Original Research

The Impact of Suspended Sediment Load on Reservoir Siltation and Energy Production: a Case Study of the Indus River and Its Tributaries

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Abstract

Suspended sediments load estimation in the Indus River and its important tributaries in Khyber Pakhtunkhwa, Pakistan is presented to determine siltation in major reservoirs in the area and to create a strategy to minimize and/or control this risk for the enhancement of hydel energy production, irrigation, and other domestic purposes. The study area is part of an orogenically active region along the northwestern collision zone of Indian-Eurasian plates. During spring and summer suspended sediment load is highest, but least in winter. Sediment load of all rivers studied is directly proportional to the melting of glaciers and/or high rainfall during spring and summer. Glacier melt, rainfall, lithology of rocks (shale, slate, phyllite, mudstone, and siltstone), discharge, and other anthropogenic factors caused the high suspended load in rivers. Mostly the fine sediments settle during winter due to flow velocity of rivers reducing appreciably and residence time of water increasing in reservoirs. The high sediment influx deposition in major reservoirs like the Terbella and Warsak, etc. reduces their storage capacity as well as power generation capacity. So it is proposed that life span of these reservoirs can be lengthened by the construction of small check dams (silt control dams) on upstream, dam cleaning tactics, effective watershed management, extensive afforestation on the steep mountain slopes upstream of the lake, and the use of runoff rivers for electricity generation using steep gradient and fast flow velocity.

Keywords: suspended load, siltation in dams, hydel power, soft rocks, Indus River, environment

Introduction

Large dams throughout the world have been beneficial during the recent past and continue supplying fuels to the economy for irrigation, domestic water supply schemes, and cheap hydro-power [1]. Pakistan, being an agrarian country, overwhelmingly depends on its water resources for both irrigation and power production. The Indus, the principal river of Pakistan, is considered extremely important because a large number of agricultural and hydro power projects are supported by it. It has been mentioned [2] that rock and soil erosion in catchment regions (sediment load) accelerate the siltation problem in dams/reservoirs, which cause negative effects on storage capacity, water quality and, subsequently, reduce power and irrigation capability. This also is true in the case of the Indus. Stream sediments

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are mixtures of detritus derived either from exposed rocks or soils through a local drainage system [3]. The transport of fine material in suspension is the major transferring mechanism of particulate material in streams worldwide [4]. Resource analyses [5, 6], sediment management (like reservoir siltation) [7]; and geomorphology [8] are mainly dependent on sediment yields and concentrations that are controlled by both natural and anthropogenic factors [9]. In recent decades it has been realized that river dynamic conditions are greatly influenced by human activities that have led to considerable changes of water quality [10, 11], water discharge, and sediment load [12, 13]. Sediment production in mountainous regions has been discussed to be additionally dependent on factors including tectonics and seismic activity, recurring earthquakes, mean elevation of the basin, glaciated area, proportion of solid precipitation, and basin lithology [14]. The occurrence and intensity of sediment transport also has been reported [15] to be dependent on the hydroclimatic and geomorphologic characteristics of the basin, together with the availability of sediment within the catchment. For this reason, total sediment yields are often based purely on suspended load data [16].

Energy resources have been reported to be of strategic importance, but international agencies are pressing hard to make use of renewable energy resources [17]. Looking to the international requirements and insufficient hydrocarbon resources for the support of rapid industrial and developmental progress, hydro power remains the most economically viable and environmentally safe method of overcoming the energy crisis in a developing country like Pakistan, where the estimated potential of hydel power is 75,000 megawatts, but only less than 10 percent is utilized currently. Multipurpose reservoirs were constructed for irrigation and power production, but thick deposition of silt reduced their storage capacity and energy production. The Warsak reservoir, for example, is now almost full of sediments, whereas Tarbela has lost about one third of its storage capacity during the last 40 years. It is therefore imperative to investigate the runoff and sediment discharge data of melt streams coming out of major glaciers in the upper Indus basin to examine their temporal and spatial variations before future construction of major structures is undertaken.

The current study includes estimation of suspended sediment concentrations in the Indus River (IR) and its tributaries in Khyber Pakhtunkhawa (KPK), northern Pakistan, which is part of an orogenically active region along the northwestern collision zone of Indian-Eurasian plates. The sediments derived from uplifted mountain ranges such as the Himalaya-Hindukush, Koh-i-Safaid, Parachinar, the Waziristan agencies, Sulaiman-Kirthar Fold belts [18-21] and Khojak-Pishin Flysch sub-basins, downstream by a number of rivers, including the Indus (IR), Chitral (CR), Panjkora (PR), Swat (SR), Kabul (KR), Kunhar (KnR), Bara (BR), Kurram (KuR), Gambila (GR), and Gomal (GoR) (Fig. 1). The sediments are derived from wide source areas characterized by a variety of rocks ranging in age from Precambrian to Holocene. All three major rock types (Igneous, sedimentary, and metamorphic rocks) feed these rivers with their detritus. Ophiolites (dunite, pyroxinite, serpentinite, etc.), basalt, granite, granodiorite, gneiss, schist, phyllite, slate, marble, quartzite, sandstone, mudstone/shale, and subordinate marls are the common lithologies of various lithostratigraphic units, and their weathered product is included in the flow regime from different directions. This study is focused on quantitative analysis of the suspended load of IR and its major tributaries of KPK to identify areas of maximum sediment input (high soil erosion) and season/months of suspended load.

Materials and Methods

IR was sampled in winter, spring, and summer from three different stations along its course in KPK such that any spatial variation caused by the Tarbela reservoir may be readily noticed along with the temporal difference. The selected stations along IR were at Besham (IRB), Khairabad (IRK), and Dera Ismaeel Khan (IRD) (Fig. 1). A major tributary of IR is the Kabul River (KR), which not only supports the hydro power station at Warsak but also supplies water for irrigation through a major canal network. KR also was sampled from three different locations, i.e. Warsak (KRW) and Nowshehra (KRN), where it has reunited into a single channel and received all of its major tributaries, and Kund (KRK) before its union with the Indus River. All the remaining rivers were, however, sampled from only one station each (Fig. 1), but for all three seasons the same as IR and KR. In order to determine the amount of sediment, each water sample was sifted through a filter paper of pre-determined weight, and volume of the filtrate

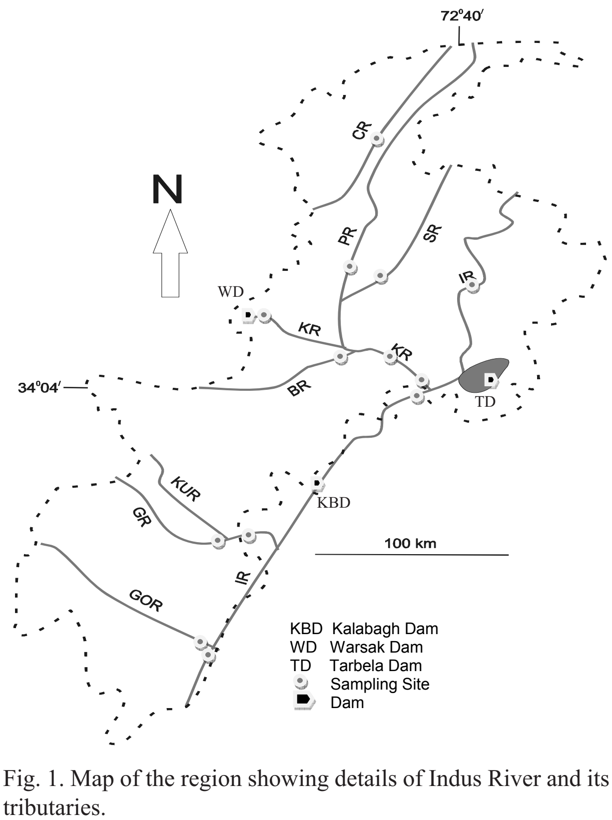

Fig. 1. Map of the region showing details of Indus River and its tributaries.

Table 1. Sediment concentrations (mg·L^{-1}).

Name of river	Spring	Summer	Winter
CR	1112	646	106
PR	443	333	8
SR	57	55	51
IRB	1692	1542	1002
IRK	431	177	39
IRD	545	313	87
KNR	5214	2750	1920
KRK	742	753	622
KRN	684	710	26
KRW	1095	337	312
BR	1152	682	Dry
KUR	1454	1306	87
GR	1037	1120	333
GOR	439	18	Dry

was recorded. The filter paper and the residue therein were dried at room temperature and weighed on an electronic balance. To determine average sediment concentration, total sediment (residue) in grams was divided by the volume of water (filtrate) in liters to get concentration in grams per liter.

Results and Discussion

Three seasons of data (Table 1) show a common trend of all rivers studied during the project, including maximum sediment concentration during spring that reduces in summers but is the least in winters, with an exception of KR and GR. IR shows that the quantity of suspended load is maximum at IRB, minimum at IRK, and intermediate at the IRD stations (Fig. 2). This anomaly is due to silting at Tarbela Reservoir, where most of the suspended load of IR settles out during the residence time of water. Hence highest and lowest suspended sediment flux immediately upstream and downstream of the reservoir, respectively. It is also evident from Fig. 2 that the concentration of suspended sediment at IRB climaxed some times between April and August as an increase of about 700 mg/L was observed from winter to spring, but the summer concentration was 150 mg/L less than that of the spring months. Whereas at IRK the increase in concentration was 400 mg/L from winter to spring, which was reduced by ~250 mg/L in August. The suspended load at this stage of the river is primarily of glacial origin. A comparative analysis of the suspended load data for stations immediately upstream and downstream Tarbela Reservoir shows a decrease of 1,365 mg/L (~90%) in summer, 1261 mg/L (75%) in spring, and 963 mg/L (96%) in winter from IRB to IRK. It must be noted that the river discharge is usually minimum during winters, which starts appreciably increasing from spring and reaches its climax during July/August. In order to maintain the required water level in the Tarbela Reservior, the outflow is regulated accordingly, which determines the length of residence time of water in this lake from season to season. Thus a high amount of siltation of suspended load occurred during winters, when the inflow and outflow are minimum and subsequently residence time greatest. By the same token, it was expected that the percentage of reduction during spring should have been intermediate between summer and winter values because the residence time of water is less relative to winters, but still greater than summer. The observed values of reduction in spring are, however, anomalous, which may be attributed to increased sediment input into the IR beyond Tarbela from other local sources, including the KR. This assumption is supported by the meteorological data, which indicates heavy rains (550 mm during April) in the catchment of the KR and its tributaries (viz. BR, CR, PR, and SR).

In-between IRK and IRD sampling stations, the IR acquires more sediment from other tributaries such as KUR and GR, which gradually increases its load further downstream. Both these IR tributaries are turbid and their sediment input is relatively much higher than the Indus load at IRD. The observed suspended load of IRD reaches a maximum of ~550 mg/L during spring, which seems a much lower value as compared to its other local tributaries. The reason for this lower concentration may be the reduced current velocity, which forces some of the coarser suspended particles to be deposited in the channel. This reduction in the current velocity can be attributed to the fact that the channel suddenly widens several kilometers as the river divides itself into many distributaries upon entry into the plain area.

KUR, GR, and GOR are three perennial but distal (far downstream of Tarbela reservoir) tributaries of the IR and drain large catchment areas and transport significant amounts of suspended load. Apart from summer, the water discharge of these rivers is not significant, yet they are con-

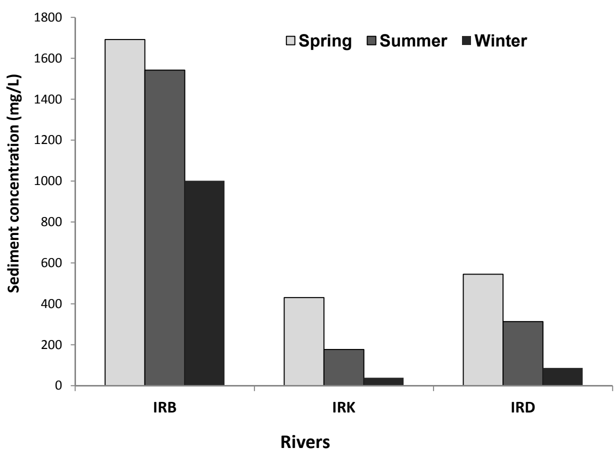

Fig. 2. Graph showing the suspended sediment concentration in Indus River stations. (IRB, IRK, IRD: Indus river at Basham, khairabad, and Dera Ismail Khan, respectively).

sidered as an important water source for municipal and irrigation uses in an otherwise arid region. In order to protect the torrential runoff from being wasted, small reservoirs have been constructed on the KUR and GOR that store water during summer rains for drinking and irrigation in the remaining part of the year. The quantitative analysis of the KUR S.L. flux (Fig. 3) shows that the peak sediment discharge (1,454 mg/L) during spring is only marginally greater than summer (1,306 mg/L). For GR, however, maximum sediment is found during summer (1,120 mg/L) followed by spring (1,037 mg/L) and winter (333 mg/L). During summers, when the area receives maximum rainfall the surface runoff brings significant quantities of sediment from the entire catchment into the river channel and hence relatively high suspended load in summer as compared to spring, when the sediment is primarily of glacial origin. This shows the importance of rains in bringing sediments to the rivers. The GOR is dry during winters at the sampling site and the difference between spring (439 mg/L) and summer (18 mg/L) is sizable. This is because the river flow does not remain confined to the channel but spreads over a wide floodplain during summers. Subsequently, the currents become sluggish and form stagnant pools where suspended sediment starts depositing on the floodplains.

The Kabul River (KR) is a major right bank tributary of the IR in central KPK and it enters Pakistan through the tribal territory of the Khyber Agency. In the Peshawar valley the KR is divided into several major distributaries and also joined by the SR and BR before it re-unites into a single channel near Noshera. The size of catchment is very large here and during the monsoon rains the river overflows its banks and inundates certain low-lying areas along its course. This is the last major tributary of IR before it reaches the proposed site for the controversial Kalabagh dam on the IR.

Spatial comparison between various stations of the KR, however, does not reveal any consistent trend (Fig. 4), apart from the fact that suspended load always increases from KRN to KRK. Because of continuous silting for the last 30 years or so, the Warsak reservoir has filled with sediment and its storage capacity has become almost exhausted. Subsequently, the hydroelectric power project designed to generate 240 MW from a reservoir is now working as a runoff river project and producing only about 65 MW at its peak. Because of the loss of storage capacity, the inflow and outflow from the Warsak reservoir is equal and the residence time of water in the lake is negligible, therefore, no significant decrease in the suspended load was expected at KRN. The temporal difference in the suspended load follows the same pattern, i.e. highest in spring (1,095 mg/L) and lowest in winter (312 mg/L) for Warsak, but for the other two stations (Fig. 4) the maximum load was observed during summer (Table 1). This may be due to the fact that eight significant industrial premises and important urban centers of the province discharge their waste directly into the main KR and its tributaries. In addition, numerous small industries are discharging effluents to channels and drains that eventually end up in the KR [22]. These effluents also include suspended solids and thus become a major controlling factor of the suspended load concentration, particularly downstream KRN. The same explanation is also true for large winter differences in sediment between KRN and KRK as illustrated in Fig. 4. Besides, the BR and SR both join the KR downstream Warsak near Peshawar and Charsadda cities, respectively, and complicate the situation. Whereas the SR may dilute the KR sediment concentration, the BR sediment load, may increase its load, particularly during spring.

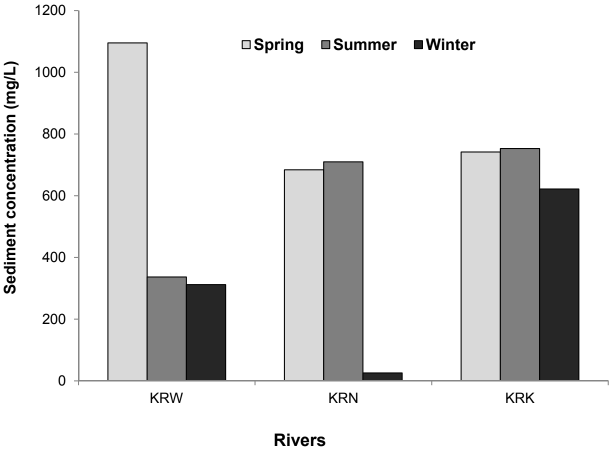

Fig. 4. Graph showing the suspended sediment concentration in different stations of Kabul river (KRW, KRN, KRK: Kabul river at Warsak, Noshera, at Kund, respectively).

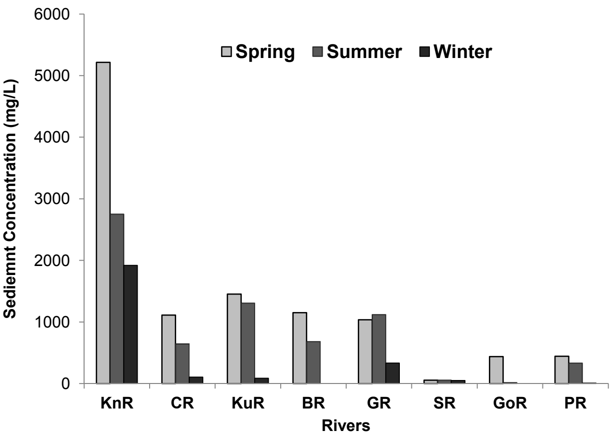

Fig. 3. Graph showing the suspended sediment concentration in different rivers of the studied area. (KnR – Kunhar River, CR – Chitral River, KuR – Kurram River, BR – Bara River, GR – Gambila River, SR – Swat River, GoR – Gomal River, PR – Panjkora River)

The Chitral River (CR) is flowing in the northernmost part of the studied area and is named as Kunnar River after it enters Afghanistan, which unites with Kabul River and re enters Pakistan upstream Warsak Dam. The results show a maximum concentration of suspended sediment (1,112 mg/L) during spring, which is about twice as much of the summer load (646 mg/L). The peak water discharge of the CR, however, is usually recorded during July [23], which does not correspond with the highest suspended load flux. The meteorological data for Chitral and Drosh towns exhibit heavy rainfall (about 250 mm in April during spring as opposed to almost no rain during August. The sediment input from surface runoff can thus be considered as an additional source for higher springtime load. The CR acquires about 70% of its sediment load from the Mastuj River between Chitral and Buni towns. This area is characterized by unconsolidated Quarternary sediment, weak rock zones (exposing slate, mudstone/shale and schist, fault gouges, scarcity of vegetation, land sliding/rock fall and man-induced processes such as blasting for road construction. A combination of the above-mentioned factors is responsible for contributing sediment input into the Mastuj River between Chitral and from Buni. Lutkho and Mastuj rivers upstream Buni town are otherwise famous for their clear water.

The PR drains the area situated between Swat and Chitral valleys. Water samples of the PR were collected from between Talash and Temargara, where the rocks are tectonically disturbed due to the suturing of Indian plate with the Kohistan Island Arc along the Main Mantle Thrust (MMT). The suspended load flux of the PR (Fig. 3) also follows the pattern of highest during spring (443 mg/L) and lowest during winter (8 mg/L). The rainfall data shows that maximum rainfall takes place in March (437 mm, whereas during the remaining part of the year it rarely exceeds 200 mm).

The SR is a snow-fed perennial stream that drains a fairly large catchment area (5,776 km^2), and is an important river from the point of view of hydropower production and irrigation. The SR records its peak mean monthly discharge during June – a period of very small rainfall but maximum glacial ablation. Unlike most other rivers studied in this project, the suspended sediment flux of the SR (Fig. 3) was found to be the same (57 mg/L) for August and April, and even the winter load (51 mg/L) was not much less. This suggests that the peak sediment flux may also have climaxed sometime between April and August in line with maximum discharge. The meteorological data of Saidu Sharif indicates that the catchment of SR receives its maximum rainfall during Feburary and March (440 mm), whereas the maximum discharge takes place during June. It can, therefore, be inferred that the main source of SR water is the glacial/snow ablation, which reaches its peak during June. The absence of any significant temporal variation in the suspended load of SR can also be due to the stability of its catchment area, which is not undergoing any notable physical weathering, soil erosion, and land sliding.

The S.L. flux of the KNR (Fig. 3) was found to be the highest among all rivers studied. This result stands out more prominently when catchment areas of the various rivers included in this study are compared. Samples of the KNR were collected from Garhi Habibullah, which has a considerably smaller catchment (2,383 km^2) than other stations in the study area. The quantity of sediment measured here varies from 5,200 to 2,750 and 1,920 mg/L during April, August, and January, respectively. Traditionally, the maximum water discharge of this station takes place during May/June. The KNR can thus be regarded as the most turbid river in this part of the country, which remains heavy all year.

The Kaghan Valley is characterized by heavy winter snow cover/small valley glaciers; rugged topography; tectonic instability; soft rocks such as unconsolidated Quaternary material and extensive alluvial fans/cones, shale of Murree Formation and phyllite/schist of the Salkhala Formation [24]; intense runoff and land sliding, etc. Glacially derived detritus from the upper reaches of the Kaghan valley (Naran) constitute a major part of the sediment load in KNR, which becomes a tributary of the Jehlum near Dulai (Azad Kashmir) and eventually enters the Mangla Reservoir near Mirpur. With a mean annual discharge rate of ~3g/L, a total of approximately 100,000 tones of suspended sediment is entering the Mangla Reservoir through the KNR alone, 60-65% of which is silt size, and about 30% is clay fraction. The majority of silt and sand size grains are deposited in the reservoir during their stay periods, which are fast reducing its storage capacity.

The present study of 10 rivers indicates that the KNR carries maximum suspended load during all seasons, whereas the SR was found to be the most clear year round. The results also show that GOR and BR remain almost dry during winter months but the latter becomes very turbid during spring and summer (1.15 g/L in April). Contrary to the expected maximum suspended load during summer and minimum during winters (in line with river discharge), the temporal variation in suspended load of various rivers indicates a peak flux during the spring/early summer (Apr-May) to a minimum during winter (Dec-Feb), while summer values mostly fall in-between those for spring and winter.

Due to a general aridity of the climate in the region and a large difference between summer and winter temperatures (e.g. the southern part of the studied area, like Bannu and Dera Ismaeel Khan Divisions) is characterized by a hot and arid climate where the mean annual rainfall is less than 250 mm with around 75% of it concentrating in July-August. So the rivers studied owe their discharge primarily (70-80%) to the glacial meltwater from snow-covered peaks and valleys in the surrounding mountains. These streams also transport a large quantity of glacially derived sediment as their bed load and suspended load, which is a major concern in the context of reservoir silting. Increased sediment load during summers adversely affects the carrying capacity of these rivers and leads to flooding. The detritus transported as bed load becomes trapped in the channels or reservoirs, whereas the suspended load is deposited on various floodplains and reservoirs.

As the area studied is part of an orogenically active one, there is a dire need of management for sediment before planning any future large dams on any of these rivers. It has been reported that construction of dams/reservoirs has reduced sediment influx in rivers downstream because of water abstraction (discharge reduction) and land use change, i.e. deforestation and afforestation [25, 26]. It is therefore strongly suggested that along small check dams, special sediment-excluding structures (like sediment excluders and sluices) will be helpful in increasing the age of storage structures constructed in the area.

Conclusions

Concentration of suspended sediment load is highest in spring followed by summer and winter seasons in all rivers studied in this study except KR and GR. KnR transport maximum sediment load during all seasons, whereas SR was found to be clear throughout the year. In lower reaches KuR and GR tributaries of IR are turbid and their suspended input is relatively much higher than at IRD. GR and BR remain dry during winter but become highly turbid due to an increase in suspended load during spring and summer seasons because of high rainfall in their catchment region. Sediment load of all rivers studied is directly proportional to the melting of glaciers and/or high rainfall during spring and summer.

The sources of sediment load identified here are glaciers melting, rainfall, erosion of soft rocks like shale, slate, phyllite, mudstone, siltstone, etc. in the catchment area, and discharge and high gradient of rivers. These factors – with the addition of anthropogenic causes – are responsible for high suspended load in rivers. All rivers drop, their suspended load as silt in winter when flow velocity of rivers drop especially in lakes and dams where residence time of water increases. So a high rate of siltation in major reservoirs of the region is recorded, for instance Suspended load is maximum at IRB and minimum at IRK at upstream and downstream of Terbella Reservoir, respectively. This result is a clear indication of great siltation occurring in Terbella Reservoir and reduces its storage capacity as well as power generation capacity. The Wasrsak Dam in the region is full of sediments and its storage capacity is nearly exhausted and generates only 65 MW instead of 240 MW and is working as a runoff river project.

Keeping in mind the alarming results of siltation in major reservoirs of the area, it is proposed that small check dams (silt-control dams) should be constructed upstream of major structures and/or dam-cleaning tactics like sluices should be introduced to lengthen the life span of these expansive structures. Some streams are inappropriate for the construction of reservoirs because of their high sediment load and these can satisfactorily be used as runoff rivers for hydel power generation. This problem can be controlled by effective water shed management and extensive afforestation on the barren and steep mountain slopes upstream of the lake. Fortunately, all tributaries of major streams/rivers in the northern part of the studied area provide excellent opportunities for electricity generation using steep gradient and fast flow velocity.

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