Nordic Hydrology, 34 (3), 2003, 221-244

Suspended Sediment Transport from the Dokriani Glacier in the Garhwal Himalayas

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Estimation of sediment load from glacierized basins is very important for planning, designing, installation and operation of hydro-power projects, including management of reservoirs. In the present study, an assessment of suspended sediment concentration, load, yield and erosion rate has been undertaken for the Dokriani Glacier drainage basin located in the Garhwal Himalayas. About 60% of the total drainage area of this basin is glacierized. Data were collected for four ablation seasons (1995-1998). The mean daily suspended sediment concentrations for June, July, August and September were 452, 933, 965 and 275 mg l^{-1}, respectively, indicating highest suspended sediment concentration in August, followed by July. Similar trends were also found for the sediment load and about 88% of the total suspended sediment load of the melt period was transported during the months of July and August. Sediment yield for the study basin was computed to be about 2,800 t km^{-2} yr^{-1}, which is comparable with glacierized basins (10-30% glacierized) in the Pamir region. For the entire ablation period, the erosion from the Dokriani Glacier basin is estimated to be about 1.0 mm. There was a poor relationship between suspended sediment concentration and discharge. The average percentages of clay, silt and sand were found to be 1.4, 67.3 and 31.3%, respectively, which suggest maximum content of silt followed by sand. There was limited variation in the content of clay, silt and sand in the suspended sediment during the ablation period.

Introduction

Assessment of water and sediment yields from glacierized basins and the grain size distribution of suspended particles is of considerable importance for the planning, design and installation of hydro-power projects. Enormous quantities of sediment are transported in glacier melt streams as a consequence of glacial erosion and other processes rendering sediment available for transport. A number of studies have demonstrated that specific sediment yield may increase downstream due to remobilization of sediments by the active glaciers and meltwaters (Ferguson 1984; Warburton 1990). Embleton and King (1975) have observed a five-fold difference in sediment yield between the glacial Hoffellsjökull river in Iceland and a nearby non-glacier-fed river, suggesting that glacial abrasion provides more material for stream transport than the non-glacial weathering and erosion processes. Based on a global survey of sediment yield from 1,358 drainage basins with areas ranging from 350 to 100,000 km^2, Jansson (1988) reported that within particular climatic zones where glaciers are active, sediment yield tends to be higher. Harbor and Warburton (1993) also observed that the higher erosion rates are produced through glacial processes than non-glacial processes, resulting in higher sediment yields in proglacial rivers. Hallet *et al.* (1996) have shown that specific sediment yields clearly tend to increase with the extent of glacial cover in the basin. On average, specific sediment yields for basins covered by glaciers (say >30% glacier cover) were about one order of magnitude higher than for glacier free basins. Gurnell *et al.* (1994) compared the discharge and suspended sediment transport for an arctic and alpine glacier, which were of similar size. They reported stronger diurnal variations in the suspended sediment concentrations in the alpine proglacier river than in the arctic environment. The widely reported "exhaustion" in suspended sediment supply to alpine proglacial streams over the summer ablations season was not observed in the arctic basin.

Measurements of the quantities of suspended sediment and solutes evacuated from glacierized catchments provide a means of estimating gross rates of denudation by glacial erosion (Østrem 1975) and chemical weathering (Reynolds and Johnson 1972), and of identifying the relative significance of various subglacial processes (Vivian and Zumstein 1973). Willis *et al.* (1996) attempted to investigate the links between the suspended sediment dynamics of a proglacial stream and glacier hydrology and glacier motion. Observations of the quality of water draining from the snout of the glacier permits investigation of the nature of erosional processes integrated over large areas of glacier bed, since melt waters acquire their characteristics during passage beneath the glacier. The status of the studies shows that little is known about the mobilization of the sediments underlying the glacier and sediment delivery processes, including sediment transport directly from the glacier and reworked along the river system.

In Himalayan glacierized basins, despite the pronounced role of the Himalayan glaciers in producing high rate of sediment transportation, limited studies have been carried out. In the Himalayan region, however, measurements of sediment concentration were initiated on the Gangotri Glacier melt stream in the 19th century (Everest 1832), but such studies were neither continued for this glacier nor attempted for other glaciers in this region. Quantification of suspended sediment load in high altitude areas becomes more important especially during the peak summer/monsoon period, as higher quantities of sediment due to intense melting or precipitation inputs may be detrimental to the hydroelectric electric power turbines and also lead to siltation of reservoirs. Most of the studies in the Himalayan region have been carried out for lower altitude basins/sites (Sharma *et al.* 1991; Rao *et al.* 1997). Only a few studies based on observations made over limited time periods are available for a few specific glaciers (Singh *et al.* 1995; Hasnain and Thayyen 1999). The present study deals with estimation of the sediment yield from the Dokriani Glacier basin along with measurements of the grain size distribution of the suspended particles. Discharge and suspended sediment data collected during four ablation seasons (1995-1998) have been used. Since a major part of the suspended sediment and runoff drains out during summer period, observations were made only for this period. The results are also compared with information available for glacierized basins in other parts of the world.

Sediment Yield from Different Himalayan Basins and its Impact on the Capacity of Reservoirs

Assessment of sediment yield from the Himalayan basins indicates high sediment transport from these basins. For example, three major river systems of the Himalayas, the Brahmaputra, the Ganga and the Indus, annually transport about 1.8×10^9 tonnes (t) of suspended sediment to the oceans, which is about 9% of the total annual load carried from the continents to the oceans world-wide (Meybeck 1976). Further, estimates of sediment yield for the Ganga and Brahmaputra rivers together are about 1.0×10^9 t yr^{-1} (Subramanian 1993), compared with the global annual sediment flux of about 15×10^9 t yr^{-1} (Milliman and Meade 1983). Table 1 shows the magnitude of specific sediment yield for few Himalayan basins located in different regions of the Himalayas. It can be noted that the specific sediment yields from the studied Himalayan basins were observed in the range of 192 to 1,946 t km^{-2}yr^{-1}. All the Himalayan rivers transport suspended sediment at a high rate, but in the Bhagirathi River the specific sediment yield is particularly high. Sundd (1991) also reported a very high sediment yield from the Ganga River as compared with other rivers of the world (Holeman 1968; Milliman and Meade 1983). The natural factors responsible for high rates of sediment transport from the Himalayan region are: the young age of the mountains, the steep topographic gradient and the poor structural characteristics of soils available on these slopes, the large and active glaciers, the high intensity monsoonal rainfall, natural weathering processes, and tectonic instability of the area. Anthropogenic activity, which includes mainly deforestation, road con-

Table 1 – Annual sediment yields in various Himalayan catchments at different locations.

Basin (state)	Site	Sediment yield ($t\ km^{-2}yr^{-1}$)	Source
Spiti basin (H.P.)	Khab	1334	Sharma *et al.* (1991)
Satluj basin (H.P.)	Khab	192	-do-
Kinnaur basin (H.P.)	Wangtu	1597	-do-
Chenab basin (J&K)	Tandi	371	Rao *et al.* (1997)
Chenab basin (J&K)	Benzwar	1597	-do-
Chenab basin (J&K)	Premnagar	1363	-do-
Chenab basin (J&K)	Dhamkund	1900	-do-
Chenab basin (J&K)	Ghousal	513	-do-
Chenab basin (J&K)	Tillar	373	-do-
Chenab basin (J&K)	Sirshi	939	-do-
Chenab basin (J&K)	Kuriya	878	-do-
Bhagirathi basin (U.A.)	Tehri	1946	Singha and Gupta (1982)
Bhagirathi basin (U.A.)	Dokriani Glacier Snout	2800	Present study

struction, mining, overgrazing and cultivation on steep slopes and development of various kinds of projects, has also accentuated the erosion processes in the Himalayan region.

Because of immense hydropower potential due to availability of abundant water and geographical setting in the Himalayan region, many hydropower projects have already been completed and many are under construction in this region. The success of these projects depends to a great extent upon the regular and sediment free water flow. Studies suggest that the useful life and capacity of reservoirs are depleting at a faster rate than planned because of excessive siltation due to accelerated erosion from the catchments. For example, annual sediment input to the Bhakra Reservoir located in the foothills of the Himalayas, is observed of the order of 35.8×10^6 m^3, giving an average 50 cm thick sediment layer (Anonymous 1986). At this rate the effective life of the Bhakra reservoir for electricity generation is calculated to be only about 150 years and the reservoir will be fully silted up in about 400 years. Dredging operations in these reservoirs are invariably difficult and expensive. Morris (1995) reported that some reservoirs in India have lost as much as 50% of their capacity to date. It is expected that 27 of the major 116 reservoirs may loose half of their original capacity by 2020, and by the year 2500, about 20% of India's existing reservoirs will have lost 50% of their capacity.

In addition to the reduction in reservoir capacity, the higher concentration and the nature and composition of the sediment particles also affect the running period of the power plants and damage the runners. In the Garhwal Himalayas, such problems are of immediate concern. To highlight a typical problem related to suspended sediment concentration and content of sediment, one example of Tiloth Hydropower Plant (3

× 30 MW) at Uttarkashi (Garhwal Himalayas) is cited here. It is to be noted that this power plant also receives the water from the Dokriani Glacier basin, which represents the focus of the present study. A diversion dam has been constructed at Maneri Bhali on the Bhagirathi River to divert water to power station through an 8 km long tunnel. There is a serious problem in this plant associated with damage to the runners due to presence of quartz particles in the sediment. At present, only water containing sediment particles <0.30 mm in size and with concentrations not exceeding 1,200 mg l^{-1} is permitted to be used for operating the hydropower scheme. In the monsoon period, the suspended sediment concentration increases substantially and sometimes reaches about 10,000 mg l^{-1}. Therefore, every year during the monsoon season, the power plant is shut down until the sediment concentration reduces to the permissible level of 1,200 mg l^{-1}. The runners are repaired/replaced every year and sufficient spare parts are kept in store to be replaced at any time, if required. Thus a substantial expenditure is incurred in maintaining such power plants. Such implications highlight the need for detailed sediment transport and particle distribution studies for the upper glacierized parts of the Himalayan basins, which produce a large amount of sediment during melt period. The present study deals with such a study.

Study Area

The Dokriani Glacier basin is located in the Garhwal Himalayan region. This basin lies between latitudes 31°49' to 31°52' N and longitudes 78°47' to 78°51' E. The location of study area and map of the basin are provided in Fig. 1. The total drainage area of the Dokriani Glacier basin is 16.13 km^2, out of which 9.66 km^2 (60%) is covered by the glacier. The elevation of the glacier varies from about 3,950 to 5,800 m. The length of the glacier is about 5.5 km, whereas its width varies from 0.1 to 2.0 km from snout to accumulation zone. The altitudinal distribution of the glacier area shows that the major part of the glacier is concentrated above 5,000 m in the basin. The mean monthly temperature near the snout of the glacier for June, July and August and September are 9.4, 10.5, 9.7 and 8.5°C and about 1,000 mm of rainfall occurs during the ablation period. However, there are no records available for annual rainfall in the study area, but it can be assumed that annual rainfall would be approximately equal to the summer rainfall because there is very little or no rain during winter period. Most of the precipitation falls as snow during winter and reliable records of winter precipitation are not available. It is to be pointed out that the magnitude of summer rainfall (~1,000 mm) observed in the study area is much higher than the summer rainfall (100-300 mm) observed in the other parts of the Himalayas at about similar altitude (4,000 m). It is understood that availability of very dense forest cover up to about 3,600 m altitude in the valley contributes to high rainfall in the study area.

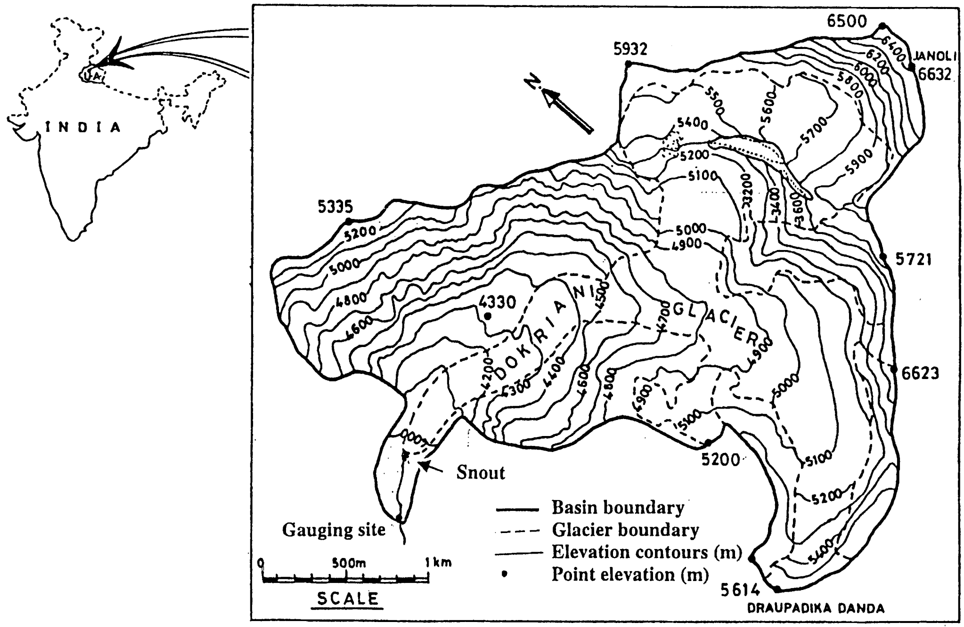

Fig. 1. Location and basin map of the Dokriani Glacier in the Garhwal Himalayas.

Like other Himalayan glaciers, the ablation zone of the Dokriani Glacier is also characterised by almost continuous surfacial cover of morainic debris. The major source of debris deposited over these zones is from the valley walls mainly by frost action and from the reworking of the old moraines. The middle part of the glacier is highly fractured and consists of crevasses, moulins, glacier tables and ground moraines. This glacier is bounded by two large lateral moraines, which are about 200-250 m in height. Besides these two lateral moraines, there are several other lateral moraines at different altitudes. The different levels of these moraines indicate the past extent of the glacier. Stern *et al.* (1989) reported that the bedrock geology in the Bhagirathi valley consists mainly of granite and augengneiss.

Collection and Analysis of Discharge and Suspended Sediment Data

A gauging site was established about 800 m downstream of the snout and about 1 km upstream of the confluence of the several small tributaries that join the main stream on its southern side. Some work was done on the channel to ensure that flow of water in the stream was confined to a single channel at this site. A stilling well was constructed at the gauging site and an automatic water level recorder was installed for continuous monitoring of water stage. For computing flow for developing the stage-discharge relationship, the velocity-area method was used and wooden floats were used to determine the velocity of flow. Surface velocity data were converted to mean flow velocity by multiplying the surface velocity by a factor of 0.90. This factor was determined by making velocity observations at different water depths using current meter. The stage-discharge relationship was developed for each ablation season and was used to convert water levels into discharges for that particular season.

In order to determine daily mean suspended sediment concentrations and loads in the Dokriani Glacier melt stream, two water samples were collected every day from the gauging site at 0830 and 1730 hours, which represent the approximate timings of minimum and maximum concentrations, respectively. A known volume of water (500 ml) was collected from the stream at about mid depth and filtered on-site using Whatman-40 ashless filter paper. The samples collected on the filter papers were analysed in the laboratory at the National Institute of Hydrology (NIH), Roorkee. Combustion of the filter papers was undertaken to provide a value of sediment concentration. The filter papers were fully combusted in preweighed crucibles in an oven at 200°C for a period of more than 24 hours. Particle size analysis was undertaken on the combusted sediment using a Malvern Mastersizer E instrument, which gives results in 32 size classes, ranging from 0.5 μm to 600 μm. Particle size analysis was undertaken for two years (1997 and 1998) and the size distributions were studied separately for each month of the ablation period. In total, 7 particle size analyses were made for the study period.

Results and Discussion

Sediment Generation and Transport

The main sources of sediment production in the glacier fed channels are the glacier system, bedrock system and channel system. The glacier system includes sedimentation from different parts of the glacier such as the accumulation zone, ablation zone, snout and the lateral moraines, whereas bedrock system deals with glacier bottom ice and bedrock. In the present study, observations were made near the snout of glacier and therefore, the channel system does not contribute much to the generation of the suspended sediment load. The Dokriani Glacier is a valley type glacier and the presence of large crevasses provides evidence of the movement of a large mass of ice down slope, which is accompanied by large amounts of sediment due to glacier bed erosion. Thousands of tonnes of debris are brought down by the glacier and dumped near the snout of glacier due to widespread glacial erosion, which serves as a major sediment source. The sediment produced by glacial erosion and fracturing of debris and rocks over wide areas of bed throughout the year is mobilised by meltwater flow with sufficient velocity and turbulence.

Another important source of sediment from the study glacier is the presence of sediment material like boulders, debris and moraines over the glacier surface. During the active melting period supraglacial material remains in contact with meltwater and becomes a regular source of sediment. The ablation zone of the glacier contributes a large amount sediment because a large amount of such material is found in this area and water travels by surface pathways in the ablation zone of the glacier. A part of the sediment material available on the glacier surface is also transported down through extensive longitudinal and transverse crevasses into englacial and subglacial tunnels. The material transported to the glacier bed is abraded and crushed into fine sediment particles within the glacier and bedrock system. From the features of the surface texture of the lateral moraines, it could be expected that chemical and mechanical processes might also mobilise the lateral moraines sediment into the glacier melt stream (Singh *et al.* 1995). For the study glacier, sediment transport follows three basic routes, namely, supraglacial, englacial and subglacial routes.

The present study basin experiences high rainfall (~1,000 mm) during the ablation period, which helps to increase the mobilisation of sediment from various sources, such as debris and moraines present over the glacier surface and soil available on the steep sidewalls of the valley, its transport to the fluvial system. Because of the high rainfall, slumping of moraines from unstable slopes and rockslides from the surrounding valley walls to the glacier surface are very common features in this basin. The material transported under such events on the glacier surface or directly in the meltwater stream produces large variation in suspended sediment concentrations. Contribution from the medial moraines, lateral moraines and debris over and near the glacier is significantly increased during rainfall events. A substantial fraction of the annual total sediment load is transported during rain-induced flood events or subglacial blocking events due to abrupt dislocation of sub glacial flow nets and supply of sediment in addition to that derived from the glacier sub-sole. Studies indicate that when heavy rains double the water flow, the scouring capacity is increased 4 times, the carrying capacity 32 times and the size of the particles carried 64 times (Tempany and Grist 1958).

Suspended Concentration and Load

A plot of daily mean suspended sediment concentration and discharge versus time for the Dokriani Glacier basin is given in Figs. 2(a) to (d). Over the period of record, daily mean suspended sediment concentrations in the melt stream varied from 80-3,830 mg l^{-1}. The suspended sediment concentration begins to increase with discharge from June onwards. However, the results indicate that discharge in the melt stream was less variable than suspended sediment concentration. Maximum daily mean suspended sediment concentrations observed in June, July, August and September were 2,592, 3,349, 3,830 and 867 mg l^{-1}, respectively. The mean daily suspended sediment concentrations observed for individual months during the different years are shown in Fig. 3. Mean concentrations of suspended sediment for

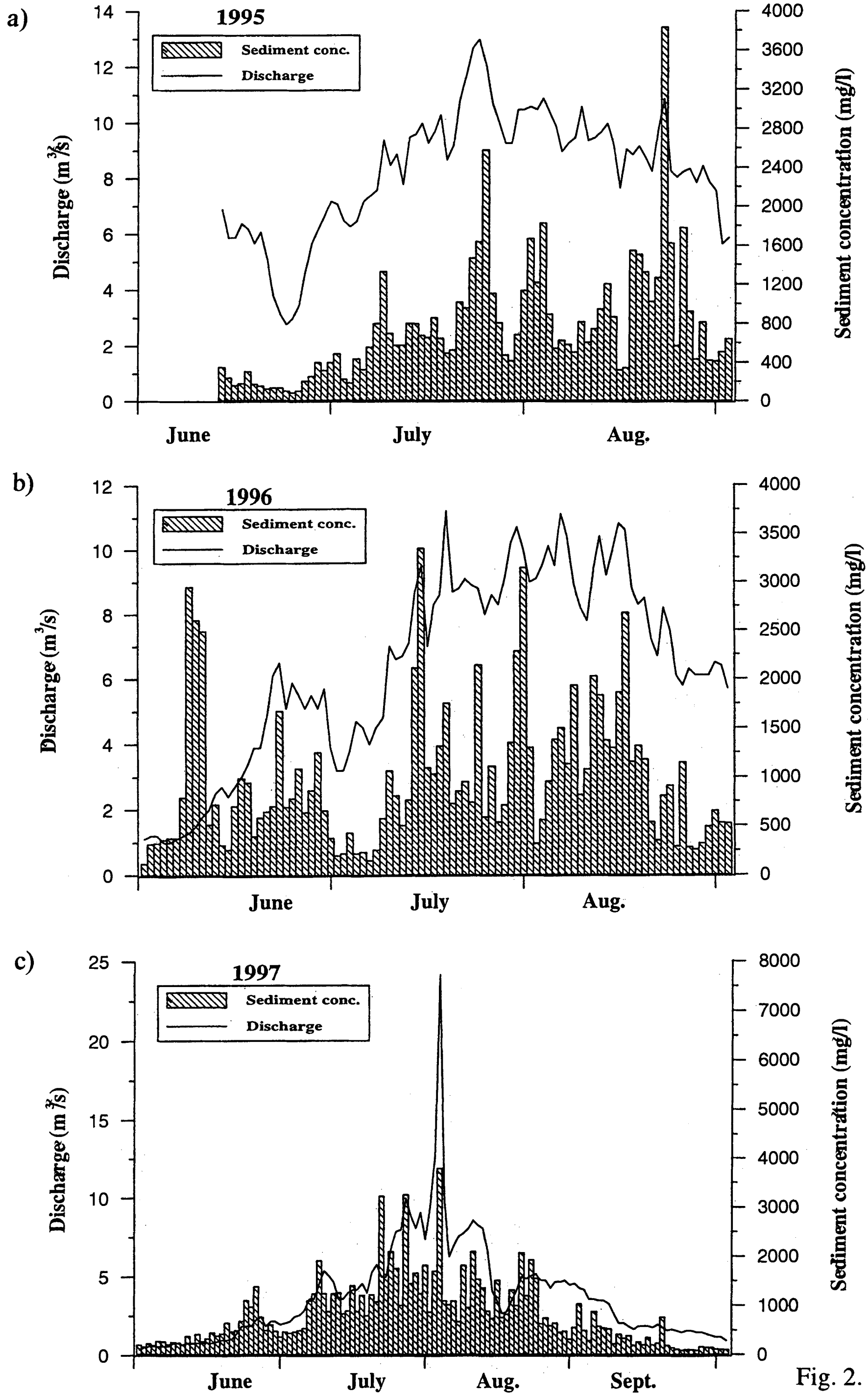
a)
1995
Sediment conc.
Discharge
Discharge (m³/s)
Sediment concentration (mg/l)
14
12
10
8
6
4
2
0
4000
3600
3200
2800
2400
2000
1600
1200
800
400
0
June
July
Aug.
b)
1996
Sediment conc.
Discharge
Discharge (m³/s)
Sediment concentration (mg/l)
12
10
8
6
4
2
0
4000
3500
3000
2500
2000
1500
1000
500
0
June
July
Aug.
c)
1997
Sediment conc.
Discharge
Discharge (m³/s)
Sediment concentration (mg/l)
25
20
15
10
5
0
8000
7000
6000
5000
4000
3000
2000
1000
0
June
July
Aug.
Sept.

Fig. 2. cont.

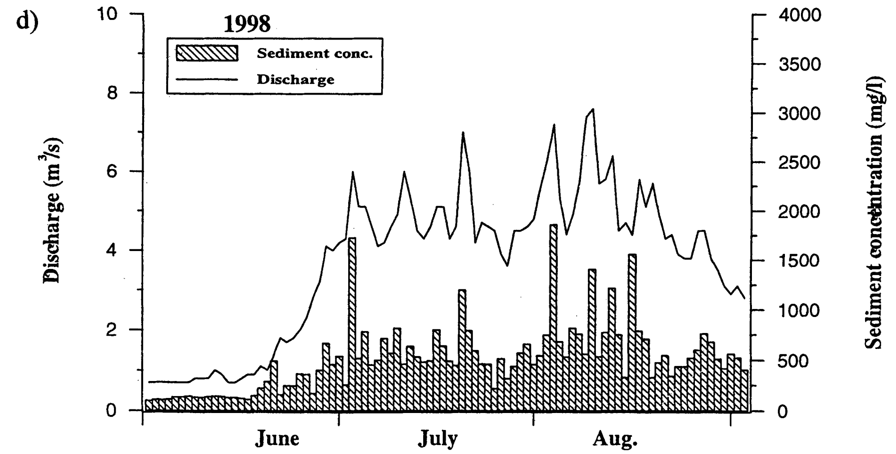

Fig. 2. Observed discharge and suspended sediment concentration in the Dokriani Glacier melt stream during 1995 to 1998 ablation periods.

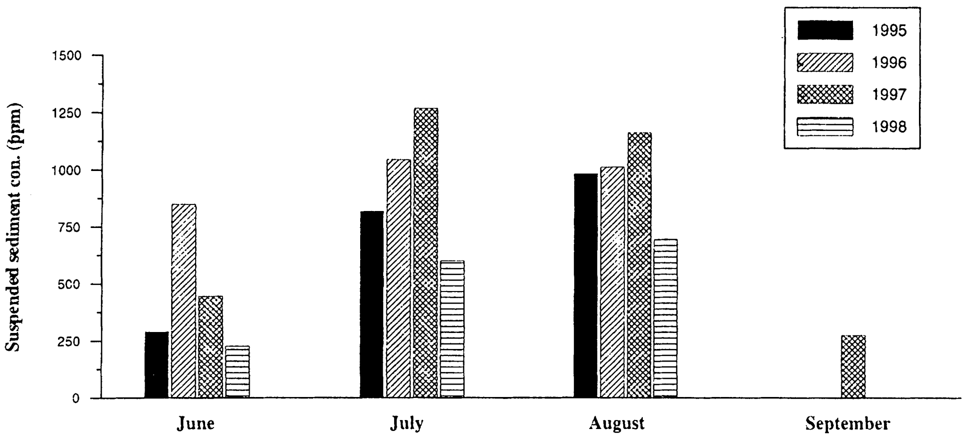

Fig. 3. Mean daily suspended sediment concentration observed at the Dokriani Glacier gauging site for different years.

June, July, August and September were observed to be 452, 933, 965 and 275 mg l^{-1} respectively, indicating highest concentration in August followed by July. Sediment concentrations in the months of July and August were found to be about twice those in June, and about three times those in September. For the entire melt season, the mean daily suspended sediment concentration was computed to be 748 mg l^{-1}.

The variation in daily suspended sediment load and daily mean discharge during the ablation period is shown in Figs. 4(a) to (d). Daily suspended sediment loads ranged between 6-7,916 t d^{-1} at the gauging site. The monthly distribution of suspended sediment load for the different years is shown in Fig. 5. The average sus-

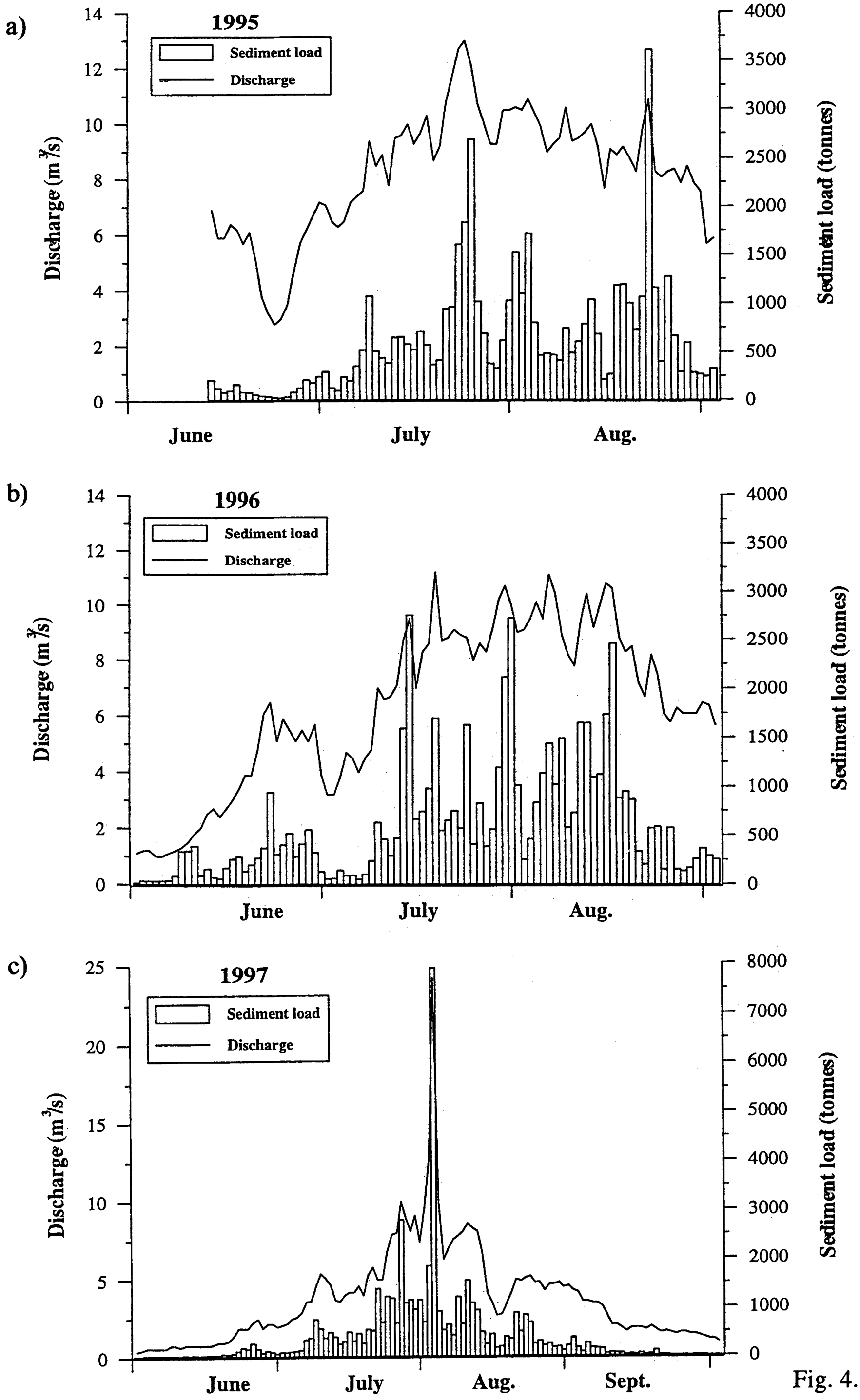
a)
1995
Sediment load
Discharge
Discharge (m³/s)
Sediment load (tonnes)
0
2
4
6
8
10
12
14
0
500
1000
1500
2000
2500
3000
3500
4000
June
July
Aug.
b)
1996
Sediment load
Discharge
Discharge (m³/s)
Sediment load (tonnes)
June
July
Aug.
c)
1997
Sediment load
Discharge
Discharge (m³/s)
Sediment load (tonnes)
0
5
10
15
20
25
0
1000
2000
3000
4000
5000
6000
7000
8000
June
July
Aug.
Sept.

Fig. 4. cont.

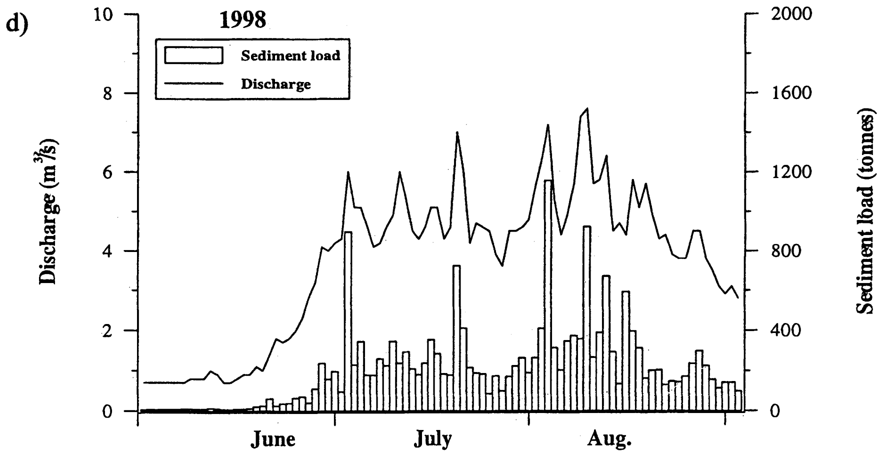

Fig. 4. Observed discharge and suspended sediment load in the Dokriani Glacier melt stream during the 1995 to 1998 ablation periods.

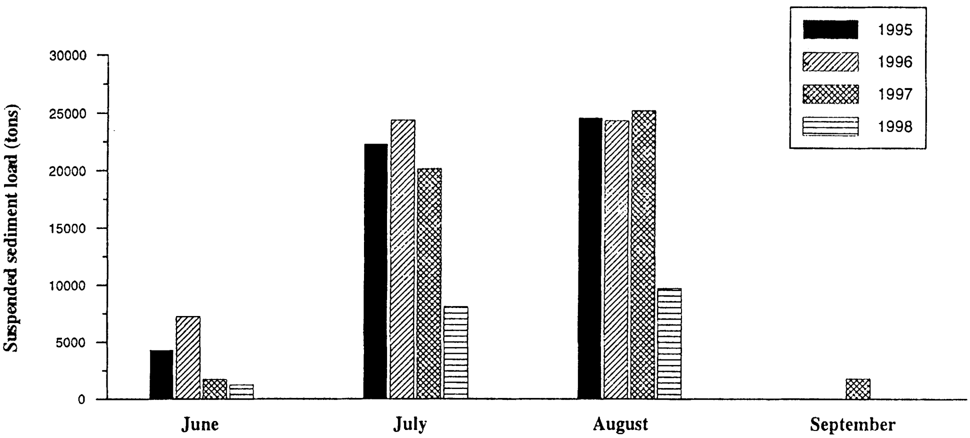

Fig. 5. Monthly suspended sediment load observed at the Dokriani Glacier gauging site for different years.

pended sediment load transported during the months of June, July, August, and September was 3,607, 18,733, 20,951 and 1,794 t, respectively. The average total suspended sediment load for the melt season was computed to be 45,085 t. As with concentration, maximum sediment loads from this glacierized basin occurred in August, followed by July. Prominent peaks in the suspended sediment load were associated with anomalously high water discharges. The highest daily suspended sediment load (7,916 t) in the melt stream was observed on 3rd August, 1997, the day with the highest rainfall (58 mm). During this period high rainfall occurred for 6 consecutive days, which contributed to higher amount of sediment as well as discharge. During high rainfall events, greatly enhanced suspended sediment concentrations are possible from debris and moraine covered glacierized basins.

The large variations in suspended sediment concentration and load during the melt season, as observed in the present study, are attributed to the location of the sediment sources, development of the drainage network, exhaustion and replenishment of the sediment supply and differences in travel distance between sediment source areas and the location of measuring station. As the ablation season progresses, the concentration of sediment first increases due to availability of sediment within the subglacial channels and then reduces due to evacuation of the sediment from the drainage system. As suggested by Østrem (1975) and Drewry (1986), actual glacial erosion may be accomplished uniformly and steadily, but evacuation of sediment from a glacier depends very much on the amount of water draining through the glacier.

Sediment Yield

There are limited observations of sediment yield near the snouts of Himalayan glaciers. Most data are from downstream sites, located at some distance from the glacier termini. Assuming that the suspended sediment yield during the melt season can be used to represent the annual yield, the average suspended sediment yield for the Dokriani Glacier basin was computed to be about 2,800 t $km^{-2}yr^{-1}$. The iso-erosion rate map of India shows that mean annual erosion rates in India vary from 350 to 2,500 t $km^{-2}yr^{-1}$ (Garde and Kothyari 1987). Thus, the results of the present study show that sediment yield from the Dokriani Glacier basin is high compared to previously reported data. Shcheglova and Chizhov (1981) reported that in central Asia, glacial rivers in the Pamir region transport sediment at higher rates than in the Tien Shan region. They reported that many basins (10-30% glacierized) in the Pamir have sediment yields of around 3,000 t $km^{-2}yr^{-1}$. Thus, the present results indicate that the sediment yield from the Dokriani Glacier is comparable to those reported for the glacial rivers in the Pamir region. It must be pointed out here that the sediment yield for the Dokriani Glacier has been computed using suspended sediment concentration data collected only twice a day and could be improved upon using higher frequency observations.

Relationship between Suspended Sediment Concentration, Load and Discharge

By far the most common model of suspended sediment transport is a rating curve, derived from ordinary least squares linear regression of either suspended sediment concentration or load, against discharge. Typically, log-transformed series are used because the scatter of data is reduced in such cases. But, application of log-transformed relationship to determine the unmeasured sediment concentration using discharge data underestimate the concentration and thus, sediment load is also underestimated and a correction factor is required (Ferguson 1986). In the present study,

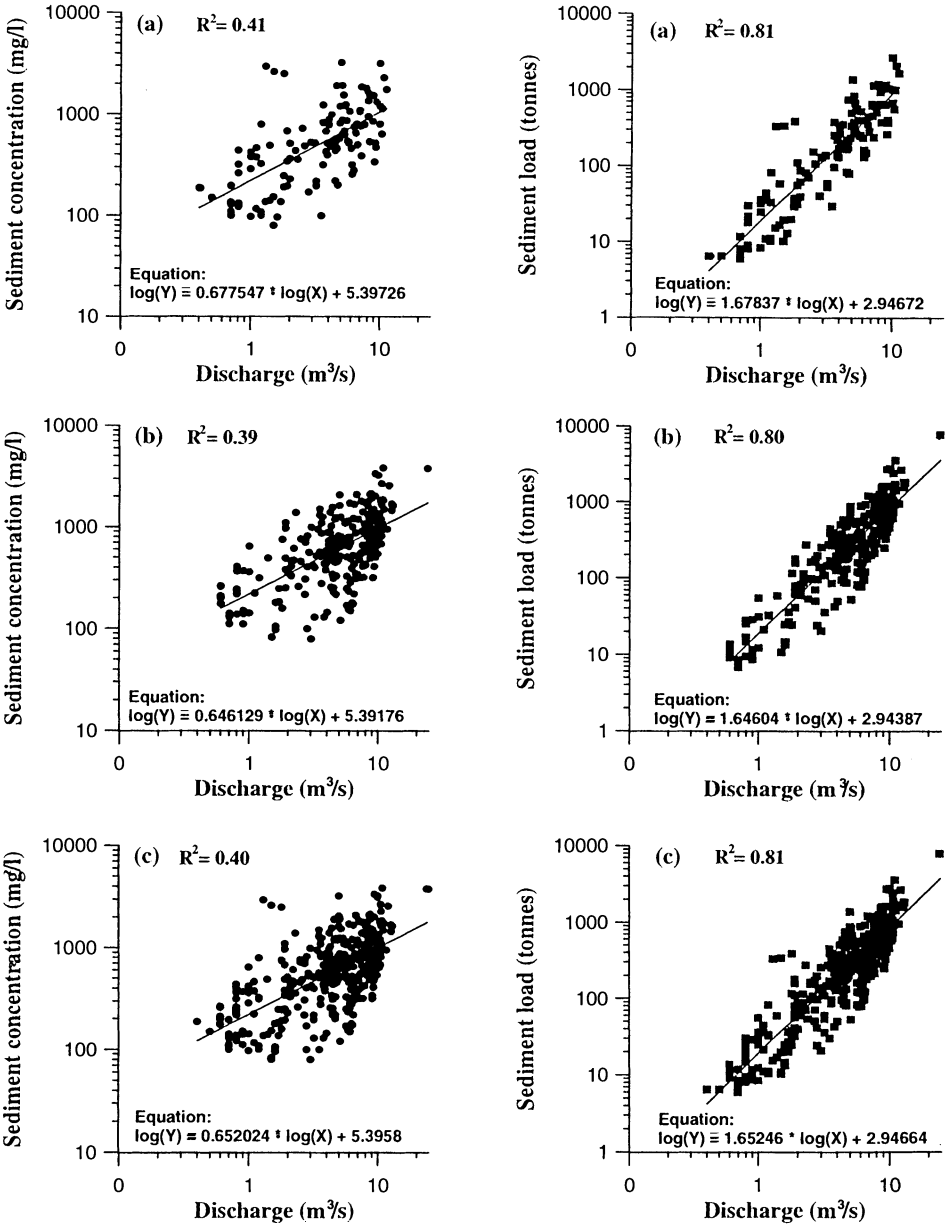

Fig. 6. Relationship between suspended sediment concentration and load and discharge for summer 1995-1998 data : (a) for non rainy days, (b) for rainy days, (c) for all days.

however, observed daily mean sediment concentration and mean discharge were used for computing load, but attempts were also made to establish the relationship between discharge and concentration/load and to explore the effect of rain on this relationship. Fig. 6(c) shows the relationships between suspended sediment concentration and suspended sediment load and discharge using 4 years (1995-1998) data. Results indicate a poor relationship between suspended sediment concentration and discharge for the study basin (r^2=0.40), but this was improved when suspended sed*iment load* was related to discharge (r^2=0.81). Such improvement reflects the presence of discharge as a common variable in both the dependent and independent variables, and the relationship improves because of such inherent correlation.

The occurrence of rainfall can be expected to influence the relationship between discharge and suspended sediment concentration/load. In order to investigate the impact of rain on these relationships, the data set was split into rainy days and non-rainy days and separate relationships were established (Figs. 6(a) and (b)). The days with rainfall less than 2.5 mm were considered as rain free days. Linear regression of log-transformed suspended sediment concentration and discharge data provided r^2 values of 0.41 and 0.39 for non-rainy days and rainy days, respectively. The corresponding values of r^2 for log-transformed sediment load versus discharge relationships were 0.81 and 0.80. These results indicate that r^2 did not improve for either case by splitting the data. It is thought that sudden increases in sediment concentration in some events, without a corresponding increase in discharge, contributed to this poor relationship. As discussed earlier, the movement of the glacier, slumping of the heavily sediment laden portal ice into the stream, occurrence of rainstorms, landslides and rockslides in the ablation zone and near the snout of the glacier, are all considered responsible for such variation in the sediment load of the glacier melt stream. A similar pattern between flow and suspended sediment has been observed in the other glacier melt streams in the Himalayan region (Singh 1993).

A number of models applicable for examining the relationship between suspended sediment concentration and discharge for glacierized catchments are discussed by Fenn *et al.* (1985) and Hodgkins (1996,1999). However, a good time series for both variables with data covered at short time intervals is needed for this purpose. Such data were not available in the present case. Willis *et al.* (1996) suggested that the existing models, which use either regression relationships between sediment concentration and discharge or transfer function techniques to predict sediment concentrations, may be improved, if the changing pattern of sediment supply to a proglacial stream in response to subglacial drainage changes are incorporated. In order to develop an improved understanding of sediment transfer processes and drainage-system structure for the glaciated region of the Himalayas, the short-term data needed for such studies are being collected by authors for other glacierized basins.

Suspended Sediment Particle Size Distribution

In a proglacial stream, the mineralogical composition of rocks and sediment generation processes are the main factors, which affect the grain size distribution of the suspended sediment. Analysis of the particle size distribution of suspended sediment in proglacial streams becomes very important if the water is used in hydropower

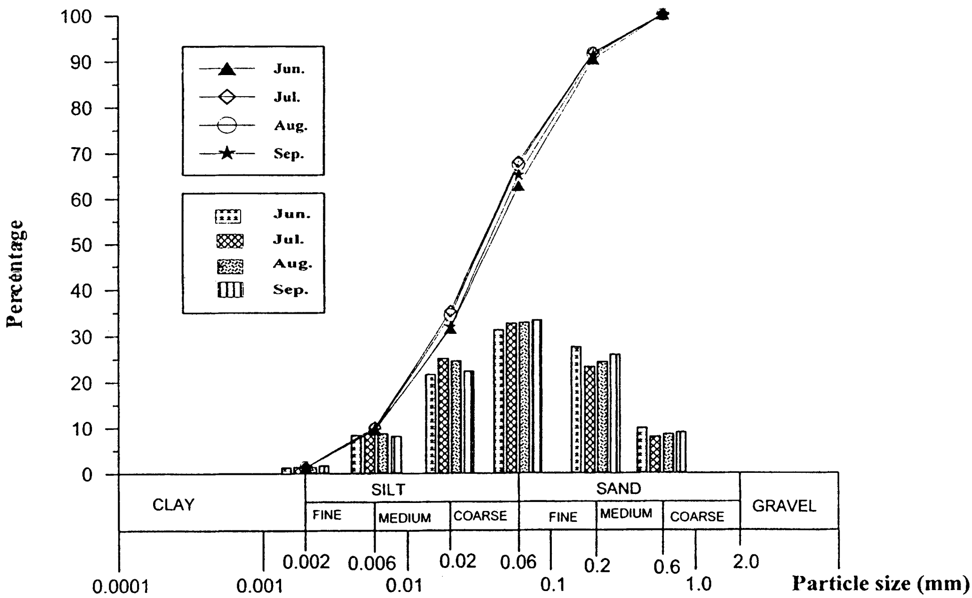

Fig. 7(a). Particle size distribution of the suspended sediment observed during the ablation period in 1997 in the Dokriani Glacier melt stream near the snout of the glacier.

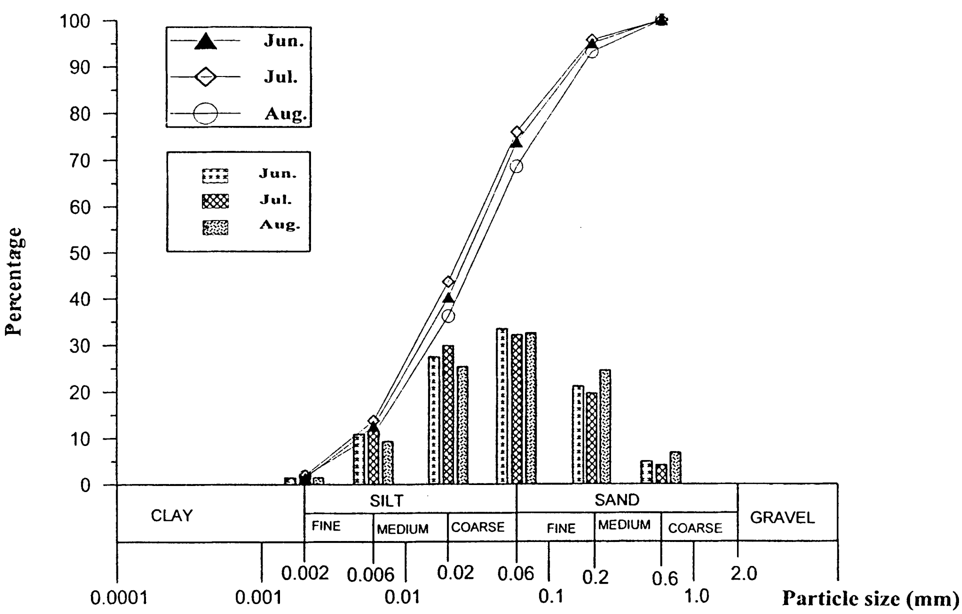

Fig. 7(b). Particle size distribution of the suspended sediment observed during the ablation period in 1998 in the Dokriani Glacier melt stream near the snout of the glacier.

generation. The efficiency of these hydropower schemes is affected by the type and size of suspended particles. Walling and Moorehead (1987) indicated that the grain size of suspended sediments also has an important impact on the trap efficiency of reservoirs. Most studies of glacio-fluvial sediment transport have dealt with relationships between discharge and either load or the concentration of suspended sediment (Østrem 1975; Collins 1979; Gurnell 1982). Less consideration has been given to grain size distributions of sediment transported in the glacial melt water streams (Rainwater and Guy 1961; Bogen 1979, 1980; Fenn and Gomez 1989; Karlsen 1991). Karlsen (1991) studied the temporal variations in grain-size distribution of suspended sediment in a glacial meltwater stream and compared the variations with discharge and sediment concentration. It was reported that a high sediment concentration does not necessarily reflect a high concentration of coarse grains. Additionally, the concentration of coarse grains was found to be independent of discharge.

In the present study, in order to characterize the grain size distribution of suspended sediment for a particular month, all the sediment samples collected twice a day during that particular month were mixed to make a representative sample for that month and then analysed. The results were grouped into six size categories. Particle size distribution curves for the different summer months in 1997 and 1998 are shown in Figs. 7(a) and (b), respectively. Fig. 7 shows that the content of clay, fine silt and medium sand in the total suspended sediment did not change during the ablation season (June to September), whereas the content of medium silt, coarse silt and fine sand varied marginally from month to month. In both years, the silt content was found to be at a maximum in the month of July, which can be explained by the higher meltwater runoff, which removes sediment from a larger surface area of the glacier and from its bed as well. Variation in the grain size distribution on a monthly basis for the ablation period is given in Table 2. The average content of clay, silt and sand for 1997 was observed to be 1, 64 and 35% of the total suspended sediment load, whereas corresponding values for 1998 were 2, 71 and 27%. The coarse silt content was found to be dominant for both years, *i.e.*, 32 and 33% in 1997 and 1998, respectively, whereas the clay content was found to be negligible for these years. As reported by Fenn and Gomez (1989), the sediment load of the outflow stream of the Glacier de Tsidjiore Nouve, Switzerland was also dominated by the silt-sized particles. The results obtained from the present study show no significant variation in the clay, silt and sand contents of sediment during the ablation period, suggesting that the sediment generation and delivery processes from the different sediment sources in the basin do not change significantly during the entire melt period.

Comparison of the Erosion Rate and Sediment Yield with other Glacierized Basins

Many estimates of glacial erosion have been inferred from sediment transport in glacial streams. Hallet *et al.* (1996) provided an excellent review on the erosion rates and sediment transfer from glaciated basins. They reported that glacial erosion rates

Table 2 – Monthly percentage distribution of suspended sediment particles of different sizes near the snout of the Dokriani Glacier in Garhwal Himalayas during summer 1997 and 1998.

Month	Clay	Silt				Sand		
	(%) (<.002mm)	Fine silt (%) (.002-.006mm)	Medium silt (%) (.006-.02mm)	Coarse silt (%) (.02-.06mm)	Total Silt (%) (.002-.06mm)	Fine sand (%) (.06-.2mm)	Medium sand (%) (.2-.6 mm)	Total Sand (%) (.06-.6mm)
June, 1997	1.24	8.50	21.79	31.22	61.51	27.49	9.76	37.25
July, 1997	1.39	8.70	25.19	32.76	66.65	23.71	8.26	32.22
Aug, 1997	1.38	8.38	24.65	32.98	66.01	24.20	8.41	32.61
Sept, 1997	1.26	8.13	22.47	33.27	63.87	26.05	8.82	34.87
June, 1998	1.44	11.13	27.67	33.48	72.28	21.27	5.01	26.28
July, 1998	1.92	11.83	29.90	32.25	73.98	19.79	4.33	24.12
Aug, 1998	1.51	9.30	25.34	32.38	67.02	24.56	6.87	31.44

vary by orders of magnitude for different regions of the world. For example, it is typically 0.01 mm yr^{-1} for polar glaciers and thin temperate plateau glaciers, 0.1 mm yr^{-1} for temperate valley glaciers, 1.0 mm yr^{-1} for small temperate glaciers and 10-100 mm yr^{-1} for large and fast moving temperate glaciers in tectonically active ranges such as in southeast Alaska. In the Swiss Alps, erosion rates are estimated to be 1-2 mm yr^{-1} for basins with small temperate glaciers (Bezinge 1987; Small 1987). These values are generally higher than the erosion rates for the Scandinavian glaciers (0.1-0.5 mm yr^{-1})(Bogen 1989). For the Rakiot Glacier (Nanga Parbat, Himalayas), the erosion rate was found 1.4-2.1 mm yr^{-1} (Gardner and Jones 1984). For the Dokriani Glacier basin, by taking a representative bedrock density of 2,700 kg m^{-3}, the average annual erosion rate for the whole drainage basin using 4 years of data is estimated to be about 1.0 mm for the whole melt period. These results suggest that erosion rates from Himalayan glaciers fall in the range reported for the Swiss Alps. The relatively young age of the Himalayan mountains, the large and active glaciers, tectonic activity seismicity, steep valleys with frequent avalanching and high rainfall are all responsible for high erosion rates in the Himalayan region.

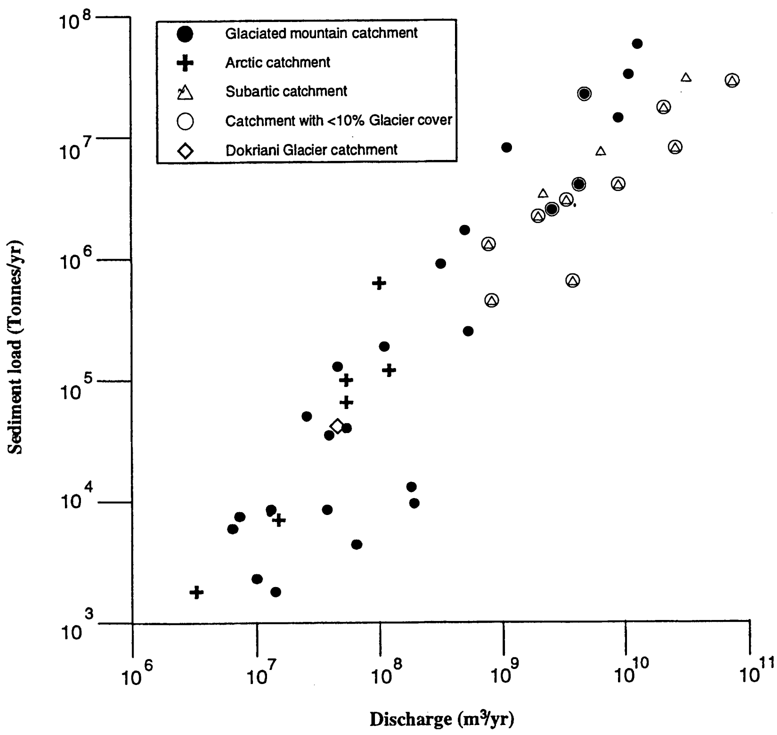

Fig. 8. Relationship between annual discharge volume and sediment load for various drainage basins (Gurnell and Clark 1987). Data from the Dokriani Glacier basin (60% glacierzed) is also illustrated in this Figure.

The annual sediment load from the small Tsidjiore Nouve Glacier basin (4.8 km^2) in Switzerland, which is about one-third in size of the Dokriani Glacier basin, varied from 6,000 to 18,000 t (Bezinge *et al.* 1989), while for Dokriani Glacier basin it was about 45,085 t. Moreover, the specific sediment yield from the Dokriani Glacier (2,800 t km^{-2} yr^{-1}) appears to be higher than the average sediment yields in the range from 100-1,300 t km^{-2} yr^{-1} reported for the glaciers in Norway, based on 16 glaciers basins (Bogen 1989; Hallet *et al.* 1996).

Gurnell and Clark (1987) reported the relationship between annual discharge and annual suspended sediment load from 43 drainage basins grouped into four categories, namely, glaciated mountain catchments, basins having glaciated areas less than 10%, sub-arctic mountain catchments and arctic catchments (Fig. 8). Fig. 8 indicates a positive relationship between annual suspended sediment load and discharge. Total mean discharge and suspended sediment load observed from the Dokriani Glacier for the whole summer period during the four different years, were also superimposed on the data set for glaciers from different regions of the world. The relationship between annual discharge and suspended sediment load for the Dokriani Glacier matches well with the trend reported for other glaciated areas and also fits in the range of data reported earlier.

Conclusions

The presence of glaciers in a drainage basin introduces an important source of sediment into the proglacial stream. In high mountain regions, glaciers scour the mountain slopes and transport rock and boulders to the lower valleys. Estimation of sediment transport in the streams becomes very important for planning, designing and operating hydropower schemes in the Himalayan region. Quantification of suspended sediment loads in their catchments is, therefore, significant especially during the peak summer/monsoon period, as increased sediment loads due to enhanced melting or the precipitation inputs may be detrimental to the turbines, besides resulting in siltation of the reservoirs which directly reduces their live capacity. The present study deals with the quantification of suspended sediment concentrations, loads and yields, and erosion rates for the Dokriani Glacier basin using data of 4 ablation seasons (1995-1998). The sources of sediment in the glacier melt water and the processes associated with sediment generation and transport in the glacierized area are discussed.

During the ablation period, the daily concentration of suspended sediment in the melt stream varied from 80-3830 mg l^{-1}, while daily suspended sediment loads were in the range 6-7,916 t d^{-1}. Mean daily values of concentration for June, July, August and September were observed to be 452, 933, 965 and 275 mg l^{-1}, respectively and the average suspended sediment loads transported in the corresponding months were 3,607, 18,733, 20,951 and 1,794 t, amounting to 45,085 t for the ablation period. The occurrence of large short-term pulses of sediment was mostly associated with short-term increases in stream discharge resulting from rainstorms. Both sediment concentration and load were found to be highest in August followed by July and about 88% of the total sediment load was transported in these two months. Sediment yield from this glacier is found to be very high as compared to the sediment yield at lower altitude Himalayan basins. Suspended sediment yield for the melt period was computed to be about 2,800 t km^{-2} yr^{-1}, which is comparable with glacierized basins in the Pamir region. The erosion rate for the ablation period for the Dokriani Glacier basin is estimated to be about 1.0 mm, which represents approximately annual erosion rate. Suspended sediment load has shown a better correlation with discharge (r^2=0.81) than the correlation between suspended sediment concentration and discharge (r^2=0.40).

The particle size distribution of the suspended sediment indicates that average percentage of clay, silt and sand was found to be 1.4, 67.3 and 31.3%, indicating that the load is predominately composed of silt-sized grains. No significant variation in the clay, silt and sand contents of suspended sediment was noticed during the ablation period. These results suggest that the sediment generation and delivery processes from the different sources of sediment in the basin do not change significantly during the entire melt period.

The study clearly shows high sediment yield from the Dokriani Glacier basin. Similar trends are expected from the glacierized part of the other basins also. There is need to estimate sediment yield from all the glacierized parts of the basins of Himalaya and to establish a long-term database by carrying out detailed investigations on concentration and load. The impact of high sediment yield on the capacity of reservoirs must be accounted for while designing of new reservoirs in the high altitude region of the Himalayas.

Acknowledgements

The authors are very grateful to the Department of Science and Technology (DST), Govt. of India, New Delhi, for providing funds to carry out the hydrological study on the Dokriani Glacier.

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Received: 10 August, 2001
Revised: 8 July, 2002
Accepted: 2 September, 2002

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