing (days)
Do nothing	656	–	–
1	635	6,688	50
2	626	5,410	40
3	624	5,255	40

Model calibration and validation

Calibration is the technique of setting the different parameters of the model to check that the observed value agrees with the estimated. The validation procedure demonstrates whether the predicted calibrated model concurs with the observed data set, which is different from the data information used during the calibration process (Ateeq-Ur-Rehman *et al.* 2018). A set of rating curves at Pattan bridge 24.5 km (station-1), 750 m upstream of the Thakot D-3 dam site (station-2), and Besham Qila gauging site just 6 km downstream of the dam site (station-3) were used in the hydraulic model calibration and validation as per guidelines recommended by Brunner (2018). Flow rate in the Indus river at Thakot D-3 usually ranges from low to high values under pre- and post-Dasu conditions (466–8,000 m^3/s). The n value in the normal case increases with decrease in water discharge and water depth. A calibrated value of Manning's n with respect to water discharge quantity used in HEC-RAS varies between 0.030 to 0.035 in the channel's center and 0.04 to 0.048 on the banks of the channel. Initially calculations were carried out for different steady flow discharges and the water discharge rating curve of station-3 was used as the downstream boundary condition. After calibration of different water surface profiles, the HEC-RAS model was further calibrated with sediment data for 10 years, i.e. 1996–2005, and then validated with 10 years of sediment data, i.e. 2006–2015. The calibration and validation results are shown in Figure 5.

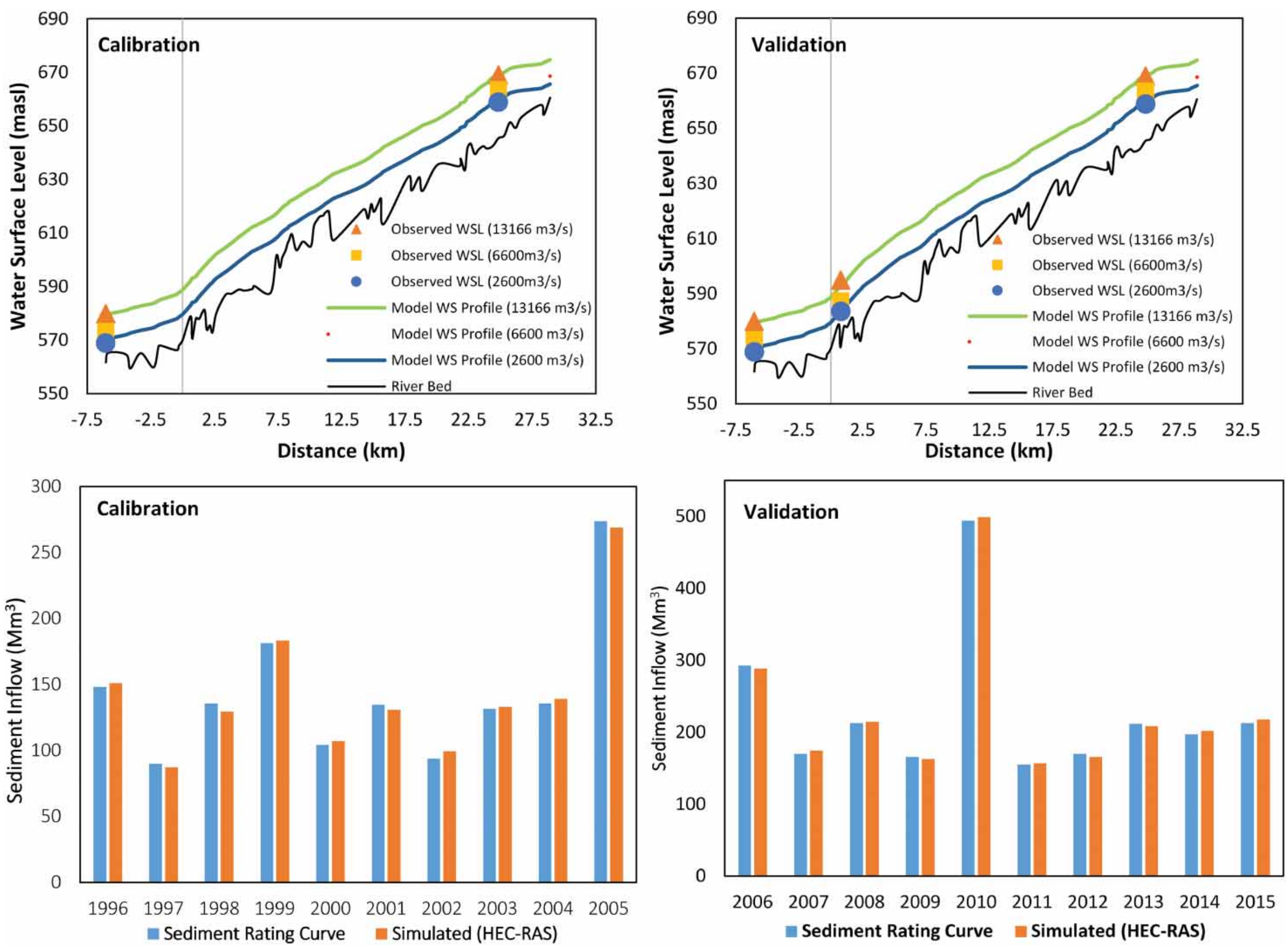

Figure 5 | Water surface profile and sediment transport rate calibration and validation.

RESULTS AND DISCUSSION

Removal of sediment deposition to maintain reservoir storage capacity/life is crucial for Thakot D-3 reservoir, which would be based on its operational policy, because efficiency of sediment flushing is directly related to the function of the reservoir. To assess and clarify the accuracy of sediment transport a one-dimensional hydraulic model was subsequently applied to the flushing of deposited sediments from Thakot D-3 reservoir. The primary operational strategy of Thakot D-3 is hydropower generation. The established numerical model was run for the different scenarios illustrated in Table 2. In the reservoir's massive sediment deposition pattern, reduction of required storage capacity due to development of a delta were changed by changing flushing techniques. These various scenarios have been determined, to work out the guidelines for the future operational strategy of the proposed Thakot D-3 reservoir under post-Dasu reservoir conditions. The simulated results after running the HEC-RAS 5.0.6 model show that the storage capacity of Thakot D-3 reservoir would be reduced by more than 70% using the Ackers–White transport formula in about five years of operation, maintaining reservoir water level at the full supply level of 656 m asl under no-flushing conditions. In this case, active layer as sorting method and Tofalleti as fall velocity method were used. The maximum erodible depth of 10 m was selected and sediment load series were considered as the upper boundary. The design capacity of the reservoir at the time of operation was calculated to be 179 MCM and after five years of operation it would deplete to 54 MCM due to massive sedimentation without management. Sediment deposition longitudinal profiles before any management are shown in Figure 6.

A do-nothing model outcome demonstrates that a sedimentation delta will quickly approach near to the dam axis, surpassing the slope stability. Due to these huge sediment depositions at the low-level spillway, power intakes may be damaged in between two and five years. It also negatively affects energy generation, damages the turbines, increases the flood risk and increases the maintenance and repair cost. So, sediment flushing with lowering reservoir level dramatically not only increases the life of the reservoir, it also increases the life of sediment and power intake outlet structures, as well as increasing the long-term energy generation capacity of the plant. Sediment transport mechanisms in the reservoir are highly dependent on water level. The progressive lowering of the level of the reservoir allows the water to erode the bed material in the upstream reach of the reservoir. Therefore, Thakot D-3 is a smaller reservoir and has a sufficient amount of water during the flood season to preserve the active storage capacity of the reservoir. Finally, for the sediment flushing and management study of Thakot D-3 reservoir the Ackers–White model was selected. To achieve

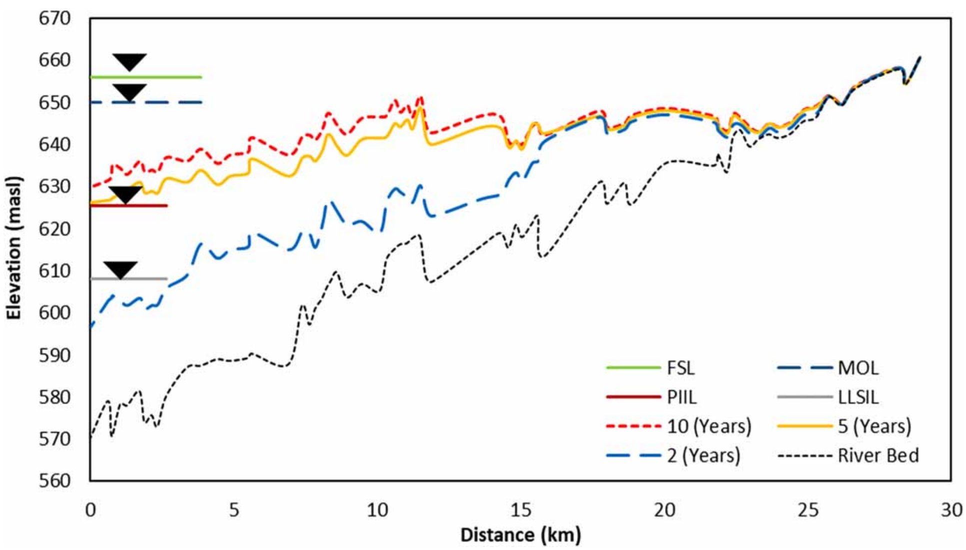

Figure 6 | Sediment profile by no-flushing condition (FSL = full supply level, MOL = minimum operation level, PIIL = power intake invert level and LLSIL = low level spillway invert level).

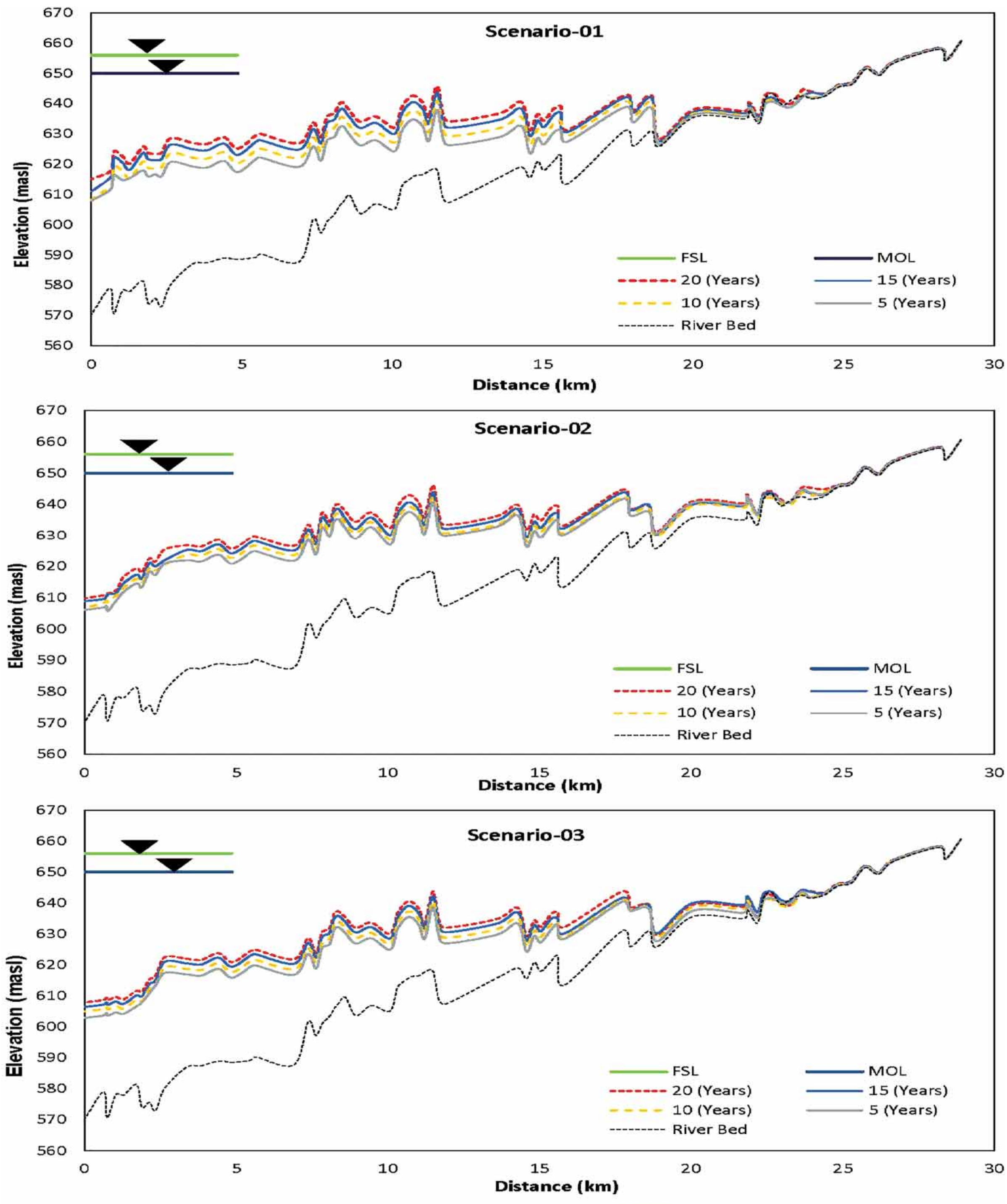

Figure 7 | Sediment flushing and management best scenarios under post-DASU conditions.

maximum long-term benefits from the proposed Thakot D-3 dam, sediment flushing and management scenarios in terms of different time durations have been developed, generally based on the best sediment flushing and management scheme of Dasu dam. According to Rehman *et al.* (2015), the reservoir's non-flushing operation period in pre-Bhasha dam conditions was limited to 15 years. After 15 years of operation, sediment flushing for 30 days in every year from 21 May to 30 June with cutoff power would be continued and a daily outflow discharge would take 2.5 days to enter into the proposed Thakot D-3 reservoir. The average outflow discharge travel time for the 66 km-long Indus reach with consideration of a reservoir at the downstream was computed with HEC-RAS. Therefore, the velocity range near to the dam site was computed to be 0.22 to 0.51 m/s respectively. Many flushing scenarios were constructed which were based on the outflow sediment discharge data of Dasu but the three best scenarios are presented in this study as shown in Figure 7.

A minimum range of operating level of 635–622 m asl is selected for the scenarios to estimate their possible impacts on sediment flushing efficiency from reservoir and conservation storage capacity. These scenarios have been developed based on the future operation of Thakot D-3 reservoir which is directly connected to the Dasu reservoir flushing operation. The spillway ogee crest level of Thakot D-3 dam is 634 m asl and the level of scenario-1 is selected as 635 m asl and is maintained for 50 days for evaluation of sediment characteristics inside the reservoir, and partial power production will be continued every year. Under this scenario, sediments would be eroded from upstream of the reservoir and redeposited near to the dam. After 15 years of operation the sediment delta would rise 3 m above the invert level of the mid-level spillway and after 20 years of operation the sediment delta would rise 7 m above the invert level of the mid-level spillway. These huge sediment depositions at the mid-level spillway would damage its capacity and increase maintenance cost. In scenario-2 the water level is selected as 626 m asl and flushing discharge as 5,410 m^3/s and are maintained for 40 days. It is found that the sediment is not significantly eroded from upstream of the reservoir and a delta built just 1.2 km upstream of the dam site and the storage capacity of the reservoir is reduced lower than in scenario-1, but for 40 days in total power production will be interrupted. In scenario-3 the water level is selected as 622 m asl and flushing discharge as 5,255 m^3/s and are maintained for 40 days, which is more appropriate for free flow flushing, and suspended loads of 0.2 to 0.4 mm are mobilized and trapped in the reservoir section over 1.8 km upstream of the proposed dam, and power production will also be interrupted for 40 days.

CONCLUSIONS

Sustainable sediment simulation through reservoir flushing using the HEC-RAS model has been carried out in this study to check the capability of the numerical model for narrow gorge reservoir flushing under a free flow scenario, and it is concluded that this is the more appropriate technique for evacuation of sediment. The period of non-flushing of sediment from Dasu reservoir is limited to 15 years (Rehman *et al.* 2015); if Thakot D-3 HPP construction is completed immediately after the commissioning of Dasu HPP, then sediment flushing is not required before Dasu flushing operations. During this period the proposed Thakot D-3 hydropower plant would contribute maximum energy into the national system. Sediment flushing through the reservoir is economically and technically vital for Thakot D-3 to increasing storage capacity for a long time, under post-Dasu conditions. Flushing scenario-3 is most favorable for 40 days in each year with a reservoir drawdown level to 622 m asl and a water discharge rate of 5,255 m^3/s. It is further concluded that construction of the upstream Diamer Basha dam in parallel time will considerably decrease sediment inflow for Dasu and Thakot D-3 reservoirs and enhance the storage life and energy generation capacity of both projects, and it will also play a vital role in sustainable operation of downstream run-of-river hydropower projects proposed on the Indus reach.

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