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Role of glaciers in watershed hydrology: a preliminary study of a "Himalayan catchment"

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Abstract. A large number of Himalayan glacier catchments are under the influence of humid climate with snowfall in winter (November–April) and south-west monsoon in summer (June–September) dominating the regional hydrology. Such catchments are defined as "Himalayan catchment", where the glacier meltwater contributes to the river flow during the period of annual high flows produced by the monsoon. The winter snow dominated Alpine catchments of the Kashmir and Karakoram region and cold-arid regions of the Ladakh mountain range are the other major glacio-hydrological regimes identified in the region. Factors influencing the river flow variations in a "Himalayan catchment" were studied in a micro-scale glacier catchment in the Garhwal Himalaya, covering an area of 77.8 km^2. Three hydrometric stations were established at different altitudes along the Din Gad stream and discharge was monitored during the summer ablation period from 1998 to 2004, with an exception in 2002. These data have been analysed along with winter/summer precipitation, temperature and mass balance data of the Dokriani glacier to study the role of glacier and precipitation in determining runoff variations along the stream continuum from the glacier snout to 2360 m a.s.l. The study shows that the inter-annual runoff variation in a "Himalayan catchment" is linked with precipitation rather than mass balance changes of the glacier. This study also indicates that the warming induced an initial increase of glacier runoff and subsequent decline as suggested by the IPCC (2007) is restricted to the glacier degradation-derived component in a precipitation dominant Himalayan catchment and cannot be translated as river flow response. The preliminary assessment suggests that the "Himalayan catchment" could experience higher river flows and positive glacier mass balance regime together in association with strong monsoon. The important role of glaciers in this precipitation dominant system is to augment stream runoff during the years of low summer discharge. This paper intends to highlight the importance of creating credible knowledge on the Himalayan cryospheric processes to develop a more representative global view on river flow response to cryospheric changes and locally sustainable water resources management strategies.

1 Introduction

The role of high mountain areas of the world as an important source of freshwater for the population living in the adjacent lowlands has been highlighted by recent studies (Bandyopadhyay et al., 1997; Viviroli and Weingartner, 2004; Barnett et al., 2005; Viviroli et al., 2007). The Himalaya is one of the focal regions, both in terms of its cryospheric resources and the dependency of a huge population on rivers originating from this mighty mountain chain. The Himalaya nourish more than 12 000 glaciers (Kaul, 1999; ICIMOD, 2001) covering an area of about 33 000 km^2 (Rai and Gurung, 2005). River Ganga is being replenished by the meltwater from around 4000 glaciers spread over India and Nepal and River Indus is being fed by more than 3300 glaciers. Snow and glacier melt together with monsoonal precipitation determines the headwater flow regimes of large parts of the Himalayas, including central and eastern Himalayan tributaries of River Ganga and Brahmaputra. Snow and glacier melt contribution are very significant in many of these Himalayan rivers. On average, the annual snow and glacier melt contribution is estimated to be 60% in Satluj river at Bhakra dam (Singh and Jain, 2002), 49% in Chenab river at

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Akhnoor (Singh et al., 1997) and 35% in Beas river at Pandoh (Kumar et al., 2007). The Himalayan cryospheric system, the largest outside the polar region, has a number of hydrological and climatic regimes, extending from the cold-arid regions of Ladakh to the humid monsoon climate of the north-eastern Himalayas (Mani, 1981). Glaciers in these regions are in a general state of recession since the 1850's (Mayewski and Jeschke, 1979; Vohra, 1981; Dobhal et al., 2004; Kulkarni et al., 2007) with a few exceptions in the Karakoram region, which are advancing (Hewitt, 2005). As these glaciers continue to recede, its impact on major glacier-fed rivers in the region is a matter of grave concern. The present understanding regarding the impact of glacier shrinkage on river flow variations has been discussed by the IPCC (2007a) which stated that "as these glaciers retreat due to global warming, river flows are increased in the short term, but the contribution of glacier melt will gradually decrease over the next few decades" and that "the enhanced melting of glaciers leads at first to increased river runoff and discharge peaks and an increased melt season" (IPCC, 2007b). However, considering the diverse climatic and hydrological regime of mountain glaciers across the world, such a uniform river flow response to glacier melting needs further evaluation. The Himalayan region has three dominant climatological regimes, which include areas experiencing monsoon and winter precipitation, areas dominated by winter precipitation from western disturbances and cold-arid regions (Vohra, 1981). Therefore, a glacier's role in influencing the flow regimes of mountain rivers across the Himalayan arc would vary considerably. The Dokriani glacier in the Ganga basin is one of the most studied glaciers in the Indian Himalaya and various facets of glacio-hydrological processes have been investigated earlier (Singh et al., 1995; Hasnain and Thayyen, 1999a, b; Hasnain, 1999; Thayyen et al.,1999, 2003, 2005a, b, 2009; Singh et al., 2000a, b, 2003a, b; Nijampurkar et al., 2002; Dobhal et al., 2004, 2008). In this work, an attempt has been made to highlight the fundamental differences between Alpine and Himalayan glacier hydrological systems and the role of glaciers in influencing runoff characteristics of monsoon dominated "Himalayan catchments".

2 Methods

2.1 Study area

This study focuses on the "Himalayan catchments" of the Western Himalayan region, mainly on the Din Gad catchment in the Ganga basin. The basin-scale response of river flow during the past years has been studied in the nearby Satluj and Beas basins which extend from 30°48′ to 32°26′ N and 76°58′ to 78°51′ E. The Din Gad catchment covers an area of 77.8 km^2, extends from 2360 to 6000 m a.s.l. and has 9.6% glacierisation. The general aspect of this valley is NW which lies between latitude 30°48′ to 30°53′ N and longitude 78°39′ to 78°51′ E. Din Gad is the pro-glacial stream of the Dokriani glacier which joins Bhagirathi river near Bhukki village (Fig. 1). The length of the Dokriani glacier is 5.5 km and covers an area of 7 km^2. This glacier has receded 726 m in 43 years (1962–2005) with an average rate of 16.8 m/yr and has lost approximately 22% of its volume from the total storage of 385×10^6 m^3 (Dobhal et al., 2004). The average accumulation rate of this glacier is 0.43 my^{-1} (Dobhal et al., 2007; Nijampurkar et al., 2002), with an average accumulation area ratio (AAR) of 0.66. Another small glacier with an area of 0.46 km^2 is also part of the Din Gad catchment, and its pro-glacial stream joins Din Gad at 3400 m a.s.l. just above the Gujjar Hut hydrometric station.

The Satluj basin lies north-west of the Ganga basin and the river flows down from China to India. The Indian part of the Satluj basin covers an area of 22 275 km^2 and 12% of the area is covered by glaciers and permanent snowfields and approximately 65% of the area receives winter snowfall (Singh and Jain, 2002). The Beas catchment shares its western boundary with the Satluj basin and has an area of 5278 km^2 with 780 km^2 (14.7%) of glaciers and perennial snow cover (Kumar et al., 2007). The area and percentage glacier cover of various catchments discussed in this study are given in Table 1.

2.2 Data collection

The main objective of glaciological studies in the Himalaya is to generate a knowledge base for managing the large frozen water reserves of glaciers and study the river flow response to the fluctuations of glaciers and snow cover (Thayyen et al., 2007a). Following the Alpine format, glaciological studies were focused on glacier mass balance, glacier discharge and monitoring of the meteorological parameters close to the glacier. The role of monsoons and snow cover has received little attention in the glaciological study frame-work, and over the years it has been found that the approach has failed in achieving the desired result of understanding river flow response to cryospheric changes. To better understand the impact of monsoon and western disturbances on glacier regimes as well as on the runoff from the catchment, three hydrometric and meteorological stations, covering different altitudinal zones of the Din Gad catchment were established in 1998 (Fig. 1). This approach enabled us to monitor the runoff variability all along the stream continuum, from the glacier portal (3900 m a.s.l.) to 2360 m a.s.l. The first discharge station was established at 600 m downstream from the glacier snout at 3800 m a.s.l. The second station at Gujjar Hut (3400 m a.s.l.) covered the snow dominated Alpine meadows and the third station at Tela (2360 m a.s.l.) covered the highly forested, monsoon dominated lower part of the catchment. These stations were monitored throughout the ablation season from 15 May to 31 October during the 1998–2004 periods, with an exception in 2002. The discharge was calculated from a rating curve established by the area-velocity method. For

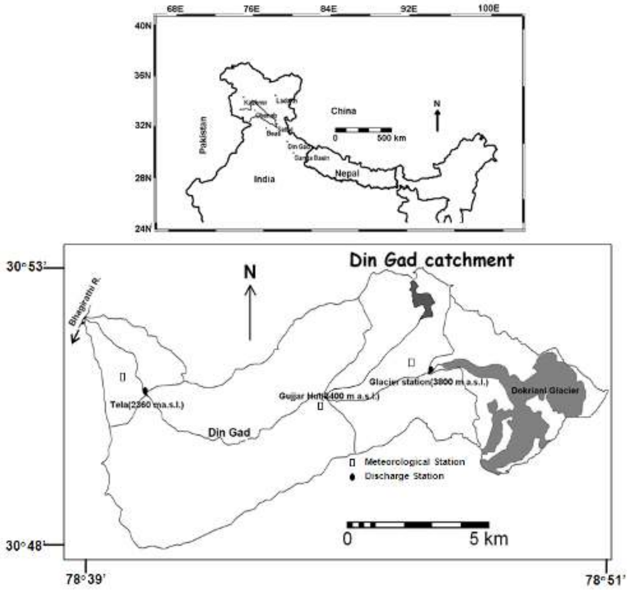

Fig. 1. Study area showing the sub- catchments and location of hydro- meteorological stations in the Din Gad catchment.

Table 1. Area and percentage glacier cover of various catchments discussed in the study ([a] Reyaz and Shamshoo, 2008, [b] Kumar et al., 2007, [c] Singh et al., 2002, [d] Puri and Swaroop, 1995).

Catchment	Catchment Area (km^2)	% Glacier cover
Din Gad (Dokriani glacier)	15.7	44.6
Din Gad (Gujjar Hut)	36.5	20.5
Din Gad (Tela)	77.8	9.6
Lidder[a]	1263	3.1
Ganglass	70	1.6
Beas[b]	5278	14.7
Satluj(India)[c]	22 305	12
Gara Glacier[d]	17	35
Shaune Garang Glacier[d]	33.5	32.2
Tipra bank Glacier[d]	41.56	31.5

continuous recording of water level at these three stations, water level recorders were installed over the stilling wells made of steel drums. Manual observations of staff gauges were also carried out four times a day, with three hour intervals to overcome the problems arising from malfunction of the chart recorder during the high flow periods of June, July and August. The chart recording was disturbed many times during the study period due to high flows and other mechanical problems. The Tela station was washed off during the high flows of July 2001. The daily discharge data have been calculated for the three stations by combining manual records and the data from the chart recorder. During the study period, the efficiency of rating curves of the glacier station ranged between 93–95.7% and that of the Gujjar Hut station between 90–94%. The efficiency of rating curves of the Tela station ranged between 87–91%. The Wadia Institute of Himalayan Geology (WIHG), Dehradun and the National Institute of Hydrology (NIH), Roorkee monitored the discharge at the glacier station separately during the 1994 and 1998 ablation periods and the error was found to be in the range of 7–14%. In the absence of discharge data acquired through any other method, the inherent standard error of 10–15% (Mutreja, 1986) in the area-velocity method of discharge measurement is deemed to be applicable in this study.

Three manual standard meteorological observatories were established at Tela (2540 m a.s.l.), Gujjar Hut (3483 m a.s.l.) and glacier Base camp (3763 m a.s.l.) and monitored throughout the ablation period. Monitoring of the winter weather was initiated at the Base camp station in 1998 and observations were carried out intermittently due to extreme weather conditions. The winter weather monitoring was extended to the Tela station in the year 2000. The standing snow depth and density were monitored four times during the December–April period at different altitudes along the valley bottom from Gujjar Hut to the Base camp. Snow depth and density measurements were extended up to 4700 m a.s.l. over the glacier at least once during April–May period to monitor the snow cover duration. The snow-line was mapped physically every year in early May, before initiating discharge measurement at Gujjar Hut and snout stations. The summer mass balance of the Dokriani glacier was estimated until 2000 to assess the glacier degradation-derived runoff component (Dobhal et al., 2008). The glacier melt derived runoff, equal to the glacier mass balance is termed as glacier degradation-derived runoff (UNESCO, 1996).

The regional similarities in runoff response at different spatial scales in the same glacio-hydrological regime were studied by using runoff data of Beas and Satluj rivers. The long-term discharge data from River Satluj, and the long-term all India summer monsoon rainfall anomalies were considered along with information on glacier fluctuations in the Himalayas during the same period to understand the relationship between monsoon strength and glacier fluctuation and the corresponding river flow response of the Himalayan catchment.

3 Hydrology of the Himalayan glacier catchments

The Himalayan region experiences diverse climate and hydrology from west to east (Fig. 2), dominated by S-W Indian monsoon in summer and mid-latitude westerlies known as western disturbances in winter (Upadyaya, 1995; Mani, 1981; Benn and Owen, 1998; Lang and Barros, 2004). While the S-W monsoon declines in strength from east to west

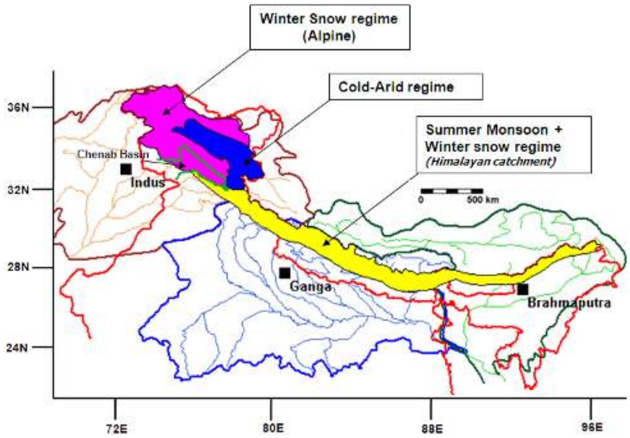

Fig. 2. Glacio-hydrological regimes of the Himalaya.

along the Himalayan arc, western disturbances weaken as they move from west to east (Gupta, 1983). The hydrology of glaciers and glacier-fed rivers, east of the Chenab basin are highly influenced by the summer monsoon and these glaciers are considered as summer accumulation type glaciers (Ageta and Higuchi, 1984; Vohra, 1981). These large areas of the Himalaya constitute the headwater regions of the Ganga and a few tributaries of rivers Indus and Brahmaputra. The winter snowfall from western disturbances dominates large areas of the Indus river systems. In India, the state of Jammu and Kashmir represents most of the winter snow dominated areas, where monsoon activity is very low. Another unique glacio-hydrological system in the Indian Himalaya is the cold-arid region of the Ladakh, which extends from Tibet to India. In this area, glaciers and permafrost melting are the major sources of water, sustaining the streamflow and water requirement of the population.

Each of these major glacio-hydrological regimes of the Himalaya are characterised by its differences in spatial and temporal distribution of precipitation and runoff. The area dominated by winter snowfall is analogous to the Alpine glacio-hydrological system, where peak glacier runoff contributes to otherwise low flow conditions, governed by lower precipitation in summer (Fig. 3a). The Himalayan catchments in the east of the Chenab basin are characterised by peak glacier runoff contributing to peak river flow from monsoon rainfall in July and August (Fig. 3b). In the cold-arid regions of Ladakh, the annual discharge peak occurs in the month of July and August (Fig. 3c), mainly due to higher glacier melting during the period. The precipitation in the region is also the highest during the same period, but the mean annual precipitation is as low as 115mm (Gupta, 1983), in which 73% occurs during the summer months. The distribution characteristics of precipitation in these three major glacio-hydrological regimes of the Himalaya are shown in Fig. 4. Here we define "the Himalayan catchment" as glacier catchments experiencing snowfall in winter and monsoon precipitation in summer, where peak discharge from the glacier contributes to the crest of the annual stream hydrograph. Figure 5 is a schematic representation of these three different glacier hydrological systems of the Himalaya which shows the relative importance of the glacier, snow and rainfall in each of these glacio-hydrological regimes during the winter and summer months. Monsoon rains dominate the hydrology of "Himalayan catchments" from July to mid-September and snow from western disturbances dominates the winter months (NDJFMA). Consequently, December to March records the lowest flows in these rivers and the peak runoff occurs in the months of July and August. These two months experience the highest monsoon rains, highest solar insolation and temperature, which translate into the highest glacier discharge. Hence the headwater river hydrology of a Himalayan catchment is collectively influenced by variations in monsoon, snow and glacier regimes. This fundamental difference between the Alpine and the Himalayan glacier hydrological systems is often overlooked, while assessing the role of glaciers in headwater river flows in a changing climate. This is evident in the fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC, 2007a) as it combined the Hindu Khush-Himalayan region and the South-American Andes together as the regions where river flow is sustained by the glacier melt in the summer season. In fact, major areas covering the southern slopes of the Himalaya, which include part of the Indus basin (Beas, Satluj & Ravi) and the whole of the Ganga basin and a few tributaries of River Brahmaputra in the eastern Himalaya, experience monsoon rains in summer and glacier melt only supplements to the peak summer flow. In this paper we focus our discussion on the "Himalayan catchment" as defined above.

In the "Himalayan catchments" glaciers and permanent snowfields are bounded within an altitudinal range of 3500 m to 8848 m a.s.l. and a very large area of the mountains above 2000 m a.s.l. experiences seasonal snow cover. The monsoon and the western disturbances are spread across the region with varying degrees of influence. Hence, flow regimes of the Himalayan rivers are highly influenced by the altitudinal distribution of precipitation. Western disturbances are upper air cyclonic systems, operating at about 500 hPa, and show a positive precipitation gradient as the altitude rises due to orographic uplift, thereby depositing large amounts of snow in the higher altitudes of the glacier basins (Bhutiyani, 1999; Singh and Kumar, 1997b; Upadyaya, 1995). The low pressure troughs of the westerlies start dominating the northern most part of the Himalaya in November and early December and have a more southerly course in February and March resulting in heavy snowfall in the Himalaya during this period, which sometimes continue up to April (Gupta, 1983). In contrast, the monsoon systems operate at around 850 hPa (Goswami et al., 2003) and they encounter the Himalayas at lower elevations and undergo orographic uplift. Therefore, the highest precipitation from the monsoon over the Himalayas occurs at an altitude of 1000 to 3500 m a.s.l. (Gupta, 1983; Upadhyay, 1995; Singh and Kumar, 1997;

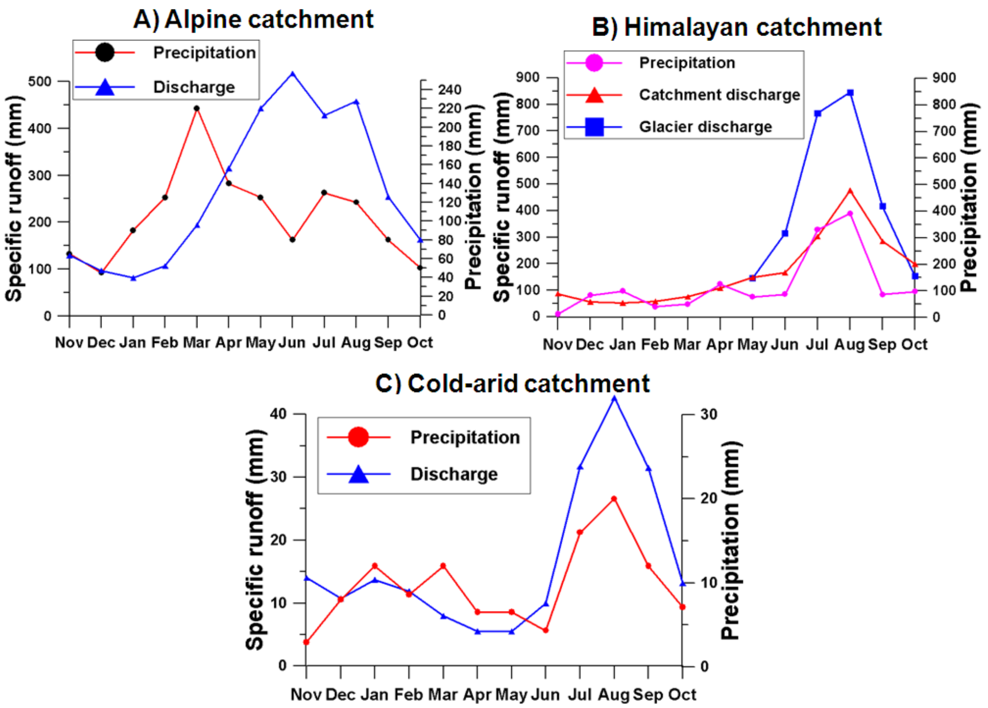

Fig. 3. Temporal distribution of runoff and precipitation in glacio- hydrological regimes of the Himalaya in a mountain water year, showing characteristically different distribution pattern **(A)** snow dominant Alpine system, Lidder valley, Kashmir **(B)** monsoon dominant Himalayan catchment, Din Gad catchment, Ganga basin and **(C)** cold-arid system, Ganglass catchment, Ladakh range. Precipitation data are point observations made at lower part of the catchment.

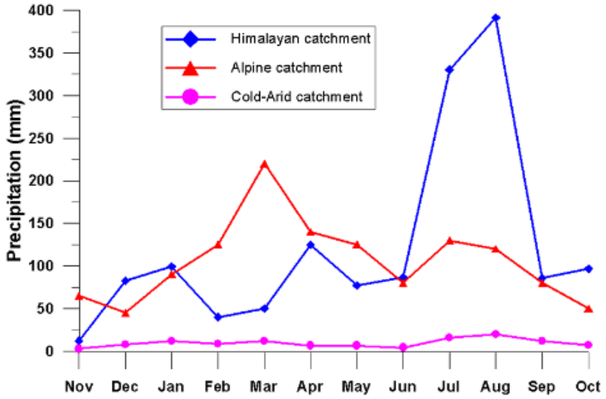

Fig. 4. Figure showing comparative temporal distribution of precipitation amount in the three glacio-hydrologic regimes of the Himalaya.

Burbank et al., 2003). The strength of the monsoon rainfall declines above this altitude and glaciers in these regions receive lesser monsoon rainfall as compared to the lower altitudes of the mountain range. The monsoon winds reach the Himalayan foothills by late June and persist until mid-September (Gupta, 1983) with July and August experiencing 80% of the monsoon precipitation.

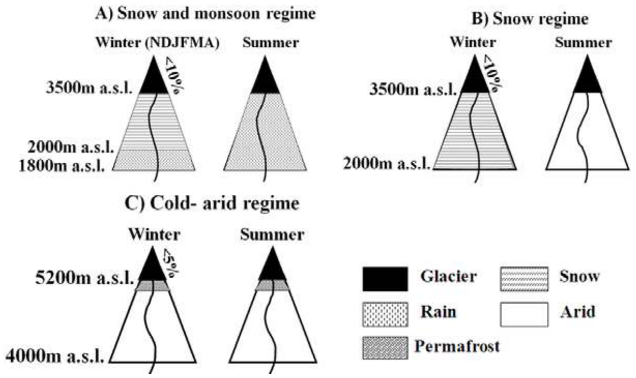

Fig. 5. Schematic diagram showing different glacio-hydrological regimes of the Himalaya and distribution of summer and winter precipitation. The hypothesis proposed suggests varying river flow response to the cryospheric/climatic changes. **(A)** River flow changes are governed by the variations in summer and winter precipitation with higher glacier component during low summer runoff. **(B)** River flow changes are dependent on variations in the snow cover characteristics and glacier melting. **(C)** Rivers are entirely fed by the glaciers and permafrost melting and flow variation is governed directly by the temperature variations.

4 Results and discussion

4.1 Variations in runoff and weather parameters

The Din Gad catchment experienced varied patterns of precipitation during the seven-year study period. Heavy winter precipitation and summer monsoon rainfall in 1997–1998 and low winter and summer precipitation in 1998–1999 and 2003–2004 were the extremes. This situation provided a very good opportunity to study the role of glaciers in headwater streamflow variations of a Himalayan catchment. The summer ablation season (May to October, M5-10) discharge in the Din Gad stream at 2360 m a.s.l. showed gradual reduction during the study period. 2004 recorded the lowest discharge of 123×10^6 m^3, which was 58% less than the discharge observed in 1998 (290×10^6 m^3). Discharge observed at 3400 m a.s.l. recorded a 50% decline during the same period. However, discharge from the Dokriani glacier at 3800 m a.s.l. did not respond in the same way (Fig. 6). The glacier runoff fluctuated during these years, varying from 52×10^6 m^3 in 1998 to the highest discharge of 78×10^6 m^3 in 2001 and the lowest value of 42×10^6 m^3 in 2004. The lowest discharge in all the three stations were recorded in the same year, while the highest discharge observed at the Tela station (2360 m) in 1998 was independent of glacier discharge. Glacier mass balance studies showed that the melting of glacier ice contributed 4.83×10^6 m^3 to 5.17×10^6 m^3 during 1994–2000 (Dobhal et al., 2007), which constituted 7.7 to 12.7% of the bulk glacier runoff. After considering the net accumulation ranges from 2.23×10^6 m^3 to 2.66×10^6 m^3, the component of glacial degraded runoff in the bulk glacier discharge varied between 3.5–7.5%. During the study period, the Equilibrium Line Altitude (ELA) fluctuated between 5030 m a.s.l. and 5100 m a.s.l. (Dobhal et al., 2008). At the non-glacierised part of the glacier catchment the transient snowline often receded to 5800 m a.s.l. On average, the monsoon rainfall component in the glacier discharge was in the range of 10–26% (Thayyen et al., 2005a).

The Din Gad catchment experiences abundant rainfall during the ablation period from May to October (see supplementary material: http://www.the-cryosphere.net/4/115/2010/tc-4-115-2010-supplement.pdf). Summer rainfall in the Din Gad catchment range between 1533 mm in 1998 and 1080 mm in 2001 (Fig. 7) with a mean rainfall of 1249 mm. Winter snowfall experienced considerable variations during the study period. Winter precipitation monitored at the Base camp (3760 m a.s.l.) range from 500 and 511 mm w.e. in 1998 and 2002 to 144 and 190 mm w.e. in 1999 and 2004, respectively. The distribution characteristics of winter and summer precipitation in the catchment, especially in the higher reaches, are not fully understood from the present data. Yasunari and Inoue (1978) suggested that the monsoon rainfall could be 4–5 times higher around the peaks and ridges of the catchment as compared to the valley bottom. Therefore, the assessment of snow and rainfall components in the streamflow has not been attempted in this study. The longest snow cover durations at the Base camp was recorded in 1997–1998 (153 days) and in 2000–2001 (128 days). On the other extreme, the shortest snow cover duration during the study period were experienced in 1998–1999 (68 days) and 2003–2004 (75 days). In 1998, the snow cover in the first week of May was extended up to the Gujjar Hut station covering 46% of the Din Gad catchment. The lowest snow cover area in May were recorded in 1999 and 2004, and amounted to 14 and 18%, respectively.

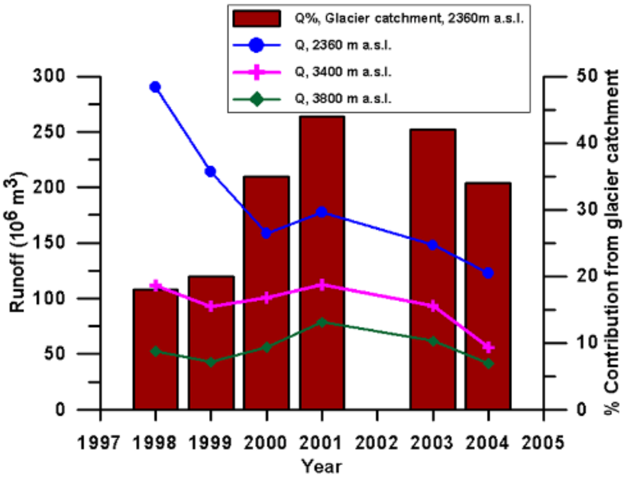

Fig. 6. Stream discharge variations observed at three elevations of the Din Gad catchment and corresponding variations in the contribution from the glacier catchment at 2360 m a.s.l. during the study period.

The temperature is another important parameter influencing the runoff regimes of snow/glacier catchments. July and August are the warmest months with mean monthly temperature ranging from 11.4–9.5 °C at 3760 m a.s.l., 13.4–11.2 °C at 3400 m a.s.l. and 18.5–16.0 °C at 2540 m a.s.l. Based on the temperature measurements at the Base camp (3763 m a.s.l.), the summer positive degree days (PDD) (15 May–31 October) were calculated to study the yearly temperature variations of the ablation months. 1998 experienced the highest summer temperature (PDD, 1691) followed by 2003 (PDD, 1575) and 2004 (PDD, 1518) and the lowest temperature was recorded in 2000 (PDD, 1296). Among the different hydrological variables discussed above, the winter precipitation the experienced largest inter-annual variation as reflected in the yearly variations in the snow water equivalent, snow cover duration and snow cover extent. The summer precipitation and temperature were highest in 1998, and during the rest of the observation years both parameters fluctuated nominally.

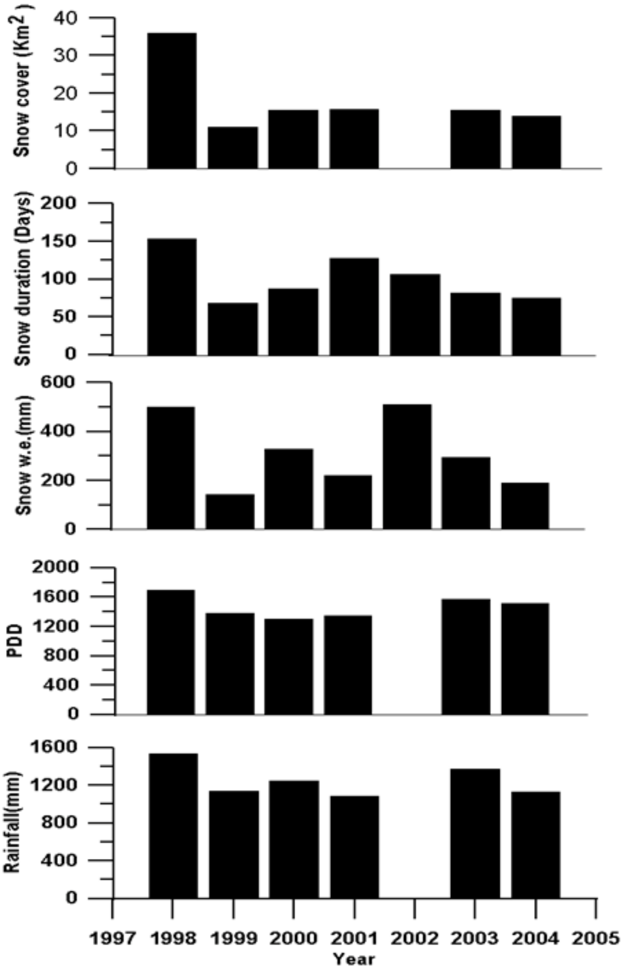

Fig. 7. Observed variations in the hydro-meteorological parameters during 1998–2004 period. Rainfall, Positive degree days (PDD), winter snow precipitation, Snow cover duration at 3763 m a.s.l. and snow cover extent in the first week of May. Rainfall shown here is arithmetic mean of the rainfall observed at three stations in the Din Gad catchment.

4.2 Variations in the runoff contributions from glacierised and non-glacierised areas

Figure 6 explains the role of glaciers and precipitation in controlling river flow variations in the Himalayan catchment. While the discharge at Tela and Gujjar Hut stations diminished by 58 and 50% respectively, from 1998 to 2004, discharge from the glacier catchment showed comparatively stable response. Analysis of specific runoff from each sub – catchment showed that the contributions from the Tela catchment (41.8 km^2) were reduced from 25 mm/day in 1998 to 9 mm/day in 2004 (Table 2). Similarly, runoff contribution from the Gujjar Hut sub-catchment (20.3 km^2) was reduced from 18 mm/day to 4 mm/day during the same period, whereas the runoff from the glacier catchment (15.7 km^2) varied from 29 to 15 mm/day. The variations observed in the summer specific runoff from the non-glacierised part of the catchment covering 62 km^2 are obviously driven by the variations in precipitation. The lowest specific runoff from the glacier catchment observed during the study period was 15 mm/day, which is much higher than the lowest specific runoff of 9 mm/day and 4 mm/day of the non-glacierised Tela and Gujjar hut sub-catchments, respectively. This highlights the buffering role of the glaciers during the years of low summer flow in glacier-fed rivers of the “Himalayan catchment”. Highest specific runoff from the Tela sub-catchment (25 mm/day in 1998) observed during the study period was higher than the specific runoff from the glacier catchments in the same year and close to the highest runoff from the glacier catchment (29 mm/day in 2001). This shows that contributions from the non- glacierised part of the Himalayan catchment equals or even exceeds that of the glacier catchment during the years of abundant precipitation. This clearly shows the overwhelming influence of the precipitation, both winter snowfall and summer monsoon, in determining runoff variations in a Himalayan catchment.

Monthly discharge flux and percentage runoff contribution from the glacier catchment to Tela and Gujjar hut stations are shown in Fig. 8a and b. During the peak runoff period of July and August, the contribution from the glacier catchment to the Gujjar hut station ranged from 41% to 86%. At the same time, contribution from the glacier catchment to the Tela station ranged from 17% to 56%. During the 1998 ablation period, the component of glacier discharge at Gujjar hut and Tela stations were 47% and 18% respectively, where as in 2004, runoff from the glacier catchment constituted 74% at the Gujjar Hut station and 34% at the Tela station. This shows that the glacier component in the bulk discharge at the Tela station (2360 m a.s.l.) has nearly doubled during the study period. It is clear from the results presented above that the reason behind such a response is the reduced runoff contribution from non-glacierised areas of the catchment, rather than any increase in the glacier discharge. Hence it is suggested that the discharge component from the glacier catchment is highest in the headwater streams of the “Himalayan catchment” during the years of lowest summer runoff. Extending this response further downstream, Alford (1992) suggested that the Himalayan component is highest in the Ganges during the years of minimum discharge.

4.3 Glacier discharge variations and role of glacier degradation-derived component

The predominance of precipitation in determining the runoff characteristics of the Himalayan catchment is inclusive of the glacier catchment as well. Four years of mass balance and runoff studies of Dokriani glacier show occurrence of higher discharge in association with more positive glacier mass balance and lower discharge during more negative mass balance years. 1999 experienced one of the lowest runoff from the glacier associated with highest negative

Table 2. Observed variations in the specific mean daily runoff (mm d^{-1}) of each sub-catchment of the Din Gad catchment during the summer period (M_{15}-O_{30}). Runoff variations in the Tela and Gujjar Hut sub-catchments are precipitation dependent and higher than the variation of the glacier catchment, illustrating the buffering role of the glaciers in a "Himalayan catchment" during the years of low summer runoff (CV – Coefficient of variation).

Year	Sub-catchment Tela (41.8 km^2) (2360–3400 m a.s.l.)	Sub-catchment Gujjar Hut (20.3 km^2) (3400–3800 m a.s.l.)	Sub-catchment Glacier station (15.7 km^2) (>3800 m a.s.l.)
1998	25	17	20
1999	17	15	16
2000	8	13	21
2001	9	10	29
2003	7	9	23
2004	9	4	15
CV	**0.6**	**0.4**	**0.2**

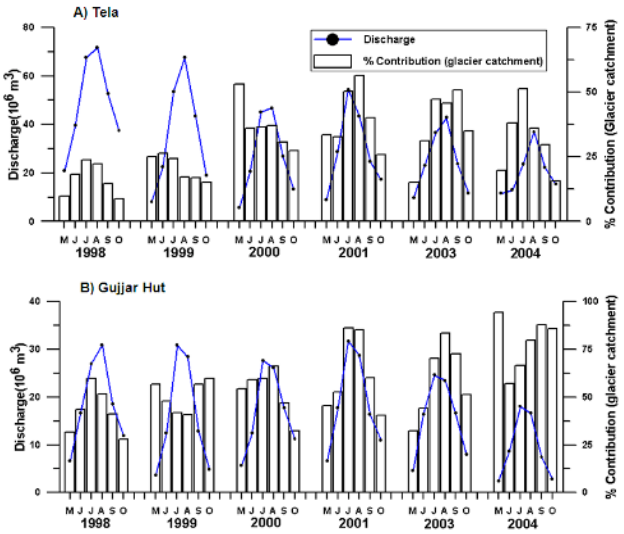

Fig. 8. Monthly variations in discharge and percentage contribution from the glacier catchment to the streamflow at **(A)** Tela and **(B)** Gujjar Hut stations.

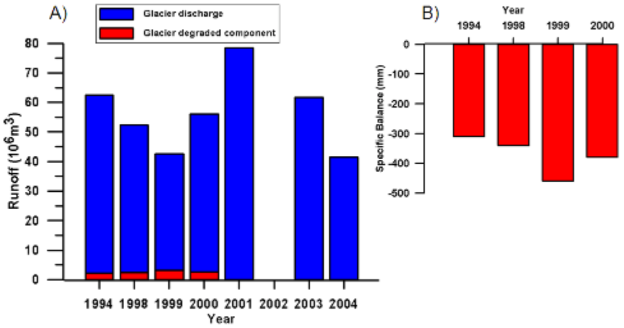

Fig. 9. **(A)** Ablation season discharge of Dokriani glacier and glacier degradation-derived runoff component, **(B)** enlarged graph of specific mass balance. Year 1994 and 1998 experienced high glacier discharge and low glacier degradation and year 1999 experienced one of the lowest summer runoff and highest negative glacier mass balance during the study period.

glacier mass balance. Similarly, 1994 and 1998 experienced higher glacier discharge in association with comparatively lesser glacier degradation (Fig. 9). Similar results were reported from other glaciers in the "Himalayan catchment" as well (Raina et al., 2008). The Geological Survey of India (GSI) studied glacier mass balance and glacier discharge at the Gara (1974–1981) and Shaune Garang glaciers (1983–1989) in the Satluj basin and the Tipra bank glacier (1982–1985 and 1989) in the Alaknanda (Ganga) basin for 5 to 7 years. The Gara and Shaune Garang glaciers even experienced a couple of years of positive mass balance during the study period. The relationship between glacier discharge and mass balance of these glaciers has also showed that the lowest glacier discharge is associated with higher negative mass balance and the occurrence of highest glacier discharge in association with more positive glacier mass balance (Fig. 10). Even though the data are available only for a limited number of years, they strongly suggest that the relationship between glacier discharge and mass balance for the Himalayan and Alpine glacier catchments may be different. Hock et al. (2005) summarised the present understanding of glacier discharge – mass balance relationship. They stated that the "total streamflow is reduced in years of positive glacier net balance, when water is withdrawn from the annual hydrological cycle and put into glacier storage. The opposite occurs in years of negative glacier mass balance since water is released from long-term glacier storage, thereby increasing streamflow". We believe that the relationship between glacier discharge and mass balance of four glaciers shown above could be a characteristic of the Himalayan glacier

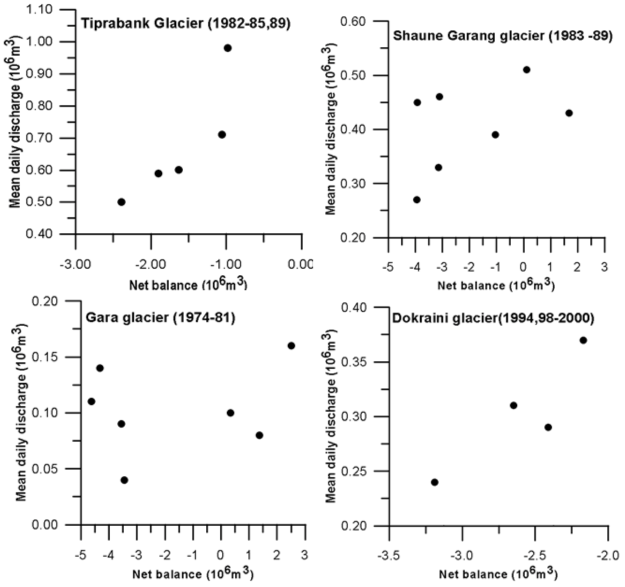

Fig. 10. Relationship between net mass balance and mean daily discharge of glaciers in the precipitation dominant Himalayan catchment. Tipra bank, Shaune Garang, Gara and Dokriani glaciers show higher glacier discharge during the years of more positive glacier mass balance (data source: Tiprabank, Shaune Garang and Gara glaciers, Raina et al., 2008).

catchments, which have lower percentage of glacier cover and precipitation dominance in the form of winter snowfall and summer monsoon. These glaciers lay deep in the valley and are surrounded by steep mountain slopes resulting in a lower percentage of glacierisation of the catchment. The glacier catchments discussed above have glacier cover ranging from 44.6% to 31.5% (Table 1). The Gangotri glacier catchment, encompassing the biggest glacier in the region also has only 51% glacier cover (Singh et al., 2008). This leaves out large non- glacierised area of these catchments, contributing snowmelt and monsoon rains directly to the glacier system which eventually emerges at the snout of the glacier. This is evident in the Dokriani glacier data as well. 1994 and 1998 experienced higher glacier discharge in association with higher precipitation and lower glacier mass balance. Whereas, 1999 experienced reduced glacier discharge due to lower precipitation in spite of receiving higher contribution from the glacier degradation-derived component. Hence, in a Himalayan catchment, precipitation plays a more dominant role than glacier degradation-derived component in determining the glacier runoff volume and its inter-annual variations. Raina et al. (2008) also indicated that any reduction in the glacier melt during the positive balance year is more than compensated by the precipitation in the glacier catchment. With the precipitation and basin characteristics discussed above, the warming induced initial increase and subsequent decline of glacier runoff (IPCC, 2001; IPCC, 2007a, b) would remain as a response of glacier degradation-derived runoff component (UNESCO, 1996) in a Himalayan catchment. The relationship between glacier mass balance and glacier discharge of four glaciers discussed above suggests that the enhanced melting of glaciers need not necessarily translate into higher glacier discharge and river runoff in a precipitation dominant Himalayan catchment as suggested by the IPCC reports. Based on a survey in 1995, the volume of fresh water locked up as ice in the Dokriani glacier is estimated to be 315×10^6 m^3 (Dobhal et al., 2004). Compared to this storage, average yearly summer runoff from the Dokriani glacier catchment is 55×10^6 m^3, which is about 17.5% of the total glacier storage. Whereas, the annual glacier degradation-derived component in the bulk flow, as derived by the mass balance measurements was about 1% of the glacier storage and an average of 5% of the bulk glacier discharge. This also shows the overwhelming role of precipitation in the runoff generation in a Himalayan glacier catchment.

4.4 Relationship between the monsoon, glacier response and river flow in a Himalayan catchment

Runoff variations of other nearby glacier-fed rivers in the recent past also buttress the point of view presented above. Runoff in the Satluj river at Bhakra in 2004 was 43% less than the 84-year normal and 50% less than the 1998 flow (Fig. 11). The decrease in the flow is much more than the 10% decline predicted under a 2 °C warming scenario for the same basin (Singh and Bengtsson, 2004). In a similar response, discharge of the Beas River at Pandoh Dam also diminished during the 1990–2004 period (Fig. 12). Discharge of Beas river in 2004 was 29% less than the 14-year normal and 44% less than the 1998 flow. A detailed assessment of discharge variations in these rivers has been carried out by Bhutiyani et al. (2008). Discharge variations in these rivers during 1998 to 2004 period were similar to the runoff response observed in the Din Gad catchment during the same period, suggesting a regional response of river flow to the prevailing climate of the region. A study of glaciers in the selected catchments within these basins and a nearby basin showed 21% deglaciation during the last four decades (Kulkarni et al., 2007), which clearly indicates that the observed flow variations in these rivers were precipitation dependent rather than glacier degradation dependent, as we have observed in the Din Gad catchment.

In a Himalayan catchment, glacier fluctuation and corresponding river flow response are considered to be intrinsically related to the strength of the monsoon. The growth of Himalayan glaciers is said to be linked to strong monsoons as these glaciers are suggested to be the monsoon accumulation type (Mayewski et al., 1980; Ageta and Higuchi, 1984; Benn and Owen, 1998). At the same time, a period of strong monsoon would invariably produce higher runoff in the glacier-fed streams. A study of runoff records of the

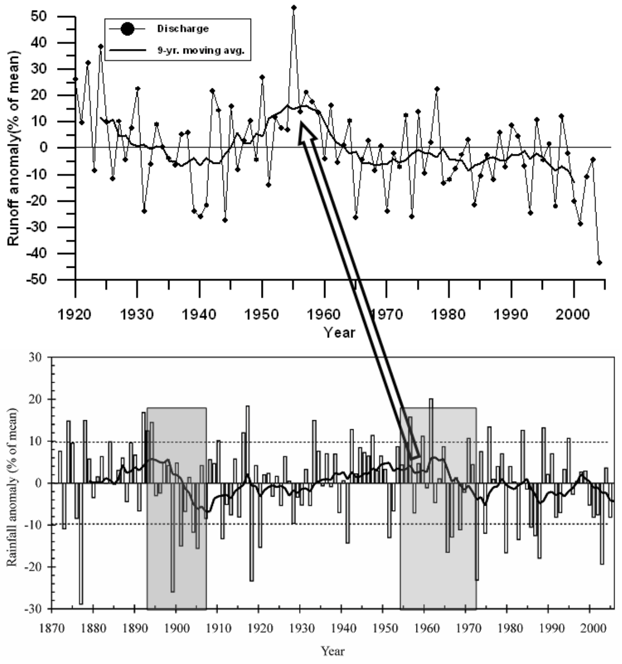

Fig. 11. **(a)** Discharge anomalies of River Satluj at Bhakra from 1920–2004 and **(b)** All-India summer monsoon rainfall anomalies from 1871–2004. Shaded bars show probable periods of lower recession/stationery/advancement of many glaciers in the Himalaya and Trans-Himalayan region. The period between 1945 and 1960 was experienced high discharge in association with strong monsoon. Since the 1970's widespread recession of glaciers are reported from the region, but with reduced runoff as compared to the 1950's (data source: Haryana Irrigation Department, 2001; Singh and Jain, 2002; www.bbmb.gov.in; Mall et al., 2006).

Satluj river along with all India summer monsoon anomalies (Mall et al., 2006) substantiates this unique river flow response to the glacier change in the Himalayan catchment (Fig. 11). An analysis of the runoff data for the Satluj river from 1920–2004 shows that the highest discharge in the river was observed during 1945–1965 in association with a period of strong monsoon. As a result, many glaciers in the Himalayan region probably experienced a positive mass balance regime and showed signs of advancement or reduced rate of recession or were stationary during the 1950's to early 1970's (Mayawski et al., 1980; Vohra, 1993; Sharma and Owen,1996; Bhattacharyya et al., 2001). Since the mid-1960's, runoff in the Satluj river has decreased compared to the discharge during the mid-1940's and 1950's. Concurrently, this period is also marked by widespread glacier recession in the region (Kulkarni et al., 2007; Thayyen et al., 2007b). The advancement of glaciers reported from the trans- Himalayan region during the 1890–1910 period is also attributed to the strong monsoon during the 1885–1900 period (Mayewski and Jeschke, 1979; Mayewski et al., 1980). This preliminary assessment proposes two important characteristics of the "Himalayan catchment": (1) it could experience higher river flows and positive glacier mass balance regime together in association with strong monsoon and reduced streamflow during the period of negative glacier mass balance. (2) The glacier melt component in the stream is highest during the years of low summer runoff.

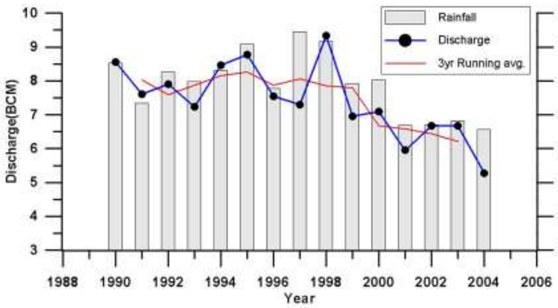

Fig. 12. Discharge (Pandoh) and rainfall variations in the Beas basin showing diminished runoff during the 1998–2004 periods (data source: Kumar et al., 2007).

Runoff variations at different spatial and temporal scales discussed above clearly suggest that the flow regimes of headwater glacier-fed rivers of "Himalayan catchments" are determined by the properties of synoptic-scale air masses crossing the mountains (Alford, 1985), rather than glacier degradation. IPCC (2007a) reported decreasing precipitation over land between 10° S and 30° N after the 1970's. Duan et al. (2006) suggested a negative correlation between the Asian summer monsoon and Northern Hemisphere temperature that lead to weak monsoons associated with warmer periods, and suggests that the long- term trend over the last century of monsoon over the northern Indian subcontinent, including the Himalaya is negative. Chase et al. (2003) also observed a consistent reduction in the intensity of all four tropical monsoon systems since the 1950's with no specific trend in monsoon intensity since 1979. Joseph and Simon (2005) suggested a weakening of the south-west monsoon since 1950's over peninsular India. In a study which is more pertinent to the Himalaya, Bhutiyani et al. (2009) observed a significant decreasing trend in monsoon precipitation in the northwestern Himalaya from 1866 to 2006 and a decreasing snow component in the winter precipitation. The snow cover variations are also equally important in determining runoff variations in the Himalayan catchment. However, long-term data of snow cover variations in the Himalaya are seldom available. The increase in winter temperature and the decrease in winter precipitation are the major changes observed in the Himalaya during the past decades (Pant et al., 2003). At a continental-scale, the Eurasian seasonal snow cover is found to be decreasing since 1979 (Groisman et al., 1994), and is accelerating in the recent past (Goes et al., 2005). Studies also revealed a significant rise in air temperature by about 1.6 °C in the northwest Himalayan region in the last century with winters warming at a faster rate (Bhutiyani et al., 2007). These observations suggest that, on a synoptic-scale, the northwestern region of the Himalaya is experiencing weak summer precipitation and changes in the characteristics of winter snow cover during the last three decades in association with rising temperature. The observed river flow variations and widespread recession of glaciers in the region reflect these climatic changes.

Our present understanding of river flow response to the cryospheric changes (IPCC, 2001; Barnett et al., 2005; Hock et al., 2005; IPCC, 2007a, b) is dominated by the knowledge generated from areas where glacier meltwater is released during the periods of otherwise low flow conditions. The decrease in the Northern Hemisphere snow cover (Armstrong and Brodzik, 2001; IPCC, 2007c) and world-wide recession of glaciers (Oerlemans, 2005; IPCC, 2007c) illustrate the global response of glaciers and snow cover to the changing climate. However, the river flow response to cryospheric changes is determined by the climate forcing on the regional hydrology, especially changes in precipitation characteristics. Therefore, there could be different streamflow responses to the cryospheric changes in different glacio – hydrologic regimes of the Himalaya. The suggested increase in river flow (IPCC, 2007a, b) from enhanced melting of glaciers may be possible for those hydrologic regimes, where cold-arid conditions and Alpine characteristics prevail. However, along the large tract of the "Himalayan catchment" east of the Chenab basin, where runoff from the precipitation is the primary flow component, the relationship between glacier response and changing precipitation characteristics of high mountain regions through the feedback mechanism (Meier, 1965) needs to be explored in more detail. Hence, a better understanding of the cryospheric system processes in each of these three distinct glacio-hydrological regimes of the Himalaya is imperative for evolving a reliable management and adaptive strategies for the region.

5 Conclusions

A "Himalayan catchment" is defined as a glacier catchment that experiences snowfall in winter and monsoon precipitation in summer with peak discharge from the glacier contributing to the crest of the annual streamflow hydrograph. The Himalayan catchment is one of the three distinct glacio-hydrologic regimes of the Himalaya. Winter snow dominated Alpine region and the cold-arid region of Ladakh range are the other two glacio-hydrological regimes identified in this study. A lack of long-term data on glacier mass balance and runoff in these glacio-hydrological regimes of the Himalaya remains a major constraint in bringing issues specific to this region into focus. This preliminary study suggests that the glacio-hydrological characteristics of the Alpine and the Himalayan catchment are significantly different. Hydrological characteristics of the precipitation dominant "Himalayan catchment" ensure that the highest runoff in a stream occur as a result of high precipitation and the glacier component in the stream discharge is highest during the years of low summer runoff. Hence under normal circumstances glacier melting would not lead to high discharge or floods in a "Himalayan catchment". Therefore, we suggest that the warming induced initial increase in discharge and the subsequent decline is a response limited to the glacier degradation- derived component of the runoff and need not necessarily translate as river flow response in precipitation dominant glacier systems as suggested by the IPCC (2001) and IPCC (2007a, b). The relative roles of the monsoons and western disturbances in the growth and decline of Himalayan glaciers are still in the realm of speculation (Benn and Owen, 1998). However, a period of glacier growth seems to be closely linked with a period of strong monsoon and higher streamflow in a "Himalayan catchment". Conversely, reduced streamflow could occur during the period of glacier shrinkage. Paucity of data and knowledge on the cryospheric systems processes across various glacio-hydrological regimes of the Himalaya remains to be the major impediment in formulating more representative global view on river flow response to cryospheric changes and locally sustainable water resources management strategies.

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