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Suspended Sediment Transfer in a Himalayan Headwater Stream: Glacier vs Monsoon

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ABSTRACT: Sediment load in the Himalayan rivers are many fold than the world average. Being the youngest and tectonically active mountains, increased erosion during the monsoon is sited as one the reasons for the higher erosion rate. Even though the glaciers are widely accepted as a powerful erosion agent, role of glaciers, occupying the higher altitude of Himalayan headwater river catchments received little attention due to lack of data generated from these areas. Hence our present understanding on the sources and processes responsible for the high sediment flux in the Himalayan Rivers is mainly in the realm of hypothesis. Dominant role of monsoon in transporting high sediment load in the Himalayan rivers is assumed because of the high quantum of sediment transported during the active monsoon months of July and August. Present study carried out in the Din Gad catchment, a micro scale Himalayan catchment, has designed for a better understanding of the role of glaciers and monsoon in controlling the suspended sediment transfer in a Himalayan glacier fed stream. Discharge and sediment concentrations were measured at three altitudes, including at the Dokriani glacier snout during the entire ablation period for three consecutive years since 1998. Overwhelming glacier contribution in the stream suspended sediment flux has been demonstrated in the present study. Average contribution of sediment flux from the glacier covering 13% of the Din Gad catchment was around 60% and 75% at 2360 m and 3400 m a.s.l. respectively. Suspended sediment yield of the glacier catchment ranged between 9611–2038 tonnes/km^2 and the area under the monsoon influence range between 179 to 1005 tonnes/km^2.This study demonstrates the dominant role of glaciers in determining the sediment transfer characteristics of Himalayan headwater rivers.

INTRODUCTION

Three major river systems of the Himalaya—Indus, Ganga and Brahmaputra together carry about 1.79 Gt y^{-1} of suspended sediments (Meybeck, 1976), nearly 9% of the total annual load carried from continent to the oceans world wide. High rate of surface erosion is attributed to the continuing tectonic activity in the region (Subramanian, 1993). Presence of strong monsoonal rains in the eastern and central Himalaya during July and August months also considered to be contributing to the high sediment yield. The glaciers higher up in the headwater regions of Himalayan rivers contribute substantial amount of sediments to the stream (Haritashya *et al.*, 2006, Hasnain and Thayyen, 1999). Considering the large number of glaciers and deglaciated region in the Himalaya, very little attention has been paid to this important component of sediment load in the Himalayan rivers. It is well known that the glaciers are one of the most powerful agent of erosion. Hence this parameter can not be over looked while assessing the characteristics of headwater hydrology and sediment transfer of the Himalayan rivers. Apart from glaciers, periglacial processes also contribute significantly to the sediment transfer from high altitude basins such as weathering due to frost action and permafrost melting. Widespread recession of Himalayan glaciers in the recent past coupled with the presence of monsoon influence the paraglacial activities and sediment transfer. Systematic data on these aspects from Indian part of the Himalaya is very limited. considering the large number of glaciers in the country and establishment of more hydropower stations in the higher reaches of these rivers, knowledge of sediment transfer characteristics of high altitude glacier basins has become all the more important. Hydrological characteristics of Himalayan glacier catchment differ significantly from the Alpine catchment. High discharge in the Alpine headwater stream occurs during the summer ablation period in association with low precipitation, where as high discharge in the Himalayan catchment occurs in association with high monsoonal precipitation and glacier melting along with higher sediment load. Hence it is hard to distinguish the role of glaciers from monsoon rainfall on sediment transfer process at lower reaches of the Himalayan catchment. Unlike in the Alps water derived from snow and glaciers are being used for various purposes including power generation only at the lower altitudes of the Himalaya. When the stream reach at lower altitude, glacier input to the stream is being modified along the stream continuum based on the hydrological regime of lower elevations of the mountain. Hence water resources management of such glacier fed streams demands comprehensive understanding of processes dominated by glaciers and monsoon. Sediment management is one of the main challenges faced in the reservoir operation in the Himalayan Rivers. Due to lack of information on hydrological processes of cryospheric regime, water resources management policies at lower reaches of the glacier fed rivers are often formulated without considering the impact of glaciers and snow cover on river hydrology (Thayyen *et al.*, 2007). In the present work an attempt has made to establish difference between suspended sediment yield of glacier catchment and non-glacierized monsoon dominated zone of the Himalayan catchment.

STUDY AREA

This study is focused on the Din Gad Catchment in the Ganga basin under the humid climate dominated by the monsoon in summer and snowfall from western disturbances in winter. This micro scale glacier catchment in the Ganga basin cover an area of 77.8 km^2 and extent from 2360 to 6000 m a.s.l. The general aspect of this valley is NW and lies between latitude 30° 48′ to 30° 53′ N and longitude 78° 39′ to 78° 51′ E. More than half of the catchment is heavily forested and nearly quarter of the catchment is occupied by the meadows. Din Gad stream originates from Dokriani glacier (7 km^2) and joins Bhagirathi River near Bhukki village (Figure 1). This glacier has receded 726 m during 1962–2005 period with an average recession rate of 16.88m/yr and lost approximately 22% of its volume from the total storage of 385 × 10^6 m^3 (Dobhal *et al.*, 2004).

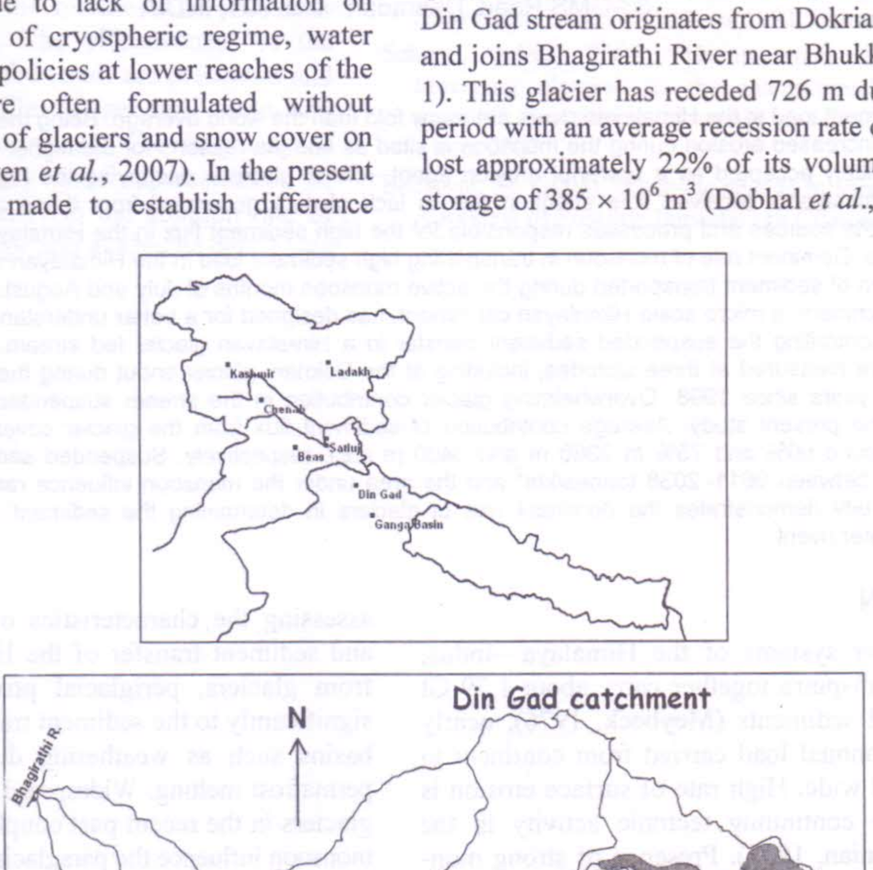

Fig. 1: Location map of Din Gad catchment and Dokriani glacier showing hydrometric stations and sub-catchments

METHODOLOGY

Data Collection

We conceptualized a data collection strategy essentially to understand the role of monsoon, snow and glacier regimes on catchment runoff and sediment transfer. Three hydrometric and meteorological stations representing different altitudinal zones of the Din Gad catchment were established (Figure 1). This approach enabled us to monitor the variability of suspended sediment and discharge along the stream continuum, from the glacier portal (3800 m a.s.l.) to 2360 m a.s.l. First discharge station was established at 600m down stream of glacier snout at 3800 m a.s.l. Second station at Gujjar Hut (3400 m a.s.l.) covering the Alpine meadows and third station at Tela (2360 m a.s.l.) further cover highly forested part of the catchment. These stations were monitored throughout the ablation season from May 15 to October 31 during 1998–2000 periods. Discharge was calculated from rating curve established by the area-velocity method. Suspended sediment were collected from three hydrometric stations. Samples were collected from May to June representing the ablation and monsoon months. Four samples were collected in a day with three hour interval, between 0800 hrs to 1700 hrs at snout discharge station. At Gujjar Hut and Tela catchment, it was observed that there was little diurnal variations in suspended sediment concentration, hence samples were collected only twice in a day, at 0800hrs and 1700 hrs. Samples were collected in narrow necked polyethylene bottles, by holding the bottle at 45° upstream (Ostrem, 1975) Turbulent flow conditions were observed at all the three stations. Samples were collected daily covering the entire six month ablation period for three years (1998, 1999 and 2000) at the three stations. Suspended sediment data generated in 1994 at the snout station (May–October) were also used in this study. Samples were filtered with pre-weighed Whatman 42 filter paper in the laboratory. Filtrates was dried and weighed to determine the suspended sediment concentration. Average daily Suspend Sediment Concentration (SSC) were determined by averaging the SSC values from 0800 hrs of the day to 0800 hrs of next day, following the entire diurnal hydrograph. With this it has been ensured that the errors arising due to missing SSC values from diurnal recessional limb of suspended sediment concentration curve are reduced.

RESULTS

Variations in the Suspended Sediment Concentration and Flux at Snout Station

Suspended sediment flux during the 1998, 1999 and 2000 ablation seasons at the Dokriani glacier snout was 3.2×10^4, 4.31×10^4 and 4.21×10^4 tonnes respectively. Suspended Sediment flux during 1994 ablation period from Dokriani glacier was 15.09×10^4 tonnes and suggested to be of subglacial origin (Thayyen *et al.*, 1999 and Thayyen *et al.*, 2003). Sediment load from 1998 to 2000 were only 21–28 % of the sediment flux observed in the 1994 ablation period. Lower sediment flux in 1998–2000 period substantiate our suggestion that the high sediment flux in 1994 were result of spring event (Thayyen et.al 1999). Figure 2 shows the discharge and suspended sediment flux and rainfall variations at three stations during 1998, 1999 and 2000 summer ablation period. During the observation years maximum sediment flux was observed in the month of July and August. During 1998 monthly maximum suspended sediment concentration (SSC) ranged between 1.29 to 9.12 g/l. The highest SSC of 9.12 g/l was observed in October, resulted due to a high intensity rainfall event. The maximum SSC in June, July and August months vary from 3.25 to 4.07 g/l. The minimum SSC during these months in 1998 varied from 0.031 to 0.068 g/l. This suggests that even in the months experiencing high sediment flux, lower range of suspended sediment concentration did not vary much. In 1999, variation in maximum monthly SSC across the ablation months range between 0.33 g/l in October to 13.9 g/l in July. SSC concentration of 13.9 g/l is resulted from an event, most probably resulted from sub glacial activity. The monthly low SSC varied from 0.017 g/l in October to 0.297 g/l in July. Whereas in 2000 maximum monthly sediment concentration range between 4.35 g/l in September and 1.07 g/l in October. Suspended sediment flux in July and August in 1998 amounts to 33 and 37% of summer flux respectively and in 1999 it was 53 and 25%. In 2000, July and August together constituted 75% of summer sediment flux.

Variations in the Suspended Sediment Concentration and Flux at Gujjar Hut Station

The Din Gad stream reaches Gujjar Hut station after flowing nearly 5 km from the snout station. The Gujjar Hut catchment cover an area of 36 sq km, of which contributions from 20.3 sq km occur below the snout discharge station. The suspended sediment flux at

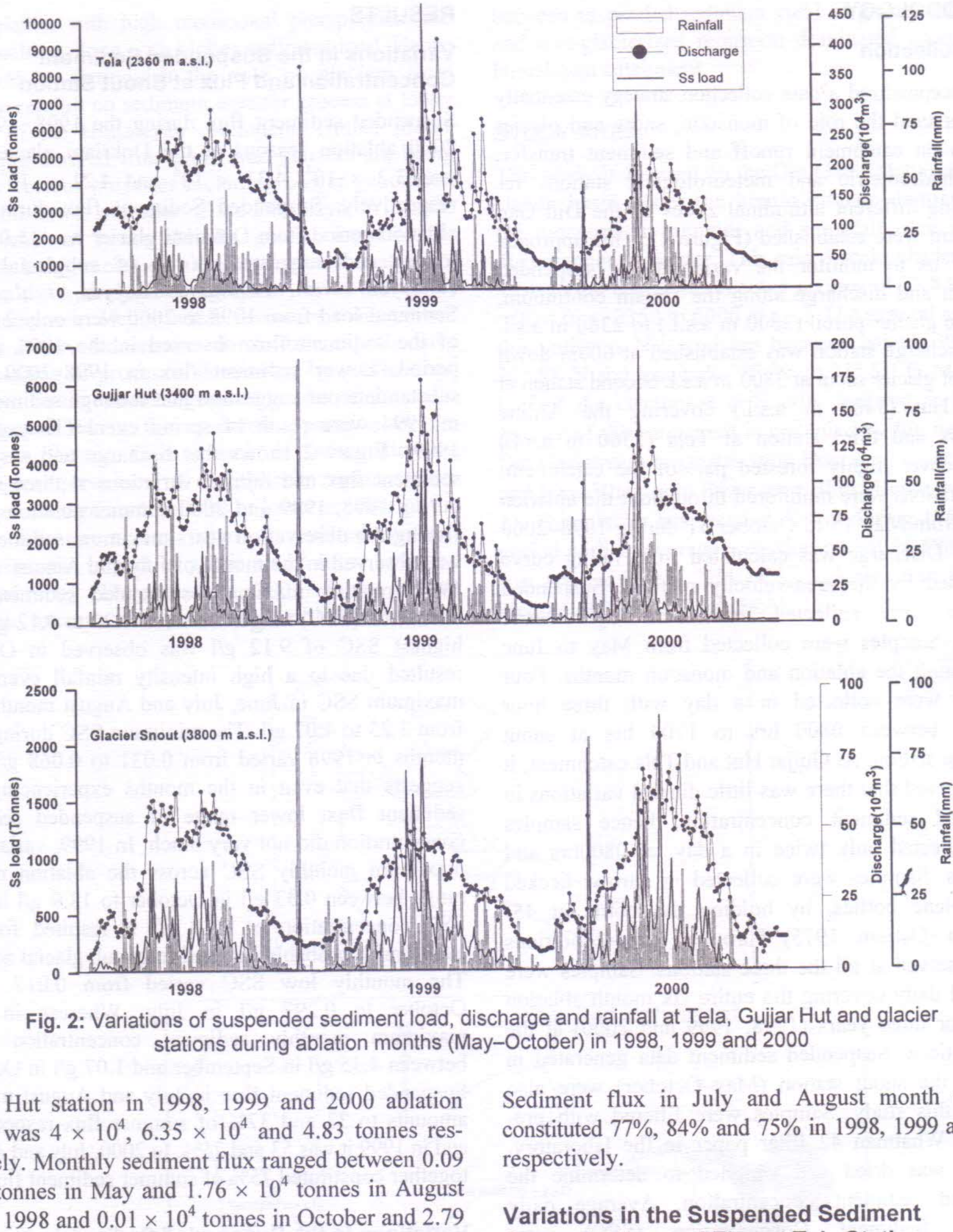

Fig. 2: Variations of suspended sediment load, discharge and rainfall at Tela, Gujjar Hut and glacier stations during ablation months (May–October) in 1998, 1999 and 2000

Gujjar Hut station in 1998, 1999 and 2000 ablation period was 4×10^4, 6.35×10^4 and 4.83 tonnes respectively. Monthly sediment flux ranged between 0.09×10^4 tonnes in May and 1.76×10^4 tonnes in August during 1998 and 0.01×10^4 tonnes in October and 2.79×10^4 tonnes in July during 1999. In 2000, highest sediment flux of 2.83×10^4 tonnes experienced in July. Monthly maximum suspended sediment concentration during 1998 ranged between 0.604 g/l in May and 2.29 g/l in August. During 1999, the maximum monthly SSC values ranged from 0.054 g/l in October and 19.378 g/l in August and in 2000 maximum Ss concentration of 9.7 g/l observed in the month of July. Sediment flux in July and August month together constituted 77%, 84% and 75% in 1998, 1999 and 2000 respectively.

Variations in the Suspended Sediment Concentration and Flux at Tela Station

Discharge and sediment from entire Din Gad catchment (77.8 km^2) is being recorded at Tela station of which 41.8 sq km lies below the Gujjar Hut station. The Din Gad stream traverses nearly 12 km from the Gujjar Hut station before reaching the Tela station. The suspended sediment flux at Tela station during the summer months (May–October) was 5.7×10^4 tonnes in 1998.

In 1999, Tela station experienced nearly two fold increase (9.33×10^4 tonnes) in suspended sediment transport. It is observed that the variations in sediment transport at Tela station were mostly due to various events during the monsoon months. 2×10^4 tonnes of sediments were transported in just two days, amounting 40% of the sediment flux of July, 1999. In the year 2000 total sediment flux at Tela station was 5.58×10^4 tonnes. Monthly sediment flux at Tela in 1998 range between 0.09×10^4 tonnes in May to 2.08×10^4 tonnes in August. In 1999 and 2000 sediment flux in July was highest amounting 4.79×10^4 and 3.09×10^4 tonnes respectively. The maximum suspended sediment concentration at Tela in 1998, 1999 and 2000 observed in the month of July and amounts to 2.269 g/l, 5.176 g/l and 6.91g/l respectively. At Tela station also highest sediment flux recorded in the month of July and August constituting 70%, 84% and 73.7% in 1998, 1999 and 2000, respectively.

DISCUSSION

Glacier Contribution to the River Suspended Sediments

Analysis of suspended sediment data from these three stations suggest that channel storage occurs in the month of May, between Snout and Gujjar Hut as well as between Gujjar Hut and Tela stations. In 1998 this was even noticed in the month of June. In 1999 and 2000 September and October months also showed similar response. In these months suspended sediment flux at Gujjar Hut and Tela stations were lower than the sediment flux observed at the glacier snout clearly demonstrating the overwhelming role of glacier in determining sediment transfer characteristics of headwater Din Gad stream during the non-monsoon months. Sediment transfer during July and August months were significant, as more than 70% sediment flux occur during these months, either from glacier origin or from monsoonal origin. Distributions of sediment flux during the summer months at three stations are shown in the Figure 3. Higher sediment flux during these monsoon months often mainly attributed to non-glacial processes such as rainfall and snowmelt (Sharma *et al.,* 1991, Hasnain and Thayyen, 1999). Contrary to this view present data set shows that the glacier contribution dominates the sediment flux of mountain streams in monsoon months of July and August. Glacier contribution of sediment flux at Gujjar hut station (3400m a.s.l.) in the month of July was 82% in 1998 and 1999 and 71% in 2000. In August it varied from 69% in 1998 to 42% in 1999 and 141% in 2000, indicating channel storage. At Tela station (2360 m a.s.l.) suspended sediment contributions from the glacier in the month of July were 56, 48 and 66% and in August 58, 35, 109% respectively in 1998, 1999 and 2000. In these three years Din Gad catchment experienced very good rainfall ranging between 1200–1600 mm with almost daily occurrence of rainfall in monsoon months. Figure 4 shows a comparative study of glacier contribution of discharge and suspended sediment at Gujjar Hut and Tela stations during the ablation months. While glacier contribution of discharge at Gujjar Hut station ranged between 47–56%, suspended sediment load was 68–87%. At Tela station, discharge contribution from glacier was in the range of 18–35% where as suspended sediment contribution was 55–75%. This clearly demonstrates the overwhelming role played by the glaciers in determining the sediment transfer characteristics of headwater glacier fed streams of the Himalayas.

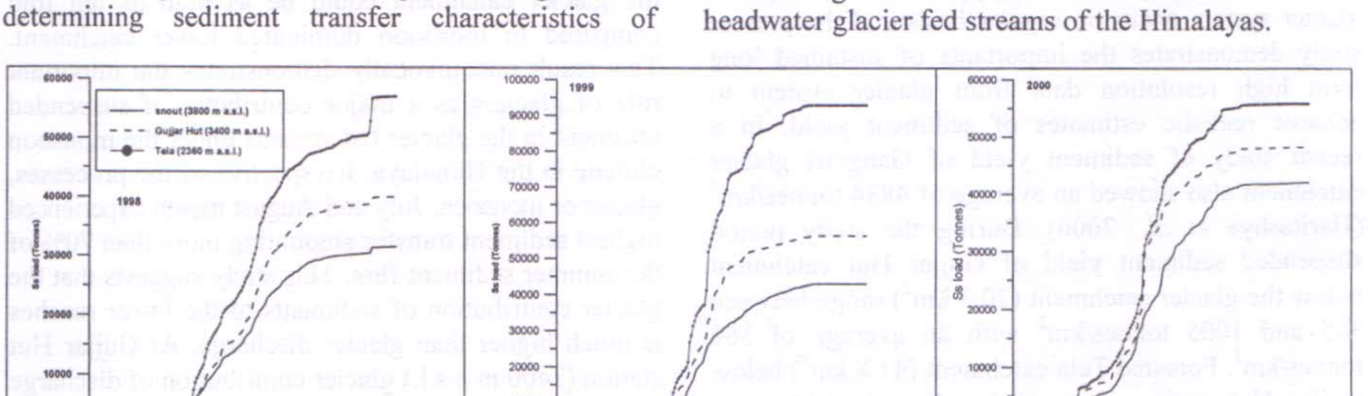

Fig. 3: Cumulative plot of suspended sediment load at three altitude of Din Gad catchment showing the dominant sediment flux in July and August months at all the three stations

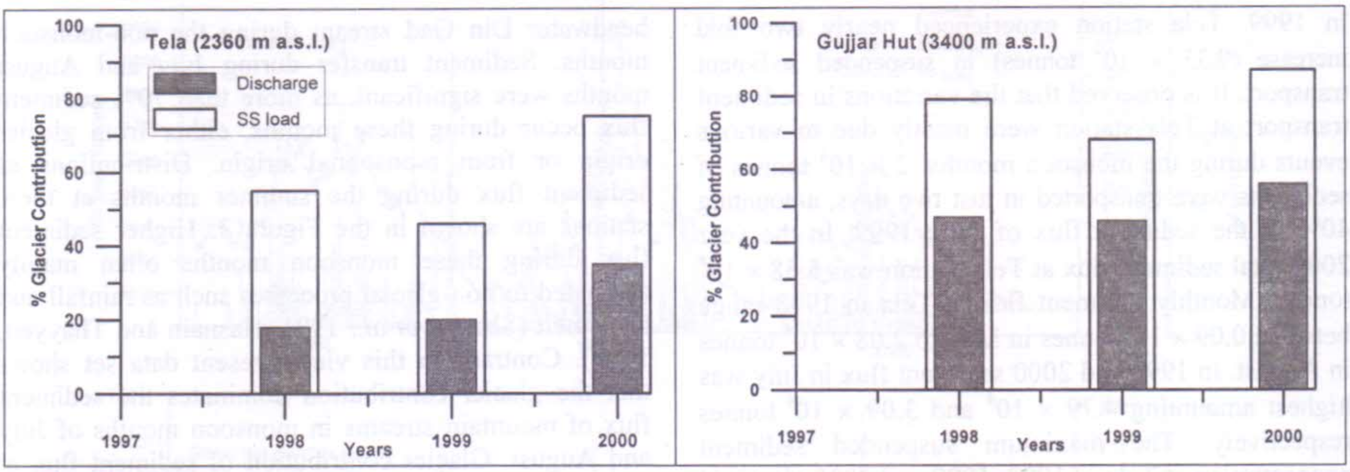

Fig. 4: Comparative plots showing the percentage glacier contribution of discharge and sediment at 2360 m a.s.l. and 3400 m a.s.l.

SEDIMENT YIELD VARIATIONS OF GLACIER AND MONSOON DOMINATED AREAS OF THE CATCHMENT

The dominant role of glaciers in higher suspended sediment transfer from Himalayan headwater stream is further demonstrated by the variations in the rates of suspended sediment yield from different zones of the Din Gad catchment. The suspended sediment (Ss) yield from glacier catchment ranged between 2038 and 2682 tonnes/km^2 between 1998 and 2000. It is important to point out here that the suspended sediment yield of the glacier catchment in 1994 was 9611 tonnes/km^2. Average suspended sediment yield during 1998–2000 period was 2488 tonnes/km^2. However, when we add 1994 suspended sediment yield, the average suspended sediment yield from glacier catchment go up to 4269 tonnes/km^2. Spring events (Thayyen *et al.*, 1999) in a glacier system occur on regular basis and the present study demonstrates the importants of sustained long term high resolution data from glacier system to achieve realistic estimates of sediment yield. In a recent study of sediment yield of Gangotri glacier catchment also showed an average of 4834 tonnes/km^2 (Haritashya *et al.*, 2006). During the study period suspended sediment yield of Gujjar Hut catchment below the glacier catchment (20.3 km^2) range between 305 and 1005 tonnes/km^2 with an average of 568 tonnes/km^2. Forested Tela catchment (41.8 km^2) below Gujjar Hut station, suspended sediment yield range between 179 and 713 tonnes/km^2 with an average of 433 tonnes/km^2. On an average suspended sediment yield of glacier catchment is ten fold higher than the monsoon dominated non-glacierised part of the catchment. However, these suspended sediment yield rates of non-glacierised catchment cannot be generalized for the entire Himalaya as Din Gad Catchment is heavily forested with very less human interference. However these rates can be safely considered as the sediment yield rates of undisturbed forested Himalayan catchments experiencing monsoonal rainfall. Burbank *et al.*, 2003 suggested that the higher erosion rates of greater Himalaya is not linked to the precipitation and they inferred that precipitation does not exert a first order control on erosion, but they attributed it to the tectonic activity. Present study suggests that the role of glaciers play a much bigger role than precipitation in controlling the sediment flux in the Himalayan headwater rivers.

CONCLUSIONS

This study shows that suspended sediment yield from the glacier catchment could be as high as ten fold compared to monsoon dominated lower catchment. This result unequivocally demonstrates the important role of glaciers as a major contributor of suspended sediment in the glacier fed streams under the monsoon climate in the Himalaya. Irrespective of the processes, glacier or monsoon, July and August month experienced highest sediment transfer amounting more than 70% of the summer sediment flux. This study suggests that the glacier contribution of sediments to the lower reaches is much higher than glacier discharge. At Gujjar Hut station (3400 m a.s.l.) glacier contribution of discharge ranged between 47–56%, while suspended sediment load was 68–87%. At Tela station (2360 m a.s.l.), discharge contribution from glacier was in the range of 18–35% where as suspended sediment contribution was 55–75%. This study also demonstrated the importants sustained high resolution data base on sediment transfer, capturing ‘sediment events’ to arrive scientifically sound sediment yield estimates of Himalayan rivers.

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