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Sediment Budget and Sediment Trap efficiency of Baglihar Hydroelectric project Reservoir – a calibrated model for prediction of longevity of the Dam

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Abstract

The field investigation of the reservoir area of Baglihar Hydropower project shows that the sediment budget to the reservoir is controlled by fragile rock type like shales, sandstones, phyllites and slates, soil characteristics, steep hill slopes, rainfall and landslides. The rocks are highly weathered, fissile and micaceous in nature and very sensitive to water absorption. The analysed sediments are characterised by dominance of sands, silts and clays with lower values of plasticity (14.3PL), liquidity (23.5 LL), cohesion (118) and shear strength (202 Kpa). The slope wash deposits are highly susceptible to landslides and slope failures and directly contribute to the sediment budget in the reservoir. In addition tributaries of Chenab River also bring sediments in the reservoir from the catchment area.

The empirical relationship for estimating the long-term reservoir trap efficiency for large storage based on correlation between the relative reservoir size and trap efficiency was simulated in 3D model which shows that the annual sediment trap efficiency of the Baglihar reservoir is of 0.39%. The extrapolation of the calculated values shows that the total sediment load shall increase by 11% in the next 30 years and 20% in the next 50 years and correspondingly 40% in the next 100 years that shall induce corresponding decrease in the reservoir volume over the time. By applying flushing schemes, life span of the reservoir can be extended. It is estimated that after 100 years the reservoir shall lose ~35.6% storage volume. On further extrapolation, the trap efficiency will decrease from 25.5% after 30 years to 23% after 100 years. The estimated trap efficiency of Baglihar reservoir is 60%, which is greater than that based on numerical results, showing a significant overestimation.

Keywords: *Baglihar Reservoir, Chenab Basin, Sediment budget, Sediment Trap Efficiency*

Introduction

Reservoirs are key tools for the management of water resources. They provide a means for reducing the effects of inter-seasonal and inter-annual stream flow fluctuations and hence facilitate water supply, flood control, hydroelectric power generation, recreation, and other water uses. Nilsson et al. (2005) found that over half of the world's large river systems are currently impacted by dams. Monitoring of catchment area, reservoir characteristics and dam itself is one of the main aspects for the civil engineering project. The efficient and effective management of hydropower reservoirs is vital for hydroelectric power plant operation. The continuous and extreme rainfall events in the catchment area and subsequent sedimentation into the reservoir are important to monitor at regular intervals to avoid the underestimation of safety measures (Khaba and Griffiths, 2017; Verstraeten and Poesen, 2000). One of the critical factors that contribute to successful hydropower reservoir management is through reliable monitoring infrastructure, equipment and technology. Therefore, the continuous monitoring of inflow is an essential tool for hydropower dam operators by providing real-time data for decision making in power generation and planning (Basri et al., 2019). This is the main reason of why most of the governments and water supply companies today continue to face the problems when it comes to the control management of dams. A potential failure mode is a physically plausible process for dam failure resulting from an existing inadequacy or defect related to a natural foundation condition, the dam or appurtenant structures design, the construction, the materials incorporated, the operations and maintenance, or aging process, which can lead to an uncontrolled release of the reservoir. Furthermore, it is necessary to execute the investigation carefully from the early stage so as not to generate stagnation or retreat because the dam project is large-scale and needs huge amount of money for construction. Because the appearance of the dam reservoir exerts adverse influence on the geo-environment, the mitigation or conservation should be considered to decrease the influence as much as possible.

The Baglihar Hydroelectric Project lies on the Chenab River in Ramban District of Jammu and Kashmir. The project is a major hydel scheme comprising of two stages i.e, Stage-I and Stage-II each producing 450 Mw of electricity. The catchment area of this project covers about 1500 km^2 comprising of glaciers bound mountains in the Pir Panjal and Dauladhar ranges in the Higher Himalaya - a perennial source of water to the Chenab River. The dam site lies at Baglihar village situated between Batote and Ramban falling in the Lesser Himalaya. The dam site is connected with Jammu by NH44 whereas the reservoir lies along the Batote-Doda Highway and is covered in the Survey of India toposheets 43 O/8, O/15 and O/16. Several active landslides and sinking zones are present within the reservoir area which contribute large amount of sediments to the reservoir (Singh et al., 2012). In addition a number of large and small upstream perennial tributaries of the Chenab River bring sediments into the reservoir.

The reservoir capacity is defined as the ratio of deposited sediment to the total sediment inflow for a given period within the reservoir's economic life time. The reservoir storage capacity, drainage area, river discharge flow and time factor have been helpful to calculate the sediment trap efficiency. The monitoring of sediment trap efficiency of the dams is of paramount importance that leads to understand the series of complex processes occurring at the interface between hill slopes and valley-floor systems (Walder and Connor, 1997). The trap efficiency depends primarily upon the fall velocity of the various sediment particles; flow rate and velocity through the reservoir; as well as the reservoir size, depth, and shape; and operation rules of the reservoir (Strand and Pemberton, 1982). The particle fall velocity is a function of sediment particle size, shape, and density; water viscosity; and the chemical composition of the water and sediment. The reservoir sediment trap efficiency tends to decrease over time as sediment fills the reservoir. However, the trap efficiency also decreases temporarily during floods as flow velocity increases through the reservoir. The relative size of the reservoir is a useful index to initially estimate the sediment trap efficiency. The reservoir sediment trap efficiency increases with the relative size of the reservoir. Churchill (1948) and Brune (1953) developed empirical relationships for reservoir sediment trap efficiency from Tennessee Valley Authority reservoirs in the southeast United States. Churchill (1948) developed a trap efficiency curve for settling basins, small reservoirs, flood retarding structures, semi-dry reservoirs, and reservoirs that are frequently sluiced. He correlated the percentage of the incoming sediment load passing through a reservoir with the ratio of the reservoir retention time to the mean velocity (sedimentation index). The sedimentation index can be made dimensionless by multiplying it by the acceleration due to gravity (g). Brune (1953) developed an empirical relationship for estimating the long-term reservoir trap efficiency for large storage based on the correlation between the relative reservoir size and the trap efficiency. Using this relationship, reservoirs with the capacity to store more than 10 percent of the average annual inflow would be expected to trap between 75 and 100 percent of the inflowing fine sediment. Reservoirs with the capacity to store 1 percent of the average annual inflow would be expected to trap between 30 and 55 percent of the inflowing fine sediment. Significant progress has been made during the recent years in estimation of the sediment trapping in the reservoirs (e. g., Garg & Jothiprakas, 2008; Revel et al., 2015; Tan et al., 2019). Heidarnejad et al. (2006) suggested monthly sediment rating curve to estimate the suspended and bed loads in the reservoir whereas, Lewis et al. (2013) suggested daily sediment trapping estimation based on the daily flow volumes. Earlier the Baghliar reservoir was studied with the objective to appraise the geotechnical and structural setup of the region and impact of reservoir on the geoenvironment (Singh et al., 2012; Kumar et al., 2020). However, reservoir monitoring and the factors affecting its longevity were not taken up. According to Singh et al. (2012), the reservoir has induced landslides within the reservoir area and adjoining areas of Baglihar due to soil response to pore water pressure. The interpolation of the previous hydrological data using geometric parameters suggests significant contribution of sediments into the reservoir. The objective of this study is to monitor catchment area of Baglihar reservoir and understand various geological, geotechnical and slope aspect related problems which increase sediment budget and sediment trapping which in turn affect the reservoir competency and longevity of the project.

Geological and Structural Setup of the Area

The study area comprises of the Lesser Himalayan rocks, bounded between two prominent thrusts i.e, Panjal Thrust (PT) in the north and Murree Thrust (MT) in the south (Fig.1). The rocks in this region are folded and faulted normally dipping towards the regional north dipping thrusts. Stratigraphically, significant part of the study area comprises of oldest Salkhalas and youngest Murree Formation (Fig.1). The

Salkhalas are the Pre-Cambrian rocks composed of metamorphosed, less varied, easily identifiable assemblage of phyllites and slates with characteristic rock type of deep black graphitic slates, black crystalline limestone, snow white marble and flaggy quartzite (Jangpangi et al., 1986). The other rock types sandwiched between PT and MT include Gamir-, Baila-, Ramban-, Bhimdasa- and Sincha formations. These are the group of metamorphic rocks with rarely occurring limestones and cherty shales (Jangpangi et al., 1986). The Murree Formation Comprises of the sandstones, mudstones and shales with ripple marks and pseudo-conglomeratic structure (Bagati, 1991). The chief rock types of the Murree strata are sandstones, shales and claystones marked by graded-bedding; ripple marks, micro cross-lamination and crude cross-stratification. The river terraces along the Chenab River constitute the youngest Quaternary-Recent units in this area (Haq et al., 2019). All the rock types exposed within the reservoir and surrounding areas are highly jointed, weathered and fragile. The phyllites of Salkhalas are highly micaceous, fissile and extremely weathered to micaceous clays.

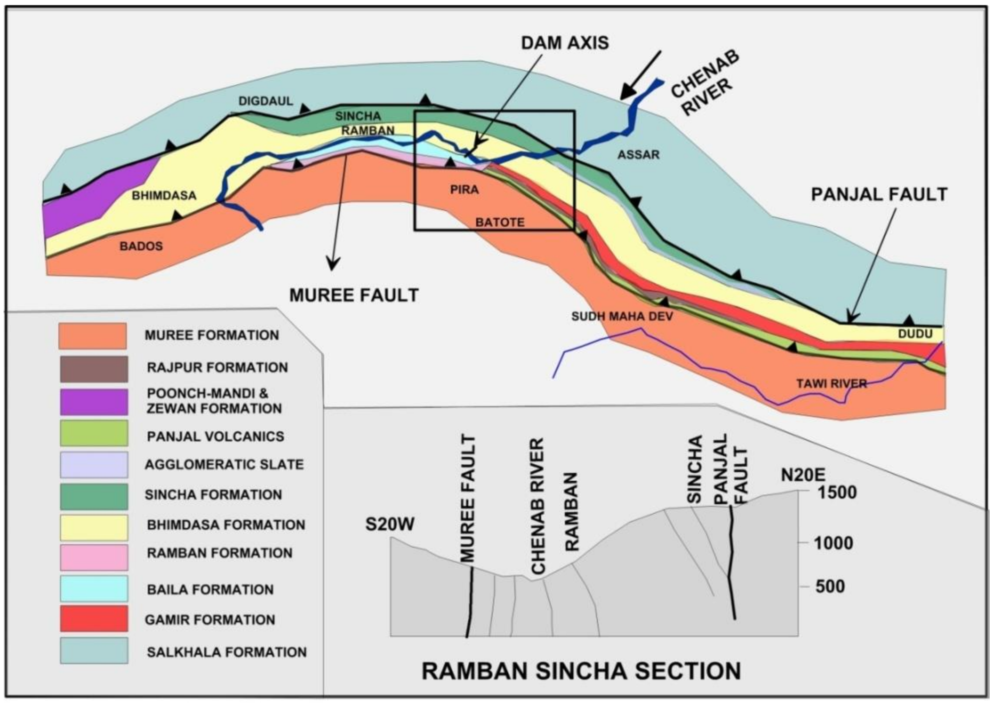

Fig.1: Geological and structural map of the study area (after Jangpangi et al., 1986).

Materials and Methods

Detailed field investigation was conducted to establish the factors responsible for contributing the sediment budget to the reservoir of the project. Field data on lithology, current landslides and structure was collected from the reservoir area. Soil samples from different locations including landslide sites within the reservoir area were collected for analysis of the engineering parameters of the soils following standard procedures in vogue. The grain size analysis was done with the help of sieving and for determination of plastic limit, liquid limit, plastic index, cohesion and shear strength, standard procedures after Lambe (1977) were applied. The rainfall data and the daily water discharge data for the period from 1976 to 2009 was taken from the detailed project report of Baglihar hydroelectric power project. The discharge flow data was collected from three standard gauge and discharge (G&D) stations installed at Dharamkund, Baglihar dam and Premnagar (Fig.2). The trap efficiency model was prepared with the help of elevation data and other geometrical parameters i.e, area of the reservoir and water storage. The data was taken from the Digital Elevation Model (DEM) with 30 m resolution available on the bhuvan website (https://bhuvan.nrsc.gov.in/bhuvan_links.php). The slope map and modelling of the sediment trap efficiency was made in the Arc GIS software. The data generated was equated by trap efficiency equation of Brown (1944):

$$Ca,t = t-1 /[1+ 0.00021 * (Ka,t-1/Wa)]$$

where Ca,t is trap efficiency (expressed as a decimal percent) of reservoir 'a' at time step 't'; Ka,t-1 is reservoir storage capacity (m^3) 'a' at time step 't – 1,', and Wa is drainage area (km^2) of reservoir 'a'.

Laboratory Observations

Grain Size Analysis

A total 10 samples were analysed to determine different soil parameters i.e, grain size by Wet Sieving Method and Atterburg's Limits on Casagranda Liquid Limit Apparatus. During grain size analysis the soil samples were subjected to wet sieve analysis. To obtain the grain size the soaked soil after treating with distilled water and sodium oxalate were passed through a series of different sieves of sizes, 4.75 mm, 2.0 mm, 1.18 mm, 1.0 mm, 150 µ, 300 µ, 600 µ and 700 µ. The fractions of materials collected from different sieves were converted into percentage by using the formulae:

$$P = (W_1/W) \times 100$$

Where, W_1 = mass retained in the sieve and W = total mass of soil sample taken for soil analysis. For absorption value, the samples were dried in oven followed by complete saturation in distilled water for 36 hours and then weighed again. The absorption value of the soil sample was calculated in percentage using the formulae:

$$A = [(S-W)/W] \times 100$$

Where, S = the saturated weight of the sample and W = total mass of soil sample taken for analysis. The soil samples were classified as per code (IS 2720).

Atterberg's Limits

The Atterberg's Limits which include liquid limit, plastic limit, plasticity index and absorption value were estimated by using standard liquid apparatus. The liquid limit test involves use of groove of standard width of 1.1 cm at the top surface under the impact of 25 blows to mark the boundary between liquid and plastic state of soil. In plastic limit, the soil samples were passed through 425-micron sieve to determine minimum moisture content at which the soil can be rolled into 3 mm threads without showing any sign of cracks to mark boundary between liquid and plastic and semi-solid state of soil. The numerical difference between liquid limit and plastic limit was calculated to estimate the plasticity index values.

The field moisture values of the samples were taken from slides. All the samples were taken at a depth of 50 cm. The airtight samples were carried to the laboratory and weight W_1 was noted carefully. The samples were then oven dried at the temperature of 105º-110º C for 24 hours and the weight W_2 was taken to calculate water content by using the formula:

$$W = [(W_1-W_2)/W_2] \times 100$$

Where, W_1 = weight of moist soil sample and W_2 = weight of oven-dry soil sample.

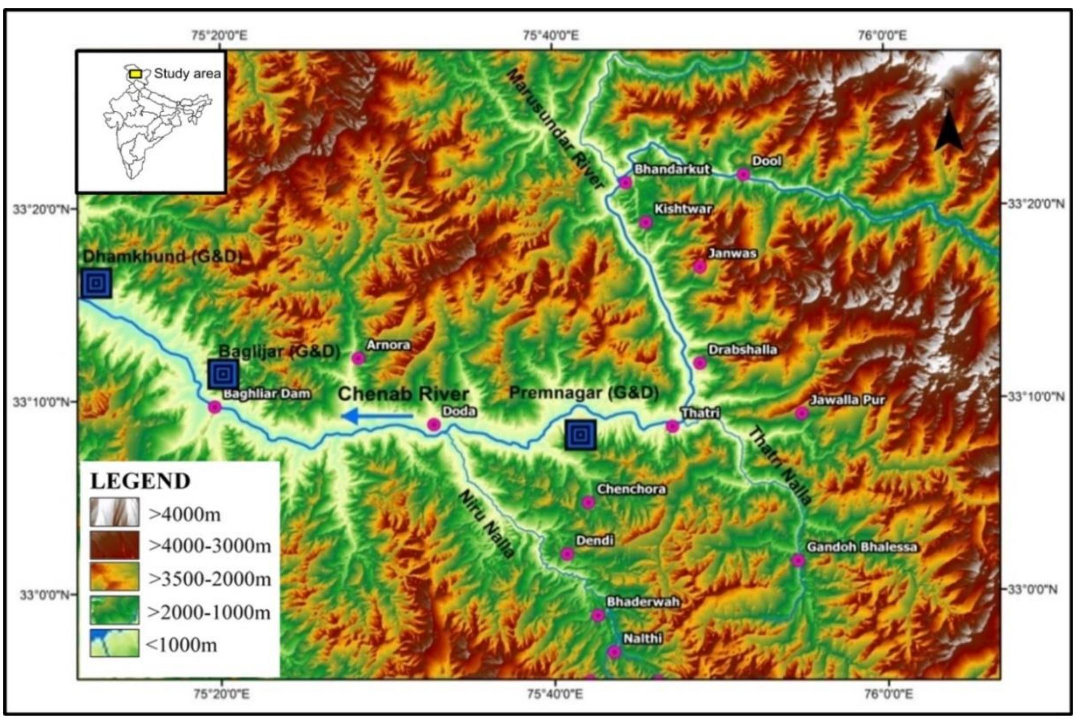

Fig.2. The topographic map of the study area showing dam site and reservoir area, the blue boxes show gauge and discharge stations installed to collect the hydrological data

Observations and Discussion

Soil Characteristics

The balance between soil forming processes and soil erosion is depicted by the depth of soil which controls the tolerance of a slope to all destabilizing factors. The inclination and orientation of structural surface have the greatest effect on the stability of the slopes (Crozier, 1986). Soil texture determines its ability to absorb and store water, generally this is referred to as liquefaction, a condition when the soil momentarily liquefies and tends to behave as dense fluid which is required for landslides to occur. Sand and silts or a combination of both are the most important textures that control liquefaction (Bryant, 1991; Msilimba, 2002; Msilimba and Holmes, 2005). Soils such as silt and clay are weaker and they have complex (colloids) or multiple planes of weakness (clay-humus complex) in common which increases the occurrence of landslides. Soils with high clay content are known to swell when it is wet and shrink in dry condition (Krhoda, 2013).

The grain size analysis of soils of the Baglihar reservoir shows the highest fraction of sand followed by silt and clay in order of dominance with average natural moisture content of 6.54% whereas the critical water absorption value of these samples ranges from 16.05-22.12% beyond these values, these soils plastically flow (Table.1). In addition, low to moderate values of liquid limit (23.5), plastic limit (14.3) and plasticity index (9.2) of these soils indicate that the soils are less consistent (Table. 2). The soils failed at these threshold values with the critical water absorption value of 22.12% (Table. 2). At this critical value of water absorption, the cohesion and shear strength values were at 118 and 202 Kpa respectively. In case of samples with higher proportion of sand content cohesion and shear strength values were relatively low at 126 and 140 kPa respectively. The reduced soil shear strength was overcome by gravity force resulting into landslides (Singh et al., 2012). The phyllites are highly crushed and weathered, and major joints run sub-parallel to the general slope of the area and percolation of rain water into these joints reduces shear strength in the soils.

Table. 1: Grain size analysis of the sediments in the study area.

S.No	Sample No.	Grain Size				Soil Type
		Gravel	Sand	Silt	Clay	
1	RS1	8.252	22.031	42.751	27.021	Silty Clay
2	RS2	26.012	11.051	34.252	28.713	Silty Clay
3	RS3	26.023	34.252	28.753	11.013	Sandy Silt
4	RS4	8.533	30.032	38.52	23.012	Silty Sand
5	RS5	23.014	9.902	27.02	40.113	Clayey Silt
6	RS6	11.531	12.613	45.31	30.614	Silty Clay
7	RS7	16.512	21.013	25.142	37.431	Clayey Silt
8	RS8	23.013	16.611	30.121	30.312	Clayey Silt
9	RS9	21.213	15.313	29.013	33.512	Clayey Silt
10	RS10	14.414	33.531	31.231	20.911	Sandy Silt

Table. 2: Atterberg's limit and Absorption values of the soil samples

S.No	Sample No	Atterberg's Limit			
		Liquid Limit (LL)	Plastic Limit (PL)	Plasticity Index (IP)	Absorption Value (in %)
1	RS1	28.012	23.012	5	7.21
2	RS2	18.532	15.512	3.02	17.43
3	RS3	24.013	17.513	6.5	12.23
4	RS4	22.714	14.613	8.101	11.13
5	RS5	31.541	17.814	13.727	7.12
6	RS6	23.513	15.131	8.382	9.23
7	RS7	25.412	14.731	10.681	21.43
8	RS8	17.012	15.821	1.191	17.53
9	RS9	24.513	17.131	7.382	9.13
10	RS10	26.012	15.641	10.371	11.12

Rainfall

Rainfall is also one of the factors that trigger landslides in the hilly areas and wash away the sediments (Van Schalkwyk and Thomas, 1991). The Baglihar catchment area receives a good amount of precipitation and due consideration has been given to its variability between the Baglihar and Dhamkund catchments. The annual isohytel maps of Chenab basin up to Baglihar and Dhamkund based on the rainfall/snowfall data in the catchment for the period of investigation was worked out at 950 mm and up to Baglihar at 937 mm. The rainfall variability between the two catchments was found only of the order of 2%. The catchments also show the peak discharge in the months of June, July and August whilst the flow recedes in the months of November, December and January. The Baglihar H.E. Project is located on Chenab downstream of the Premnagar site and upstream of the Dhamkund site where daily discharge observations were carried out by Central Water Commission (Fig.3). During the summer periods, the prolonged rainfall changes the moisture content of the regolith or weathered rock materials on the hill slopes that adversely affect slope stability. An increase in pore water pressure increases the weight and gravitational force activates the slides. Further, saturation of soil also reduces cohesion and friction between the grains, and increased moisture also reduces frictional resistance along the zones of weakness in the bedrock and soil interfaces, causing materials above to slide along the lubricated bedding plane.

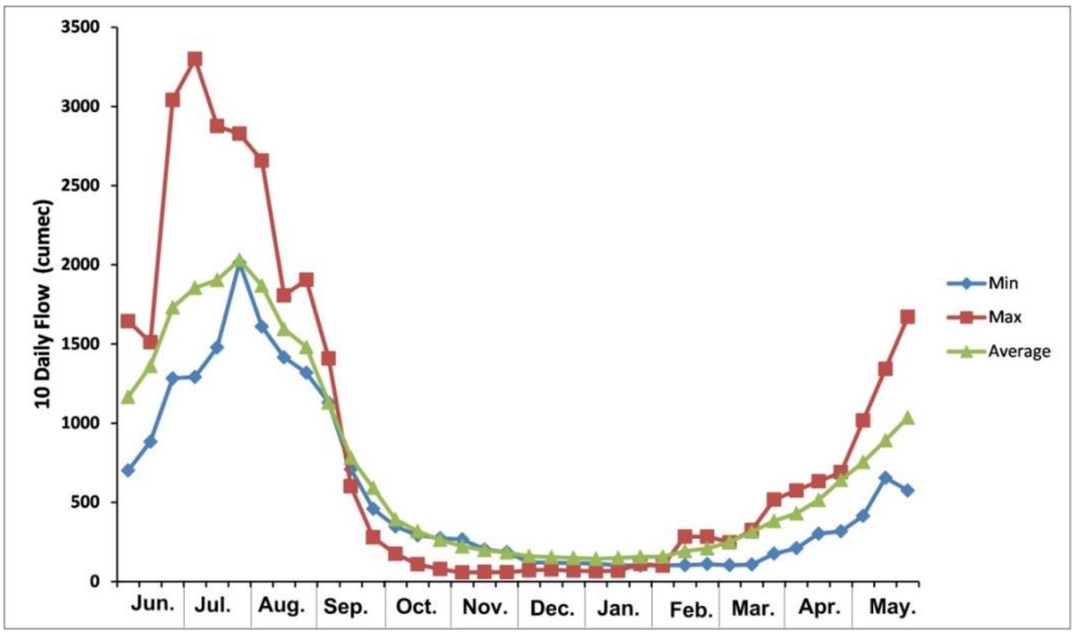

Fig.3. Maximum, Minimum and Average computed flow at Baglihar HEP, (source: DPR of the project; modified).

Landslides

The anthropogenic activities are still the major factors that cause slope failures (Sharpe, 1938; UNESCO/UNEP, 1988). Human activities in the study area increase the frequency of landslides and rockslides due to undercutting for roads and removal of lateral support to the existing building structures. Landslides are easily triggered by removal of lateral support that causes slope failure especially along the roads cuts, construction of houses and foot paths on the slopes. The catchment area of Baglihar show steep slopes and had witnessed some of the prominent landslides during the recent years and resulted in the blockade of roads, destroying the existing infrastructure and more importantly damming the reservoir at number of places (Fig.4; Fig.5a-f). The Assar landslide is a prominent shallow rotational slide in this area induced by capillary rise in the reservoir area (Singh et al., 2012). The slope materials within the reservoir area include weak and weathered rocks mostly of slates and phyllites, slope wash debris which directly contribute sediments to the reservoir and cause silting problem to the reservoir (Fig. 5g).

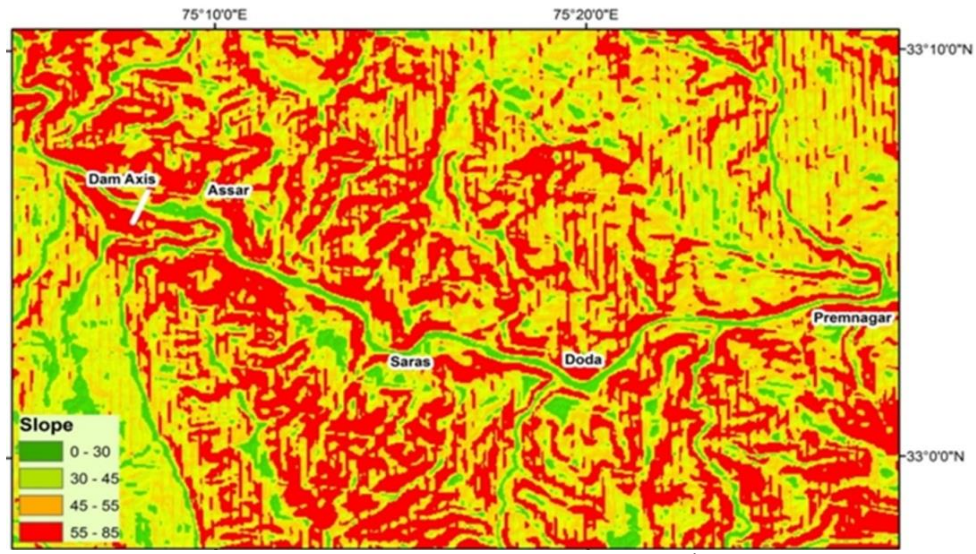

Fig.4. Slope map of Baglihar catchment showing steep slopes (slope>80^0)

Fig.5. Field photographs showing the prominent landslides within the reservoir area of the dam

Sediment trap efficiency Model

Reservoir trap efficiency is defined as the ratio of deposited sediment to the total sediment inflow for a given period within the reservoir's economic life. Trap efficiency is influenced by many factors, of which primary factors are: the sediment fall velocity, the flow rate through the reservoir and the reservoir operation rules. The relative influence of each of these factors on the trap efficiency has not been evaluated to the extent that quantitative values can be assigned to individual factors. The retention-storage time with respect to character of sediment appears to be the most significant governing factor in most reservoirs (Gottschalk, 1964). Trap efficiency estimates are empirically based upon measurements of deposited sediment in a large number of reservoirs mainly in USA. Among others, Brune's curves are the most widely used (Fig.6). Brune presented a set of envelope curves applicable to normal ponded reservoirs using the capacity-inflow relationship. Based on the empirical relationship it is inferred that the high flux of sediments to Baglihar reservoir is primarily due to the fragile lithology, steep slopes, distinguished physical soil characteristics and excess of rainfall. The calibrated model was applied for the prediction of long-term simulations of the water and bed level changes in the river reach and the effect of flushing activities on the trap efficiency of the reservoir. The results of reservoir capacity changes due to sedimentation for a long time period show that after 100 years the reservoir will lose 40% of its initial volume. By applying flushing schemes, life of the reservoir can be reasonably increased; after 100 years the reservoir will lose only 35.6% storage volume. The predicted trap efficiencies will decrease due to the reduction of reservoir storage capacity. Applying flushing schemes, the trap efficiency will decrease from 25.5% after 30 years to 23% after 100 years. According to Brune's curves, the estimated trap efficiency of Baglihar reservoir is 60%, which is greater than the estimates based on numerical results, showing a significant overestimation (Fig.7).

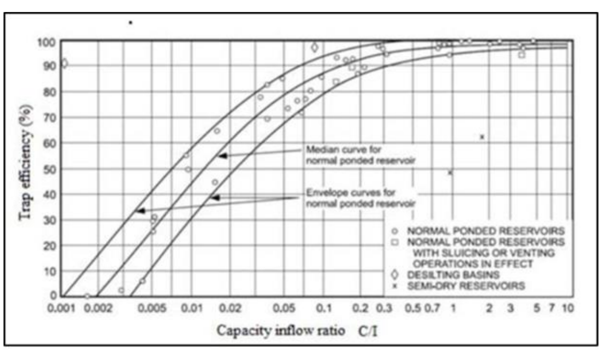

Fig.6. Reservoir trap efficiency as a function of capacity inflow ratio (Brune, 1953).

Conclusions

The field investigation of the reservoir area shows a number of causative factors are responsible for contributing sediments to the reservoir. The major among them include fragile rock type, slope wash deposits on steep hill slopes, rainfall and landslides. The landslide hazard in the reservoir area is due to lithology, structure, soil depth and texture, geomorphology, slope angle, etc. The steep slopes (slope>80º) and convexity of the slope increases the landslide hazard in the catchment area. The presence of highly weathered phyllites, shales and slates in the catchment area shows more susceptibility to landslides than hard and massive rock types in the area. The soil parameters also reveal the dominance of sands and silts in the slide zones with lower values of plasticity (14.3PL), liquidity (23.5 LL), cohesion (118) and shear strength (202) Kpa.

Furthermore, the saturation of soils during rainfall also reduces cohesion and friction between grains, and increase in the moisture content reduces the friction along the zones of weakness in the bedrock and soil interfaces, causing material above to slide along the lubricated bedding planes resulting in slope failures. The human activities in the study area increase the frequency of landslides and rockslides due to undercutting for roads and removal of lateral supports to the existing built structures which results into the damming of reservoir.

Estimation of changes in reservoir storage capacity, and thus sedimentation volume showed that the estimated trap efficiency of Baglihar reservoir is 60% with annual efficiency of 0.39%. The predicted trap efficiencies will decrease due to the reduction of reservoir storage capacity. The sediment trap efficiency of the reservoir reveals the annual sediment trap efficiency of the Baglihar reservoir is of 0.39% with increase in the load of 11% in the next 30 years and 20% in the next 50 years and subsequent 40% in the next 100 years that reflects the corresponding decrease in the reservoir volume as well. Applying flushing schemes, the trap efficiency will decrease from 25.5% after 30 years to 23% after 100 years.

The countermeasures for the reduction in sedimentation rate in the reservoir are needed for the longevity of dam reservoir. The most important ones

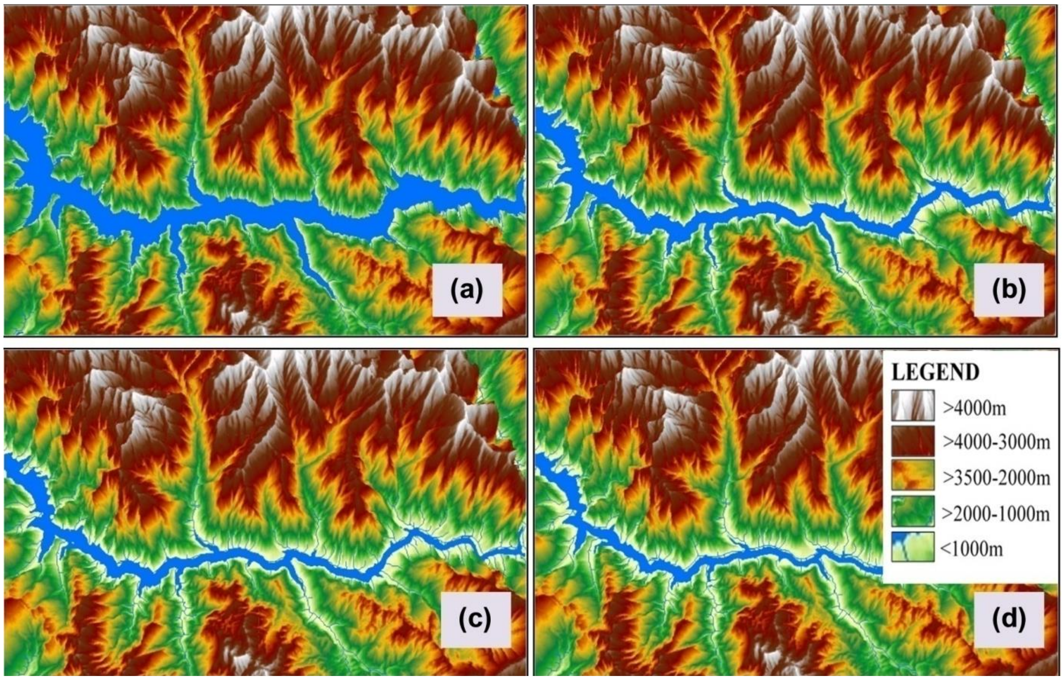

Fig.7. Calibrated model for the prediction of long-term simulations of the water and bed level changes in the river reach and the effect of flushing activities on the trap efficiency of Baglihar reservoir (a) Present condition (b) trap efficiency of 11% in next 30 yr. (c) trap efficiency of 20% in next 50 yr. (d) trap efficiency of 40% in next 100 yr. (values calculated form trap efficiency equation after Brown, 1944).

for the area are: (1) landslides on both the right and left banks of the reservoir can be stabilize at places where feasible by stepping and terracing to reduce the slope gradient (2) In the reservoir area, landslides and slope failures can be prevented by using reservoir rim treatment to stop capillary action that destabilise the slope soil cover on either side of the reservoir.

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