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Reservoir Sustainability and Sediment Management - Case Study: Jagdulla Peaking Run-of-River Hydroelectric Project, Dolpa, Nepal

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Abstract

Reservoir sedimentation is the biggest threat to the reservoir. Sediment in reservoir fills the dead storage causing the decrease in the live storage of the dam and effects the sustainability of the reservoirs. To maintain the sustainability, before the construction of the dam it is utmost important to identify the sediment management techniques. Recently, sediment flushing operations have been more common to release part of the stored sediment in reservoirs. It entrains and transports reservoir delta deposits by drawing the reservoir down to run off river flows. This study considers the case of Jagdulla Peaking Run-of-River Hydroelectric Project to evaluate the performance of 1D model built in open software HEC-RAS. This is used to develop a hydraulic analysis of sediment transportation model. Calibration is done by applying various sediment transport functions and Manning's roughness coefficient. The model output indicates the hydraulic performance, sediment transportation, sediment deposition and the sustainability of the reservoir of the project. The output of the model combined with local knowledge can help to attenuate the problem arising due to the sediment.

Keywords

Sediment deposition, Sediment flushing, HEC-RAS, Reservoir Sustainability

1. Introduction

Almost all of the Nepalese rivers are alluvial and such rivers contain eroded sediments in any of the three forms; bed load, suspended load, or wash load. Different factors like sediment type, basin slope, particle size, drainage condition, vegetation, land use, climatic condition effects the sediment transportation. When the freely flowing water is distributed by human intervention such as dam the sediment is trapped to the bottom. Dams are designed such that it do not lose its storage capacity and its performance doesn't decrease [1]. Practically sediments do not build up evenly along a horizontal plane resulting in loss of live storage. The actual process of sediment deposition is unique to every reservoir and is impossible to predict accurately. The movement of sediment particle occurs when the instantaneous force of flowing water exerted on the particle is greater than the resisting force of the particle[2] has defined a critical Shields' parameter for the critical value of bed shear stress depending upon the particle size and water turbulence. In alluvial rivers, it is safe to assume that the amount of bed-material load transported is always equal to the sediment transport capacity. For semi-alluvial rivers, the transported sediment is generally less than the transport capacity.

The selection of appropriate formula depends upon the flow and sediment conditions of the specific case. The general deposition pattern of sediment in reservoirs is not uniform. The coarser particles are deposited first which form a delta at the upstream reach of the reservoir [3]. The finer particles settle more downstream, and the finest particles reach the deepest point just upstream of the dam. The longitudinal sediment deposition in reservoirs can be divided into three zones as top set bed, forest bed and bottom set bed [4]. In cross-sectional direction, the initial deposition is concentrated in the deepest region of the section, which creates a near horizontal bed surface irrespective of initial shape of section [4].PRoR projects in Nepal are mostly located in the upper reaches of the catchment due to higher head availability. These locations are vulnerable to various hazards like GLOF, landslide and debris flow leading to high sediment yields which cause sedimentation issues in the reservoir [5].

Reservoir is the most important component for the management of the transported sediment. The main function of Reservoir is to ensure the live storage and supply the designed discharge to the intake from hydropower plants [6]. In hydropower plants, bed load are excluded by providing under sluice/bed load sluices and gravel traps. They should function to achieve bed control in front of the intakes such that intake of bed load into the conveyance structures can be prevented. The Performance of flushing under various flow and sediment load condition need to be assured for the sustainable life of the reservoir. Free flow flushing and pressure flushing are two different flushing operations Morris and Fan [4]. During the flushing erosion occurs rapidly due to high discharge. The riverine flow with higher flow velocities causes the scouring of the sediment and transports it downstream through the dam outlets. Flushing is considered a good option for sediment management in reservoirs having small hydrologic size (reservoirs having ratio of storage capacity to annual inflow less than 0.3) [4]. For large reservoirs flushing may not be feasible option because of the volume of water lost during drawdown and a longer time required to refill again after flushing. While flushing without drawdown, high flow velocities are only localized at the outlet, which has no significant effect [7].

Physical models are widely used in order to evaluate the performance of sediment exclusion devices and overall performance of the head works. However, physical model tests are time consuming and costlier and they also provide very less flexibility in quick observation of the performances after implementing the design modifications. The main objective of this study to prepare the sediment flushing strategy and study the sustainability of live storage of the project. Alternatively, with the development of fast processing computers, numerical methods have also developed as potential alternative tools to physical models [8]. HEC-RAS models are widely used to study complex sediment transportation phenomena and sediment deposition pattern [9].

2. Study Area

The Jagdulla PROR (peaking run-of-river) Hydro Electric Project of 106 MW is located at Jagdulla and Mudkechula Rural Municipality, Dolpa District, Karnali Pradesh. The Project area lies between $82^0$30'00" E to $82^0$38'32" E and $29^0$00'00" N to $29^0$08'11" N. Total catchment area of the project is 663 km² with annual mean flow of 26.03 m^3/s. The design discharge and design flood (Q 1000) of the project is 3.77 m^3/s and 141 m^3/s respectively. The reservoir volume capacity is 0.34-0.94 MCM for 20-30 m weir height with crest length of 48.7m. The Dam crest level is 2698.00 m, Full supply level (FSL) is 2696.00 m, and minimum draw down level (MDDL) is 2690.00 m. The project utilize gross head of 810 meters. It produces a total average annual energy of about 545.22 GWh with an average annual dry season energy production of about 164.61 GWh and an average annual wet season energy of about 380.76 GWh. For the sediment flushing 3 sluice spillway of size 7m x 7m are provided. The study area is as shown in the figure 1.

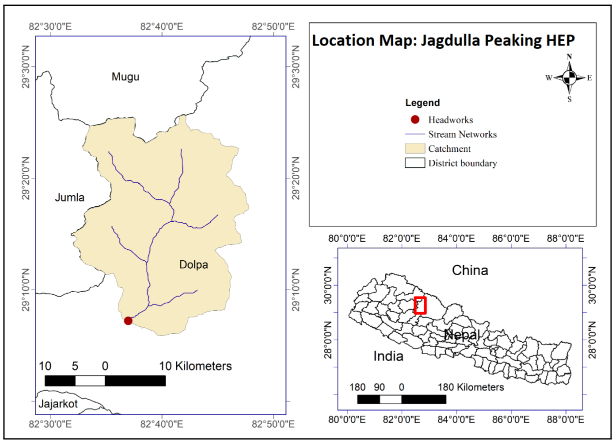

Figure 1: Location of Jagdulla Hydroelectric Project

3. Methodology

3.1 Data collection

Topographical data measured daily discharge data long term estimated flow series and measured sediment was obtained from NEA Engineering and climatic data was obtained from Department of Hydrology and Meteorology. The discharge rating curve and sediment rating curve were developed.

$$Q = 5.9125x(H - 0.4)^{2.2136}$$

$$C = 0.0374Q^{2.5124}$$

Where, C= Concentration of the sediment for corresponding discharge, Q = Daily discharge

3.2 Load Estimation

In the project site only the suspended load measurement is done but the bed load measurement is not carried. The bed materials are very coarse and flow velocity is very high making it impractical to measure the bed load by conventional method. Hence to address the unmeasured bed load 20 percentage [3] has been added to suspended load to compute the total load for the modeling purpose. The loads taken for the simulation is as shown in the figure 2.

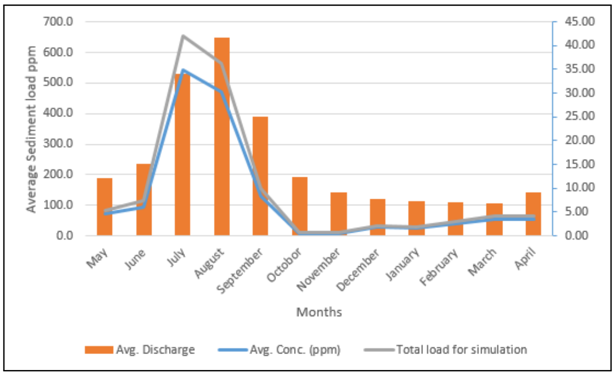

Figure 2: Figure Average monthly discharge and sediment variation

3.3 Calibration of manning's n

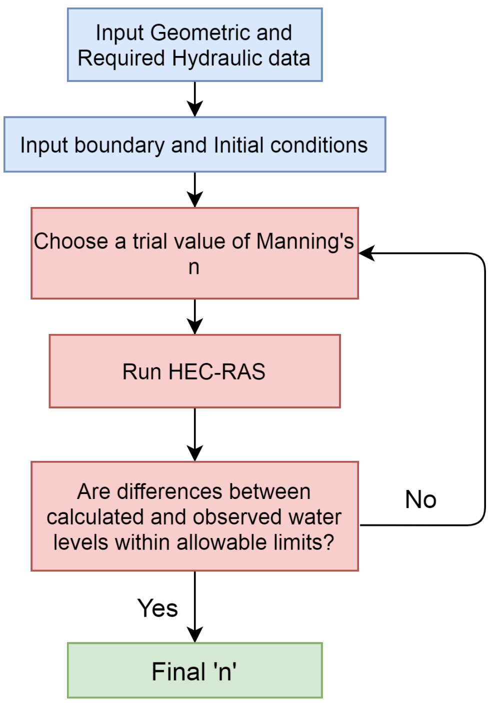

Figure 3: Figure Manning's n calibration flow chart

The Calibration was performed by comparing the result of the water level obtained by the model with the measured stage. The initial value of n was selected to be in the range of 0.020 to 0.0350 with an increment of 0.005 [10].The value has been calibrated to be 0.028 for the channel and 0.05 for the banks. The procedure followed in the calibration is given in the figure 3.

3.4 Hydraulics and Sediment Modelling

For the study of reservoir sustainability and sediment management different modelling software like GSTARS, SRH, and HEC-RAS are used. A one –dimensional model built in HEC- RAS 5.0.7 modelling software is used in this study.It requires the data like geometric file, flow file quasi –unsteady, sediment data file, and sediment analysis plan file. The Methodological flow chart is as shown in the figure 4.

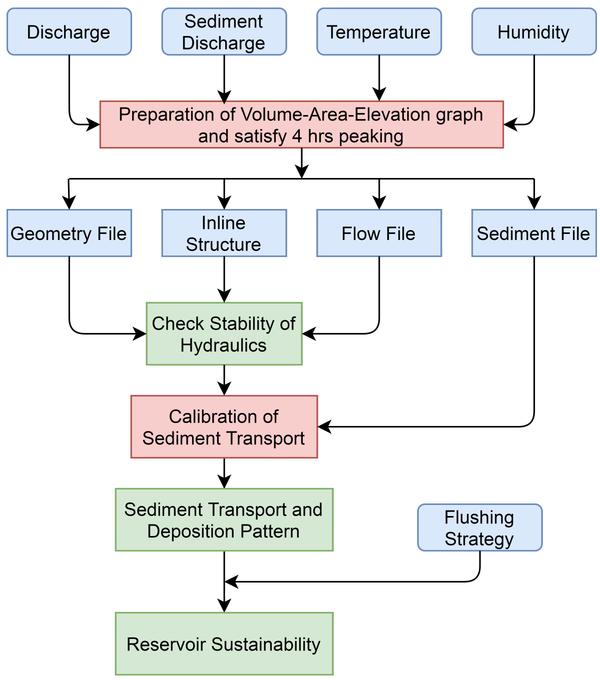

Figure 4: Figure Methodological flow chart

HEC-RAS has the ability to model inline structure. Jagadulla hydroelectric project consists of spillway of 31m X 2m opening with crest level at 2698.00m for the safe passage of flood. For the flushing purpose there are three sluice gates of 7m X 7m with invert level at 2678.00m. A geometric model comprising of 150 sections spaced at 25 m spacing for hydraulic analysis and model comprising of 25 sections spaced at 100 m spacing for sediment analysis was prepared for a total length of 3.25km.

Different flow profile based on the flood analysis was given for the analysis and the gate opening was performed based on the flow. Normal depth was given as the upstream and downstream boundary conditions.

It models steady and unsteady flow for variety of hydraulic cases and simulate mobile bed sediment transport phenomenon [3]. Stabilizing the model with unsteady flow regime is very painstaking, and hence, sediment transport has been simulated using quasi steady flow regime. It assumes constant hydrodynamic properties over the duration of a given flow. This model divides the time into three-time steps: Flow duration, Computational time step and Mixing time step.

Several sediment transport methods (functions) have been implemented in HEC RAS to compute transport potential. Once transport capacity is computed, the sediment continuity equation is solved over each control volume. Continuity principal is applied for each grain size as the capacity is compared to the inflowing supply. If transport capacity exceeds supply, material is removed from the control volume, while deposition results if supply is greater. This is quantified by the Exner (sediment continuity) equation [9]. Daily flow hydrograph and sediment rating curve, time wise stage relationship, normal depth was used as the upstream, internal and downstream biundary condition.

Sediment transport capacity and after flush profiles were estimated using different transport functions and compared. Out of which Ackers White transport function along with Ruby Fall Velocity Method with Copeland (Exner 7) sorting method was found to best represent the transport capabilities for project. As the contribution of sand sized particles is dominant in this site and Ackers-White is a total load transport function best suited for relatively uniform particles ranging from 0.19mm to 0.93 mm and uniform slope. In Jagdulla HEP, discharge ranging from 42 -52 m3/sec contributes to almost 70percent of the average annual sediment inflowing into the reservoir. To avoid the excessive sediment inflow and deposition into the reservoir, force flush is activated at 2year return period flood. The flushing should require minimum day for plant shut down [11]. To ensure evacuation of the deposited sediments by the end of monsoon, a force flush on 15th September for 3-days duration has been set each year. During Dry season, water level is fixed to FSL while during the monsoon it is dropped to MDDL to avoid the sediment deposition and loss of live storage volume of the reservoir. Water levels during the flushing durations has been computed based of the discharging capacities of the 3 Sluice. For the first simulation, different flushing strategy were made and study was carried.

3.5 Model Calibration

As the project is in study phase, there is no data for the proposed reservoir that can be used for calibration. In absence of the calibrating data, two different procedures have been used for model validation to check model behavior for reasonableness of the results. The first validation procedure was to simulate the existing river profile in HEC-RAS. The profiles of the Himalayan Rivers are continuously influenced by the input of materials from landslide and debris flow, but the reach under study does not have recent perturbations of this type and may be relatively stable with respect to its longitudinal profile. The model was run for the river in normal scenario and inflowing load of the coarse bed material was adjusted until the riverbed stabilized, neither aggrading nor degrading to an appreciable degree. Second validation process was to confirm the transported sediment with the measured sediment in the station. Total of 380 days measured sediment discharge was available, from the known temperature kinematic viscosity was calculated, the depth and velocity was taken from hec-ras. For different discharge the sediment discharge was calculated. The calculated and the measured value are plotted in the figure 5 and the obtained nash efficiency obtained is 0.63.

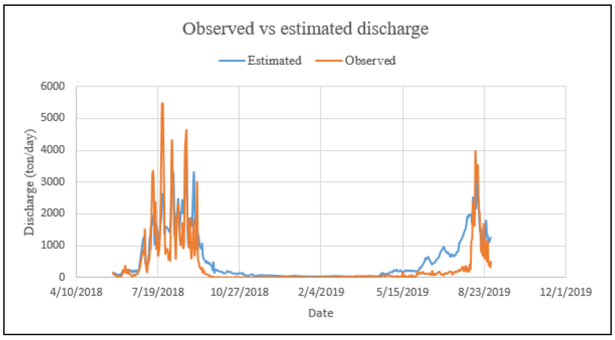

Figure 5: Figure Estimated vs. Observed discharge sediment discharge

4. Results and Discussion

For the hydraulic check, the geometric model comprising of 10 sections spaced at 25 m spacing was prepared. One of the most sensitive parameter of manning's n was used by calibration and it was calibrated to be 0.028 for channel and 0.05 for the banks. Normal depth boundary condition was given as the upstream and downstream boundary condition. Once the model was hydraulically stable in lined structure was added to it and under the various design flood the model was run and it was found that the provided spillway can pass the design flood of 1000yrs return period and for more than that the sluice gate need to be operated. The cross section of the flood passage with gate closed and the longitudinal section of flood passage with the gate open is as shown in the figure 6 and figure 7.

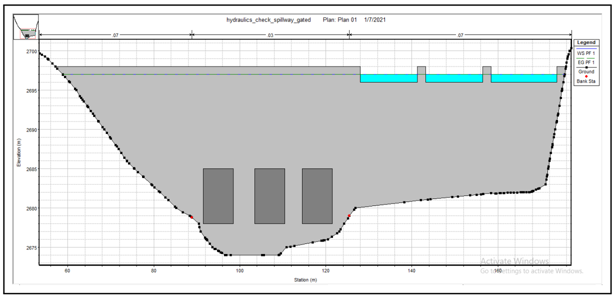

Figure 6: Figure cross-section of flood passage (gate closed)

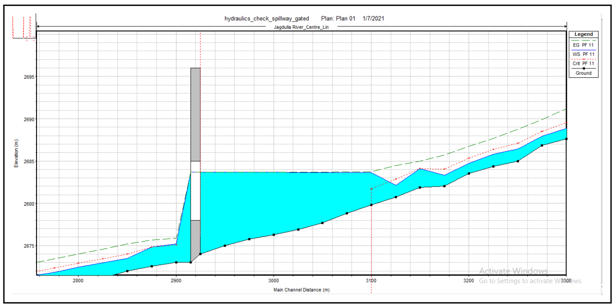

Figure 7: Figure Longitudinal section of flood passage (gate open)

Once it is stable hydraulically, sediment transport analysis was carried. To validate the sediment transportation river bed equilibrium was studied for 10 years of period. This equilibrium bed gradation was taken for further analysis.

The Sediment deposition pattern patter without flushing is as shown in the figure 9. From the year 1984 to 2009 (26 years) simulation was done and the sediment deposition in the reservoir was studied. Clear delta formation on the upstream of the reservoir was studied.

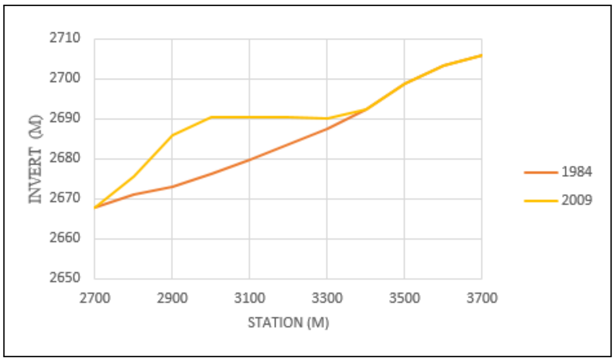

Figure 8: Figure Original and simulated bed level

The sediment flushing operation was done using 3radial sluice gate of 7m * 7m. The invert level, Mddl and Fsl was fixed at 2678masl, 2690masl, 2696masl respectively. For the simulation under the strategy-I, no flushing was considered for the dry season and flushing is done when the discharge is greater than 58m3/s. In this case no significant difference is seen from the sediment deposition pattern. So, this strategy was not effective the flushing. The bed profile under the strategy-I is as shown in the figure 9

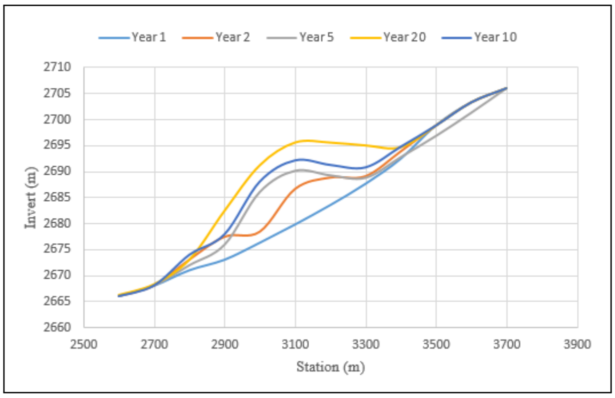

Figure 9: Sediment bed profile over simulated year (Strategy-I)

For the simulation under the strategy-II, no flushing was considered for the dry season and flushing is done when the discharge is greater than 58m3/s, and 15th September of every month. In this strategy of flushing no significant change to the first strategy is seen. At the end of 20years, complete dead srorage was filled and more of the live storage was also filled. So, this strategy was also not efficient for the sustainability of the reservoirs. The bed profile under the strategy-II is as shown in the figure 10

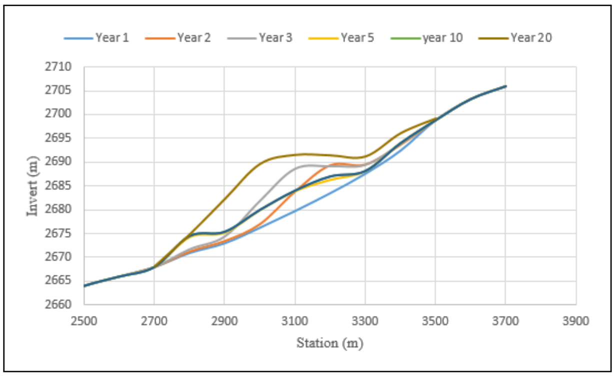

Figure 10: Sediment bed profile over simulated year (Strategy-II)

For the simulation under the strategy-III, no flushing was considered for the dry season, flushing was done when the discharge is greater than 58m3/s, every 15th September of every year ans after the every 3 weeks of flushing. In this strategy, more of the live storage was retained but not significant. So, this strategy also cannot be adopted for the reservoirs. So, another strategy was studied. The bed profile under the strategy-III is as shown in the figure 11

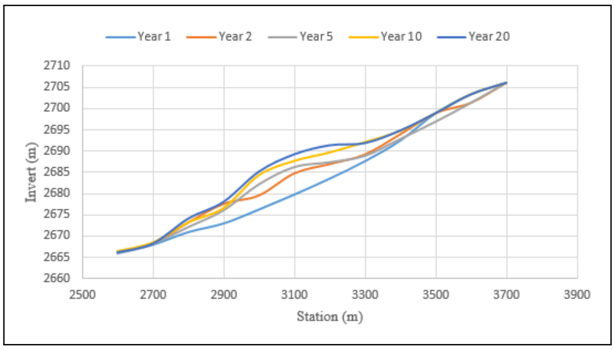

Figure 11: Sediment bed profile over simulated year (Strategy-III)

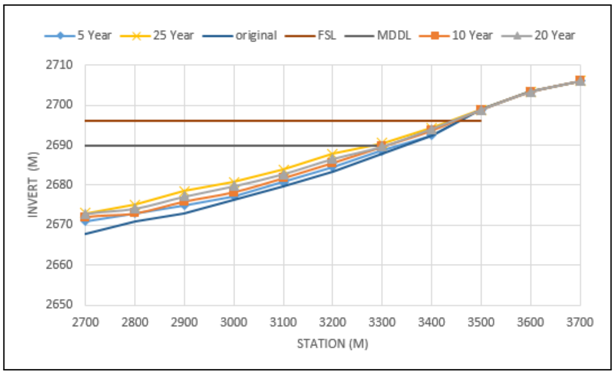

Figure 12: Sediment bed profile over simulated year (Strategy-IV)

For the simulation under the strategy-IV,no flushing was considered for the dry season, flushing was done when the discharge is greater than 58m3/s, force flush on 15th September for 3 days every year and after the every 3 weeks of flushing. In this strategy, live storage is retained. So, this strategy can be adopted for the reservoir flushing. The bed profile under the strategy-IV is as shown in the figure 12

Sediment accumulated at the upstream of the reservoir gets flushed out once the sluice gate is opened. From the simulation result we can find that the live storage of the reservoir is retained for 26years and the reservoir is sustained. Moreover the dead storage also is not filled completely at the end of the simulation.

Various modes of flushing strategy and operation rules are Studied in the simulation. Flushing is considered from the 3 under sluice gates of opening 7m x 7m. Flushing the reservoir 8.11 days per year the sediment in the reservoir can be managed and the reservoir sustainability can be achieved. Flushing more than that does not give the significant difference. Choosing transport function, sorting method, fall velocity method and bed gradation is more important than increasing the flushing duration and grid size. It is seen that under the flushing consideration made for this case study, the size and number of sluice spillway allocated to the project is adequate to retain the live storage volume even at the end of simulation period. However, in absence of the calibrating data for this numerical simulation, physical modeling must be carried out to support and validate the simulation results. During operation phase the sediment deposition must be monitored regularly to optimize the reservoir flushing. The model is hydraulically stable and the spillway can pass 100year return period flood but for 1000year return period, sluice gate need to be operated. After the construction of dam, in the upstream sediment is deposited in the delta shape and it is deposited up to the elevation of 2690.56masl, 0.56m above the MDDL. With the force flush on 15th September for 3-days and average 8.11 days flush per year a part of the storage volume reduced due to sediment deposition can be recovered. At the end of simulation year the live storage of the reservoir is retained , thus we can conclude the reservoir is sustainable.

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