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Role of glaciers in watershed hydrology: "Himalayan catchment" perspective

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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 melt water contributes to the river flow during the period of annual high flows produced by the monsoon. Other two major glacio-hydrological regimes of the Himalaya are winter snow dominated Alpine catchments of the Kashmir and Karakoram region and cold-arid regions of the Ladakh mountain range. 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. Discharge data generated from three hydrometric stations established at different altitudes of the Din Gad stream during the summer ablation period of 1998, 1999, 2000, 2001, 2003 and 2004. These data has been analysed along with winter/summer precipitation, temperature and mass balance data of the Dokriani glacier to study the role of the glacier and precipitation in determining the runoff variations along the stream continuum from the glacier snout to 2360 m a.s.l. Study shows that the inter-annual runoff variations in a "Himalayan glacier catchment" is directly linked with the precipitation rather than mass balance changes of the glacier. Study suggest that warming induced initial increase of glacier degraded runoff and subsequent decline is a glaciers mass balance response and cannot be translated as river flow response in a "Himalayan catchment" as suggested by the IPCC, 2007. Study also suggest that the glacier runoff critically influence the headwater river flows during the years of low summer discharge and proposes that the Himalayan catchment could experience higher river flows and positive glacier mass balance regime together in association with strong monsoon. This paper intended to highlight the importance of creating credible knowledge on the Himalayan cryospheric processes to develop a global outlook on river flow response to cryospheric change and locally sustainable water resources management strategies.

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1 Introduction

The Himalaya has 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 melt water from around 4000 glaciers spread over India and Nepal and the 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 is very significant in many of these Himalayan Rivers. On an average, 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 Akhnoor (Singh et al., 1997) and 35% in Beas river at Pandoh (Kumar et al., 2007). The Himalayan cryospheric system, largest out side the polar region has number of hydrological and climatic regimes, extending from cold-arid regions of the Ladakh to humid monsoon climate of the north-eastern Himalayas (Mani, 1981). Glaciers in these regions are in a general state of recession since 1850's (Mayewski and Jeschke, 1979; Vohra, 1981; Dobhal et al., 2004; Kulkarni et al., 2007) with few exceptions in the Karakkoram 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. Present understanding regarding the impact of glacier shrinkage on the river flow variations is discussed in 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 "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. Himalayan region itself have 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, glacier's role in influencing the flow regimes of the Mountain Rivers across the Himalayan arc would vary considerably. In this work, an attempt has been made to highlight the fundamental difference between Alpine and Himalayan glacier hydrological systems and the role of glaciers in influencing the runoff characteristics of monsoon dominated "Himalayan catchment".

2 Methods

2.1 Study area

This study is focused on the "Himalayan catchments" of Western Himalayan region, mainly on the Din Gad catchment in the Ganga basin. Basin scale response of river flow during the past years has been studied in the near by Satluj and Beas basins which extent from 30° 48′ to 32° 26′ N and 76° 58′ to 78° 51′ E. Din Gad catchment cover an area of 77.8 km^2 and extent from 2360 to 6000 m a.s.l. and have 9.6% glacierisation. 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. Din Gad is the proglacial stream of the Dokriani glacier which joins Bhagirathi River near Bhukki village (Fig. 1). Length of the Dokriani glacier is 5.5 km and covers an area of 7 km^2. This glacier has receded 726 m in forty three 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). Average accumulation rate of this glaciers 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.

Satluj basin lay north-west of Ganga basin and the river flow down from China to India. Indian part of the Satluj basin covers an area of 22 275 km^2 and 12% of the area is covered by the glaciers and permanent snowfields and approximately 65%

area receives winter snowfall (Singh and Jain, 2002). Beas catchment shares its western boundary with Satluj basin and has an area of 5278 km^2 with 780 km^2 (14.7%) of glaciers and perennial snow cover.

2.2 Data collection

The main objective of glaciological studies in the Himalaya is to generate knowledge base for managing the large frozen water reserves of the glaciers and study the river flow response to glaciers and snow cover fluctuations (Thayyen et al., 2007). Following the Alpine format, glaciological studies were focused on the glacier mass balance, glacier discharge and monitoring of the meteorological parameters close to the glacier. The role of monsoon and snow cover has received little attention in the glaciological study frame work and over the years it is realized that the approach has failed in achieving the desired result of understanding the river flow response to the cryospheric changes. In order to 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. First discharge station was established at 600 m down stream of the glacier snout at 3800 m a.s.l. The second station at Gujjar Hut (3400 m a.s.l.) cover the snow dominated Alpine meadows and third station at Tela (2360 m a.s.l.) covered highly forested, monsoon dominated lower part of the catchment. These stations were monitored throughout the ablation season from 15 May to 31 October during 1998–2004 periods, with an exception in 2002. Discharge was calculated from rating curve established by the area-velocity method. For continuous recording of water level at these three stations, water level recorders were installed over the stilling wells made of steel drums. Manual observation of staff gauges were also carried out four times a day, with three hour interval to over come problems arising due to malfunction of chart recorder during high flow period of June, July and August months. Chart recording was disturbed many times during the study period due to high flows and other mechanical problems. Tela station was washed off during the high flows of July in 2001. By combining the manual records and the data from the chart recorder, daily discharge data has been calculated for the three stations.

Three manual standard meteorological observatories were established at Tela, Gujjar Hut and glacier Base camp and monitored through out the ablation period. Monitoring of winter weather was initiated at Base camp station in 1998 and observations were carried out intermittently due to extreme weather conditions. Winter weather monitoring was extended to the Tela station in the year 2000. Standing snow depth and density were monitored four times during December–April period at different altitude along the valley bottom from Gujjar Hut (3400 m) to the Base camp (3760 m a.s.l.). Snow depth and density measurements were extended up to 4700 m a.s.l. over the glacier once or twice during April or early May to monitor the snow cover duration. Snow line was mapped physically every year in early May, before initiating discharge measurement at Gujjar Hut and snout stations. Summer mass balance of the Dokriani glacier was estimated till 2000 to assess the degraded runoff component (Dobhal et al., 2008).

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. Long-term discharge data of river Satluj, and 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 corresponding river flow response of the Himalayan catchment.

3 Hydrology of the Himalayan glacier catchments

Himalaya 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 S-W monsoon decline in strength from east to west along the Himalayan arc, western disturbances weakens as it move from west to east (Gupta, 1983). Hydrology of the glaciers and glacier fed rivers, east of 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 Ganga and few tributaries of River Indus and Brahmaputra. Winter snow precipitations from western disturbances dominate large areas of 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 Indian Himlaya is the cold-arid regions of the Ladakh, which extend from Tibet to India. In this area, glaciers and permafrost melting is the major source of water sustaining the stream flow and water requirement of the population.

Each of these major glacio-hydrological regimes of the Himalaya is characterized 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 contributing to other wise low flow conditions, governed by lower precipitation in summer (Fig. 3a). Where as the Himalayan glacier hydrological system is characterized by the peak glacier runoff contributing to the peak river flow from monsoon rainfall in July and August months. (Fig. 3b). In the cold-arid regions of the Ladakh, annual discharge peak occur in the month of July and August (Fig. 3c), mainly due to higher glacier melting during the period. Precipitation in the region is also highest during the same period, but mean annual precipitation is as low as 115 mm (Gupta, 1983), in which 73% occur during the summer months. The distribution characteristics of precipitation in these three major glacio-hydrological regimes of the Himalaya are shown in the 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 relative importance of the glacier, snow and precipitation in each of these glacio-hydrological regimes. Peak discharge of headwater streams in the "Himalayan catchments" comprises of monsoon rains, snow and glacier melts. Monsoon rains dominates the regional hydrology during July to mid September and snowfall from western disturbances dominate winter months (NDJFMA). Consequently, December to March records lowest flows in these rivers and peak runoff occur in the month of July and August. These two months experiences highest monsoon rains and highest solar insolation and temperature, which translate into highest glacier discharge. Hence headwater river hydrology of a Himalayan catchment is collectively influenced by the variations in monsoon, snow and glacier regimes. This fundamental difference between Alpine and Himalayan glacier hydrological systems is often over looked, while accessing the glaciers role 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 Hindu Khush-Himalaya and 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 southern slopes of the Himalaya, which include part of the Indus basin (Beas, Satluj & Ravi) and whole of the Ganga basin and few tributaries of the River Brahmaputra in the eastern Himalaya, experiences monsoon rains in summer and glacier melt is only an add on component of 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. Compared to this, very large area of the mountain above 2000 m a.s.l. experiences seasonal snow cover. Monsoon and western disturbances spread across the region with varying degree of influence. Hence, flow regimes of Himalayan Rivers are highly influenced by the altitudinal distribution of the precipitation. Western disturbance are upper air cyclonic systems operating around 500 hPa level and shows positive precipitation gradient as altitude rises due to orographic capture and deposit large amount of snow in the higher altitudes of the glacier basins (Bhutiyani, 1999; Singh and Kumar, 1997; Upadyaya, 1995). Low pressure troughs of the westerlies start dominating the northern most part of the Himalaya in November and early December and have most southerly course in February and March resulting in heavy snowfall in the Himalaya during this period, which sometime continue till April (Gupta, 1983). Where as the monsoon systems operates around 850 hPa level (Goswami et al., 2003) and encounter Himalayas at lower elevations and undergo orographic upliftment. Therefore, highest precipitation from monsoon over the Himalayas occurs at an altitude of 1000 to 3500 m a.s.l. (Gupta, 1983; Upadhyay, 1995; Singh and Kumar, 1997; Burbank et al., 2003). Strength of the monsoon rainfall declines above this altitude and the glaciers in these regions receive lesser monsoon rainfall as compared to the lower altitudes of the mountain. Monsoon winds reach the Himalayan foot hills by later half of June and persists till mid September (Gupta, 1983) with July and August months experiencing 80% of the monsoon precipitation.

4 Results and discussion

4.1 Variations in runoff and weather parameters

Din Gad catchment experienced varied patterns of precipitation during the seven-year study period. Heavy winter precipitation and summer monsoon in 1997–1998 and low winter and summer monsoon precipitation in 1998–1999 and 2003–2004 were the extremes. This situation provided a very good opportunity to study the role of glaciers in the head water stream flow variations of a Himalayan catchment. Summer ablation season (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 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). Glacier runoff fluctuated during these years, varying from 52×10^6 m^3 in 1998 to a highest discharge of 78×10^6 m^3 in 2001 and lowest (42×10^6 m^3) in 2004. Lowest discharge in all the three stations were recorded in the same year, while highest discharge observed at 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 to 5.17×10^6 m^3 during 1994–2000 periods (Dobhal et al., 2007), which constituted 7.7 to 12.7% of the bulk glacier runoff. After considering the net accumulation ranging from 2.23×10^6 to 2.66×10^6 m^3, component of glacial degraded runoff in the bulk glacier discharge varied between 3.5–7.5%. On an average, monsoon rainfall component in the glacier discharge is in the range of 10–26% (Thayyen et al., 2005).

Din Gad catchment experiences good rainfall during the ablation period from May to October. 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 snow water equivalent 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. Distribution characteristics of winter and summer precipitation in the catchment, especially in the higher reaches are not fully understood from the present data. Therefore, assessment of snow and rainfall components in the stream flow has not attempted in this study. Highest snow cover duration at the Base camp was recorded in 1997–1998 (153 days) and in 2000–2001 (128 days). On the other extreme, lowest snow cover duration during the study period experienced in 1998–1999 (68 days) and 2003–2004 (75 days). In 1998, snow cover in the first week of May was extended up to Gujjar Hut station covering 46% of the Din Gad catchment. Lowest snow cover area in May was recorded in 1999 and 2004, amounts to 14 and 18%, respectively.

Temperature is another important parameter influencing the runoff regimes of snow/glacier catchments. July and August are the hottest 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 Base camp (3763 m a.s.l.) summer positive degree days (PDD) (15 May–31 October) were calculated to study the yearly temperature variations of the ablation months. Year 1998 experienced highest summer temperature (PDD, 1691) followed by the year 2003 (PDD, 1575) and 2004 (PDD, 1518) and lowest temperature was in the year 2000 (PDD, 1296). Among the different hydrological variables discussed above, winter precipitation experienced largest inter-annual variation as reflected in the yearly variations in the snow water equivalent; snow cover duration and snow cover extent. Summer precipitation and temperature was highest in 1998 and during the rest of the observation years both parameters fluctuated nominally.

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

Figure 6 explains the role of glaciers and precipitation in controlling the river flow variations in a Himalayan catchment. While discharge at Tela and Gujjar Hut stations were reduced by 58 and 50 percentage, respectively from 1998 to 2004, discharge from the glacier catchment showed comparatively steadied response. Analysis of specific runoff from each sub-catchment showed that the contributions from Tela catchment (41.8 km^2) reduced from 25 mm/day in 1998 to 9 mm/day in 2004 (Table 1). Similarly, runoff contributions from the Gujjar Hut sub-catchment (20.3 km^2) reduced from 18 mm/day to 4 mm/day during the same period, whereas runoff from the glacier catchment (15.7 km^2) varied between 29 to 15 mm/day. 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 the precipitation. The lowest specific runoff of 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 the 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 of 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 equal or even exceeds that of the glacier catchment during the years of good precipitation. This clearly shows the overwhelming influence of precipitation, both winter snowfall and summer monsoon, in determining the runoff variations in a Himalayan glacier catchment.

Monthly discharge flux and percentage runoff contribution from the glacier catchment to Tela and Gujjar hut stations were shown in the Fig. 8a and b. During the peak runoff period of July and August months, contribution from the glacier catchment to Gujjar hut station ranged from 41 to 86%. At the same time contribution from the glacier catchment to Tela station ranged from 17 to 56%. During 1998 ablation period, bulk glacier discharge in the runoff at Gujjar hut and Tela stations were 47 and 18%, respectively. Where as in 2004 runoff from the glacier catchment constituted 74 and 34%, respectively. This shows that the discharge component of the glacier catchment in the bulk discharge at the lower most station at Tela (2360 m a.s.l.) has nearly doubled during the study period (Fig. 6). It is clear from the results presented above that the reason behind such a response is 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 “Himalayan catchment” during the years of lowest summer runoff. Extending this response further down stream, Alford (1992) suggested that the Himalayan component is highest in the Ganges during the years of minimum discharges. Two important conclusions emerge from the discussion above 1. Highest runoff in a glacier fed stream of “Himalayan catchment” is always occurs as a result of high precipitation. This implies that the melting of glaciers is not responsible for high discharge in a glacier fed stream in a Himalayan catchment (except that of Glacier Lake Outburst Flood) and 2. Glacier melt component in the stream is highest during the years of low summer runoff in a “Himalayan catchment”.

4.3 Glacier discharge variations and role of glacier degraded component

Domination of the 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 shows that the year 1999 experienced one of the lowest runoff from the glacier associated with highest glacier degradation (Fig. 9). Similarly, 1994 and 1998 experienced higher glacier discharge in association with comparatively lesser glacier degradation. We believe that this kind of response is specific to "Himalayan catchment" due to its hypsometric characteristics. Himalayan glaciers lay deep into the valley and surrounded by imposing mountain slopes resulting into a lower percentage of glacierisation of the catchment. In the Dokriani glacier catchment, percentage glacierisation is 44.6% (Thayyen et al., 2005). Gangotri glacier catchment, the biggest glacier of the region also has only 51% of glacierisation (Singh et al., 2008). This leaves out large non-glacierised areas of these catchments, contributing snow melt and monsoon rains directly to the glacier system which eventually emerges at the snout of the glacier. Hence, the bulk runoff measured at the glacier snout consist of runoff contribution from large area dominated by the snowmelt and monsoon precipitation and play a dominant role in determining the glacier runoff volume and its variations. This explains the higher discharge from Dokriani glacier in 1994 and 1998, reflecting the higher winter/summer precipitation and lower discharge in 1999 and 2004 reflecting the lower precipitation during these years. Under these precipitation and basin characteristics of the Himalayan catchment discussed above, warming induced initial increase and subsequent decline of glacier runoff (IPCC, 2001, 2007a, b) is strictly remains as a glacier mass balance response (UNESCO, 1996). Relationship between glacier degraded runoff and discharge variations from Din Gad catchment suggests that the increased glacier degradation need not necessarily translate into higher glacier discharge and river flow in a Himalayan catchment as suggested by the IPCC reports. Based on a survey in 1995, volume of fresh water locked up as glacier 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 Dokriani glacier catchment is 55×10^6 m^3, which is about 17.5% of the total glacier storage. Where as, annual glacier degraded component in the bulk flow, as derived by the mass balance measurements was about 1% of the glacier storage. This shows the overwhelming role of the precipitation in the runoff generation in a "Himalayan catchment".

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

Runoff variations of other near by glacier fed rivers in the recent past also espouse 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. 10). The decrease in the flow is much more than 10% decline predicted under 2°C warning scenario for the same basin (Singh and Bengtsson, 2004). In a similar response, discharge of Beas River at Pandoh Dam also reduced during 1990–2004 period (Fig. 11). Discharge of Beas River in 2004 was 29% less than the 14 year normal and 44% less than the 1998 flow. Discharge variations in these rivers during 1998 to 2004 period was 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. Study of glaciers in the selected catchment within these basins and a nearby basin showed 21% degradation of glaciers during 1962–2001/2004 period (Kulkarni et al., 2005, 2007), which clearly indicate that the observed flow variation in these rivers were precipitation dependant rather than glacier degradation, 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. Growth of Himalayan glaciers are said to be linked with strong monsoon as these glaciers are suggested to be monsoon accumulation type. (Mayewski et al., 1980; Ageta and Higuchi, 1984; Benn and Owen, 1998). At the same time, period of strong monsoon would invariably produce higher runoff in the glacier fed streams. Study of runoff records of the Satluj River along with all India summer monsoon anomalies (Mall et al., 2006) substantiate this unique river flow response to the glacier change in the Himalayan catchment (Fig. 10). Analysis of runoff data of Satluj river from 1920–2004 show that the highest discharge in the river observed during 1945–1965 period in association with a period of strong monsoon. As a result, many glaciers in the Himalayan region probably experienced positive mass balance regime and showed signs of advancement or reduced rate of recession or were stationery during 1950's to early 70's (Mayawski et al., 1980; Vohra, 1993; Sharma and Owen, 1996). Since mid 1960's, runoff in the Satluj river has been reduced as compared to the discharge during mid 1940's and 50's. Concurrently, this period is also marked by widespread glacier recession in the region (Kulkarni et al., 2007; Thayyen et al., 2007b). Advancement of glaciers reported from the trans-Himalayan region during 1890–1910 period is also attributed to the strong monsoon during 1885–1900 period (Mayewski and Jeschke, 1979; Mayewski et al., 1980).

Runoff variations in different spatial and temporal scales discussed above clearly suggests that the flow regimes of headwater glacier fed rivers of "Himalayan catchments" are determined by the properties of synoptic scale air mass 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 Asian summer monsoon and Northern Hemisphere temperature leading to weak monsoon associated with warmer periods and suggests that long term trend over the last centaury of monsoon over northern Indian subcontinent, including Himalayas is negative. Chase et al. (2003) also observed consistent reduction in the intensity of all four tropical monsoon systems since 1950's with no specific trend in monsoon intensity since 1979. Joseph and Simon (2005) also suggested weakening of south-west monsoon since 1950's in the peninsular India. Snow cover variations are also equally important in determining the runoff variations in the Himalayan catchment. However, long term data of snow cover variations in the Himalaya is seldom available. Increase in the winter temperature and decrease in the winter precipitation is the major changes observed in the Himalayas during the past decades (Pant et al., 2003). In a continental scale, Eurasian seasonal snow cover is found to be decreasing since 1979 (Groisman et al., 1994), which is accelerated during the recent past (Goes et al., 2005). These observations suggest that, on a synoptic scale, Himalayan region is experiencing weak winter and summer precipitation during the last three decades. River flow variations and widespread recession of glaciers observed during this period may be linked with the changes observed in the precipitation regime.

Present understanding of river flow response to cryospheric changes (IPCC, 2001, 2007a, b; Barnet et al., 2005) is dominated by the knowledge generated from the areas, where glacier melt water is released during the periods of otherwise low flow conditions. 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, river flow response to the cryospheric changes is determined by the climate forcing on the regional hydrology, especially the changes in the precipitation characteristics. Therefore, there could be different stream flow responses to the cryospheric changes in different glacio-hydrologic regimes of the Himalaya. The suggested increase in the river flow (IPCC, 2007a, b) from enhanced melting of glacier may be possible for those hydrologic regimes, where cold-arid conditions and Alpine characteristics prevails. However, along the large tract of the "Himalayan catchment" east of the Chenab basin, where runoff from the precipitation is the primary flow component, glaciers role in determining the precipitation characteristics of high mountain regions through the feedback mechanism (Meier, 1965) needs to be explored in great detail. Hence, better understanding of the cryospheric system processes in each of the three distinct glacio-hydrological regimes of the Himalaya is imperative for evolving a better management and adaptive strategies for the region.

5 Conclusions

"Himalayan catchment" is defined as glacier catchments experiencing snowfall in winter and monsoon precipitation in summer with peak discharge from the glacier contributing to the crest of the annual stream flow hydrograph. Himalayan catchment is one of the three distinct glacio-hydrologic regimes of the Himalaya. Other two are the winter snow dominated Alpine catchment and cold-arid region of the Ladakh. This study suggests that the hydrological characteristics of Alpine and Himalayan catchment are significantly different. Hydrological characteristics of the "Himalayan catchment" ensure that the highest runoff in a stream always occur as a result of high precipitation and 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 suggests that the warming induced initial increase in discharge and subsequent decline is a response limited to the glacier degraded component of runoff and not necessarily translated as river flow response in all glacio-hydrological regimes as suggested by the IPCC (2001) and IPCC (2007a, b). Role of monsoon and western disturbances in the growth and decline of Himalayan glaciers are still in the realm of speculation (Benn and Owen, 1998). However, period of glacier growth seems to be closely linked with period of strong monsoon and higher stream flow in a "Himalayan catchment". 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 a globally valid river flow response to cryospheric changes and locally sustainable water resources management strategies.

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References

Ageta, Y. and Higuchi, K.: Estimation of Mass Balance components of a summer-accumulation type glacier in the Nepal Himalaya, Geogr. Ann. A., 66A(3), 249–255,1984.

Alford, D.: Hydrological aspects of the Himalayan region, ICIMOD occasional paper No. 18, Katmandu, 1992.

Alford, D.: Mountain hydrological systems. Mt. Res. Dev., 5(4), 349–363,1985.

Armstrong, R. L. and Brodzik, M. J.: Recent Northern Hemisphere Snow Extent: a Comparison of data derived from visible and Microwave Satellite Sensors, Geophys. Res. Lett., 28(19), 3673–3676, 2001.

Barnett, T. P., Adam, J. C., and Lettenmaier, D. P.: Potential impacts of a warming climate on water availability in snow-dominated regions, Nature, 438, 17303–17309, 2005.

Benn, D. I. and Owen, L. A.: The role of Indian summer monsoon and the mid-latitude westerlies in Himalayan glaciation-review and speculative discussion, J. Geol. Soc. Lond., 155, 353–363, 1998.

Bhutiyani, M. R.: Mass-balance studies on Siachen Glacier in the Nubra valley, Karakoram Himalaya, India, J. Glaciol., 45(149), 112–118, 1999.

Burbank, D. W., Blythe, A. E., Putkonen, J., Pratt-Sitaula, B., Gabet, E., Oskin, M., Barros, T., and Ojha, P.: Decoupling of erosion and precipitation in the Himalayas, Nature, 426, 652–655, 2003.

Chase, T. N., Knaff, J. A., Pielke Sr., R. A., and Kalnay, E.: Changes in global circulations since 1950, Nat. Hazards, 29, 229–254, 2003.

Dobhal, D. P., Gergan, J. T., and Thayyen, R. J.: Mass balance studies of Dokriani Glacier from 1992 to 2000, Garhwal Himalaya, India, Bull. Glaciol. Res., 25, 9–17, 2008.

Dobhal, D. P., Gergan, J. T., and Thayyen, R. J.: Recession and morphogeometrical changes of Dokhriani glacier (1962–1995), Gharwal Himalaya, India, Curr. Sci. India, 86(5), 692–696, 2004.

Dobhal, D. P., Gergan, J. T., and Thayyen, R. J.: Mass balance and Snout Recession measurements (1991–2000) of Dokriani glacier, Garhwal Himalaya, India. Climatic and Anthropogenic impacts on the variability of the water resources, Tech. Doc. Hydrol., 80, IHP-IV, UNESCO, 53–63, 2007.

Duan, K., Yao, T. and Thompson, L. G.: Response of monsoon precipitation in the Himalayas to global warming, J. Geophy. Res. Earth, 111, D19110, doi:10.1029/2006JD007084, 2006.

Goes, J. I., Thoppil, P. G., Gomes, H. R., and Fasullo, J. T.: Warming of the Eurasian Landmass is making the Arabian Sea more productive, Science, 38, 545–547, 2005.
Goswami, B. N., Ajayamohan, R. S., Xavier, P. K., and Sengupta, D.: Clustering of synoptic activity by Indian summer monsoon intraseasonal oscillations, Geophy. Res. Lett., 30(8), 1431, doi:10.1029/2002GL016734, 2003.
Groisman, P. Y., Karl, T. R., Knight, R. W., and Stenchikov, G. L.: Changes of snow cover, temperature and radiative heat balances over the Northern Hemisphere, J. Climate, 7, 1633–1656, 1994.
Gupta, R. K.: The Living Himalaya (vol. 1): Aspects of Environment and Resource Ecology of Garhwal, Today and Tomorrows Printers and Publishers, New Delhi, 1983.
Haryana Irrigation Department: Development of Haryana State Water Plan – Final Report. Haryana Irrigation Department, Government of Haryana, 2001.
Hewitt, K.: The Karakoram anomaly? Glacier expansion and the "Elevation effect" Karakoram Himalaya, Mt. Res. Dev., 25, 332–340, 2005.
ICIMOD: Inventory of Glaciers, glacial Lakes and Glacial Lake outburst Floods, monitoring and early warning system in the Hindu Kush-Himalayan region, Nepal,(UNEP/RC-AP)/ICIMOD, Kathmandu, 2001.
IPCC: Climate Change; Impacts, Adaptation and Vulnerability, edited by: McCarthy, J. J. and Canziani, O. F., Cambridge University Press, Cambridge, UK, 2001.
IPCC, Kundzewicz, Z. W., Mata, L. J., Arnell, N. W., Döll, P., Kabat, P., Jiménez, B., Miller, K. A., Oki, T., Sen, Z., and Shiklomanov, I. A.: Freshwater Resources and their Management, in: Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Parry, M. L., Canziani, O. F., Palutikof, J. P., van der Linden, P. J., and Hanson,C. E., Cambridge University Press, Cambridge, UK, 173–210, 2007a.
IPCC, Rosenzweig, C., Casassa, G., Karoly, D. J., Imeson, A., Liu, C., Menzel, A., Rawlins, S., Root, T. L., Seguin, B., Tryjanowski, P.: Assessment of Observed Changes and Responses in Natural and Managed Systems, in: Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Parry, M. L., Canziani, O. F., Palutikof, J. P., van der Linden, P. J., and Hanson, C. E., Cambridge University Press, Cambridge, UK, 79–131, 2007b.
IPCC, Lemke, P., Ren, J., Alley, R. B., Allison, I., Carrasco, J., Flato, G., Fujii, Y., Kaser, G.,

Mote, P., Thomas, R. H., and Zhang, T.: Observations: Changes in Snow, Ice and Frozen Ground, in: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L., Cambridge University Press, Cambridge, UK and New York, NY, USA, 2007c.

Joseph, P. V. and Simon, A.: Weakening trend of the southwest monsoon current through peninsular India from 1950 to the present, Curr. Sci. India, 89(4), 687–694, 2005.

Kaul, M. K.: Inventory of Himalayan Glaciers. Sp. Pub. No. 34, Geological Survey of India, 1999.

Kulkarni, A. V., Rathore, B. P., Mahajan, S., and Mathur, P.: Alarming retreat of Parbati glacier, Beas basin, Himachal Predesh, Curr. Sci. India, 88(11), 1844–1850, 2005.

Kulkarni, A. V., Bahuguna, I., M., Rathore, B. P., Singh, S. K., Randhawa, S. S, Sood, R. K., and Dhar, S.: Glacial retreat in Himalaya using Indian remote sensing satellite data, Curr. Sci. India, 92(1), 69–74, 2007.

Kumar, V., Singh, P., and Singh, V.: Snow and glacier melt contribution in the Beas River at Pandoh Dam, Himachal Pradesh, India Hydrolog. Sci. J., 52(2), 376–388, 2007.

Lang, T. J. and Barros, A. P.: Winter storms in Central Himalayas, J. Met. Soc. Jpn., 82(3), 829–844, 2004.

Mall, R. K., Gupta, A., Singh, R., Singh, R. S., and Rathore, L. S.: Water resources and climate change: an Indian perspective, Curr. Sci. India, 90(12), 1610–1625, 2006.

Mani, A.: The climate of the Himalaya, in: The Himalaya – Aspects of change, edited by: Lall, J. S. and Moddie, A. D., Oxford University press, Delhi, 3–15, 1981.

Mayewski, P. A. and Jeschke, P. A.: Himalayan and Trans-Himalayan glacier fluctuations since AD 1812, Arctic Alpine Res., 11(3), 267–287, 1979.

Mayewski, P. A., Pregent, G. P., Jeschke, P. A., and Ahmed, N.: Himalayan and Trans-Himalayan glacier fluctuation and the south asian monsoon record, Arctic Alpine Res., 12(2), 171–182, 1980.

Meier, M. F.: Glaciers and Climate, in: The Quaternary of the United States, edited by: Wright, H. E. and Frey, D. G., Princeton University Press, New Jersey, 795–805, 1965.

Nijampurkar, V., Rao, K., Sarin, M., and Gergan, J. T.: Isotopic study on Dokriani Bamak glacier, central Himalaya: implications for climatic changes and ice dynamics, J. Glaciol., 48, 81–86, 2002.

Oerlemans, J.: Extracting a climate signal from 169 glacier records, Science, 308, 675–677, doi:10.1126/science.1107046, 2005.
Pant, G. B., Borgaonkar, H. P., and Rupakumar, K.: Climate variability over the western Himalaya since the little ice age: dendroclimatic implications, Hydrol. Rev. (INCOH), 18(1–2),111–120, 2003.
Rai, S. C. and Grung, A.: Raising awareness of the impacts of climate changes, Mt. Res. Dev., 25(4), 316–320, 2005.
Sharma, M. C. and Owen, L. A.: Quaternary glacial history of NW Garhwal, Central Himalayas, Quaternary Sci. Rev., 15, 335–365, 1996.
Singh, P. and Jain, S.,K.: Snow and glacier melt in the Satluj River at Bakhra Dam in the Western Himalayan region, Hydrolog. Sci. J., 47, 93–106, 2002.
Singh, P. and Bengtsson, L.: Hydrological sensitivity of a large Himalayan basin to climate change, Hydrol. Process., 18, 2363–2385, 2004.
Singh, P. and Kumar, N.: Effect of orography on precipitation in the western Himalayan region, J. Hydrol., 199, 183–206, 1997.
Singh, P., Haritashya, U. K., and Kumar, N.: Modelling and estimation of different components of stream flow for Gangotri basin, Himalayas, Hydrolog. Sci. J., 53(2), 309–322, 2008.
Singh, P., Jain, S. K., and Kumar, N.: Estimation of snow and glacier contribution to the Chenab River, Western Himalaya, Mt. Res. Dev., 17(1), 49–55, 1997.
Thayyen, R. J., Gergan, J. T., and Dobhal, D. P.: Monsoonal control on glacier discharge and hydrograph characteristics. A case study of Dokriani glacier, Garhwal Himalaya, India, J. Hydrol., 36(1–4), 37–49, 2005.
Thayyen, R. J., Gergan, J. T., and Dobhal, D. P.: Role of glaciers and snow cover on headwater river hydrology in monsoon regime – micro scale study of Din Gad catchment (Dokriani Glacier), Garhwal Himalaya, India, Curr. Sci. India, 92(3), 376–382, 2007.
Thayyen, R. J., Goel, M. K., and Kumar, N.: Change estimation of selected western Himalayan glaciers, National Inst. of Hydrol., WHRC, Jammu, 2007.
UNESCO: Variations of snow and ice in the past and at present on a global and regional scale, edited by: Kotlyakov, V. M., IHP-IV Project H4.1, Paris, 1996.
Upadhyay, D. S.: Cold Climate Hydrometeorology, New Age International Publishers, New Delhi, 1995.
Vohra, C. P.: Himalayan Glaciers, in: The Himalaya: Aspects of change, edited by: Lall, J. S. and Moddie, A. D., Oxford University press, Delhi, 138–151, 1981.

Vohra, C. P.: Himalayan Glaciers, in: Harnessing the Eastern Himalayan Rivers, Regional Cooperation in South Asia, edited by: Verghese, B. G. and Ramaswamy, R. I., Konark Publishers, New Delhi, 59–69, 1993.

Table 1. Observed variations in the specific mean daily discharge (mm d^{-1}) of each sub-catchment during the summer period (M_{15}-O_{30}). Runoff variations in the Tela and Gujjar Hut sub-catchments are precipitation depended and higher than the variations of the glacier catchment, illustrating the buffering role of glaciers in a Himalayan catchment.

Year	Tela (41.8 km^2) (2360–3400 m a.s.l.)	Gujjar Hut (20.3 km^2) (3400–3800 m a.s.l.)	Glacier (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*

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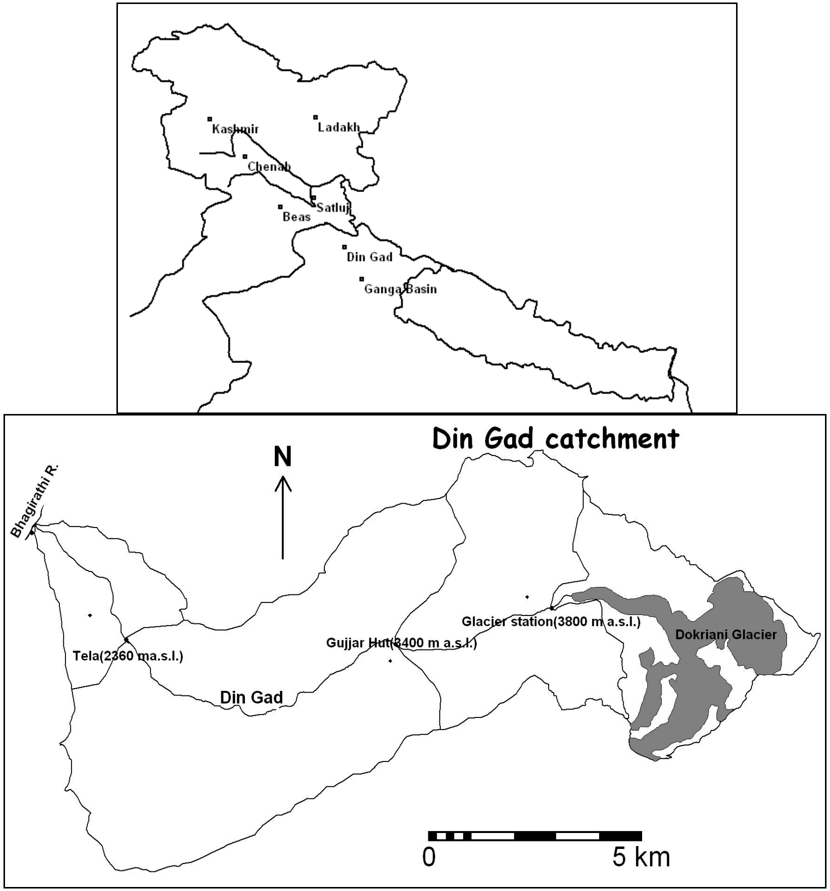

Fig. 1. Study area showing the sub-catchments and location of hydro-meteorological stations in the Din Gad catchment.

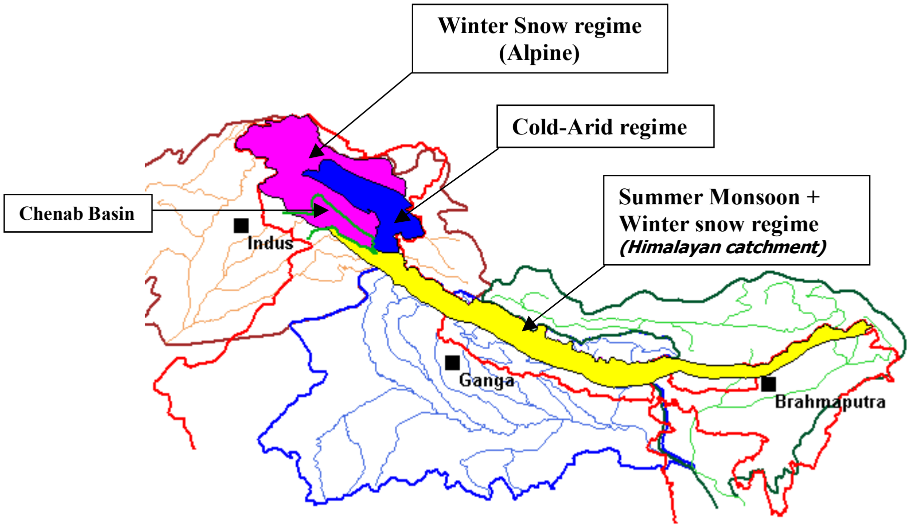

Fig. 2. Glacio-hydrological regimes of the Himalaya.

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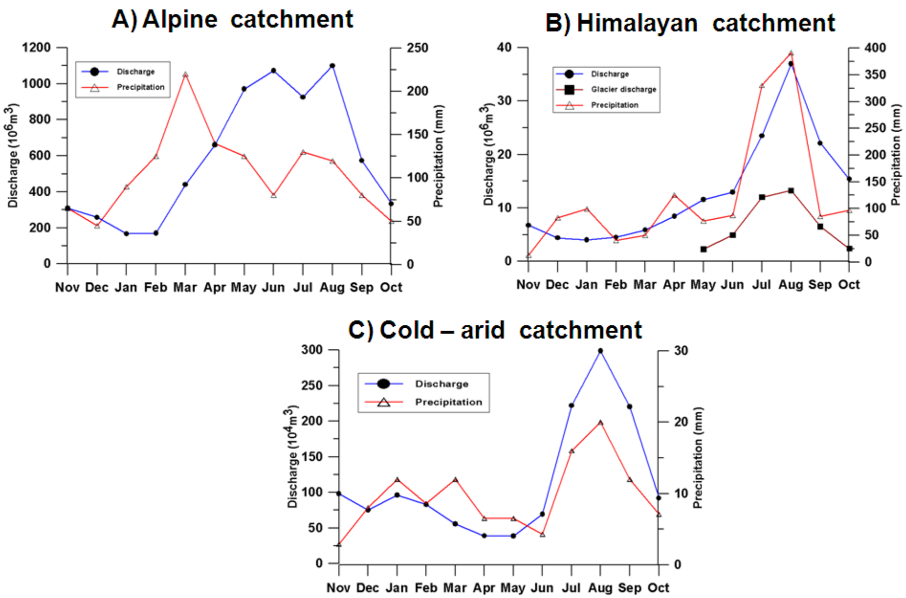

Fig. 3. Temporal distribution of runoff and precipitation in glacio-hydrological systems of the Himalaya in a mountain water year, showing characteristically different distribution pattern **(A)** Snow dominant Alpine system, Lidder valley, Kashmir **(B)** Monsoon dominant Himalayan system, Din Gad catchment, Ganga basin and **(C)** Cold-arid system, Ganglass catchment, Ladakh range.

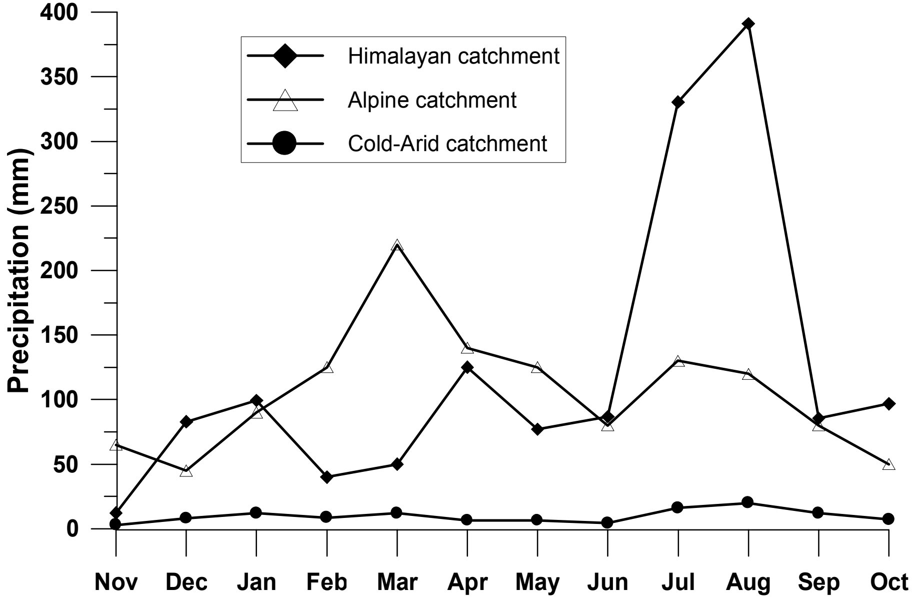

Fig. 4. Figure showing comparative temporal distribution of precipitation amount in the three glacio-hydrologic regimes of the Himalaya.

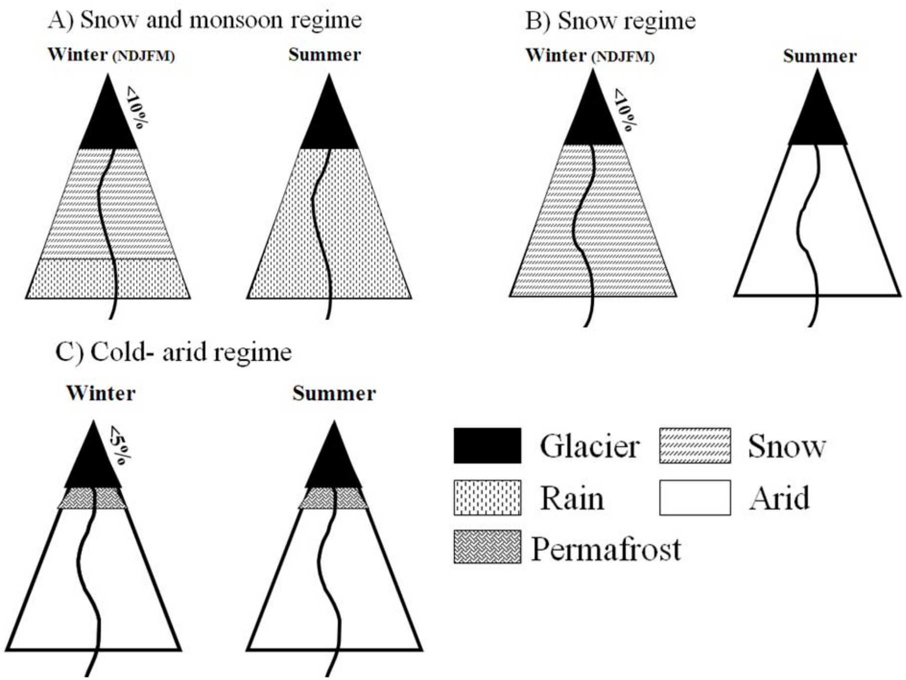

Fig. 5. Schematic diagram showing different glacio-hydrological systems of the Himalaya and altitudinal distribution of summer and winter precipitation. Hypothesis proposed suggests varying river flow response to the cryospheric/climatic changes. **(A)** River flow changes are governed by the variations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

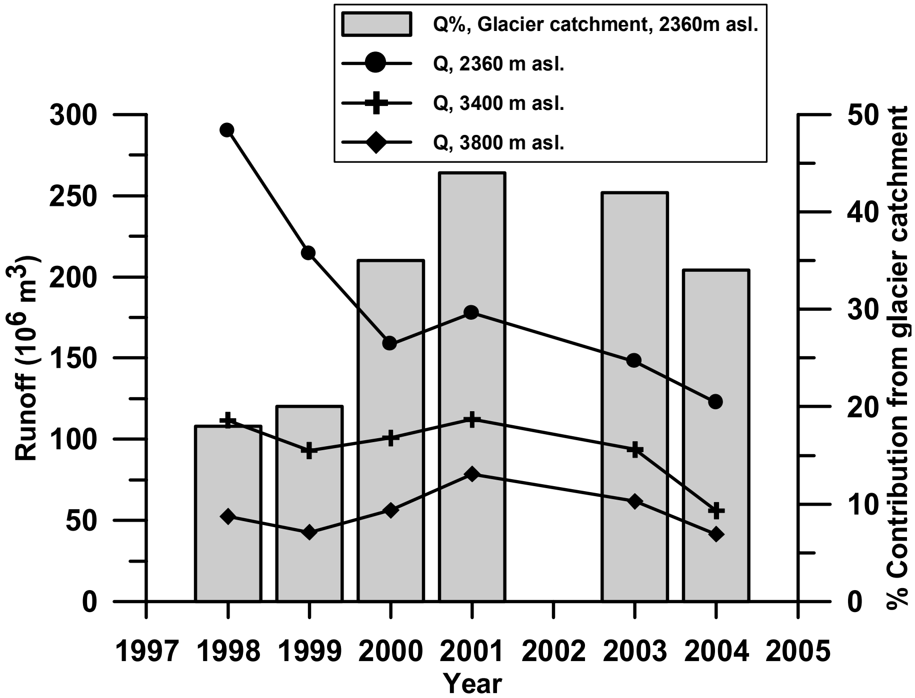

Fig. 6. Stream discharge variations observed at three elevations of the Din Gad catchment and corresponding variations in the contribution from the glacier catchment at 2360 m a.s.l. during the study period.

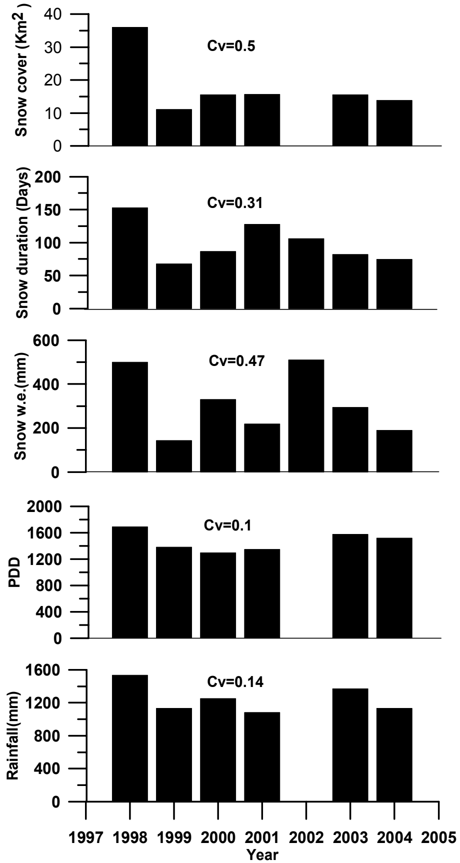

Fig. 7. Variations in the hydro-meteorological parameters during 1998–2004 period. Rainfall, Positive degree days (PDD), winter snow precipitation, Snow cover duration at 3763 m a.s.l. and snow cover extent in the first week of May.

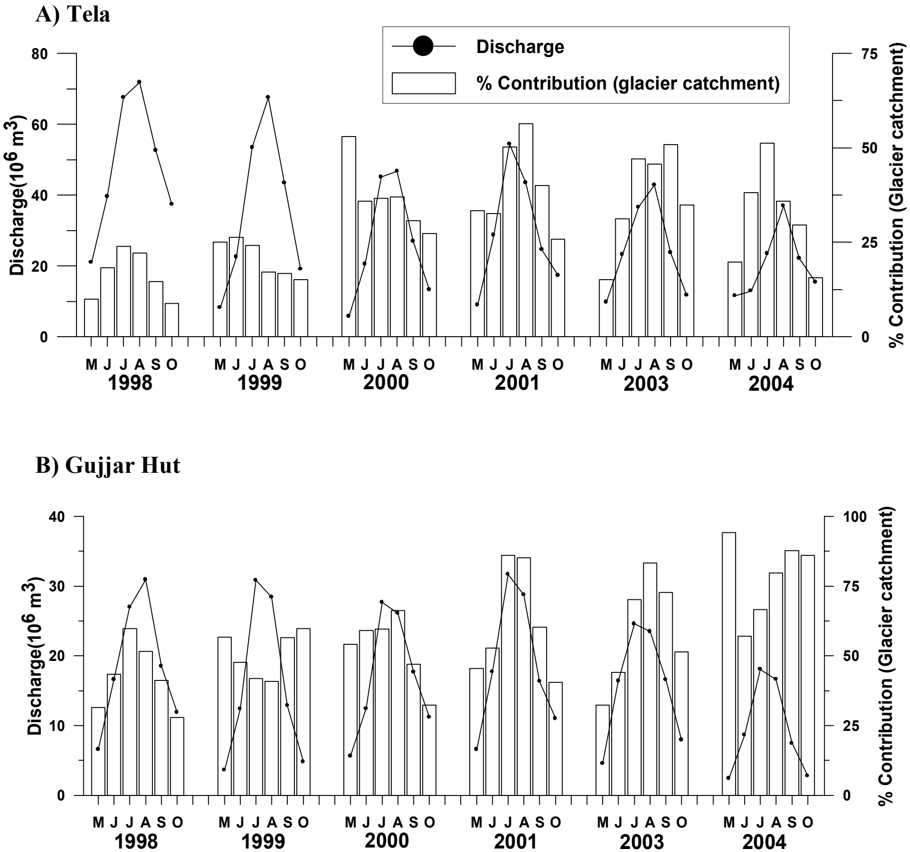

Fig. 8. Monthly variations in discharge and percentage contribution from the glacier catchment in the stream flow at **(A)** Tela and **(B)** Gujjar Hut stations.

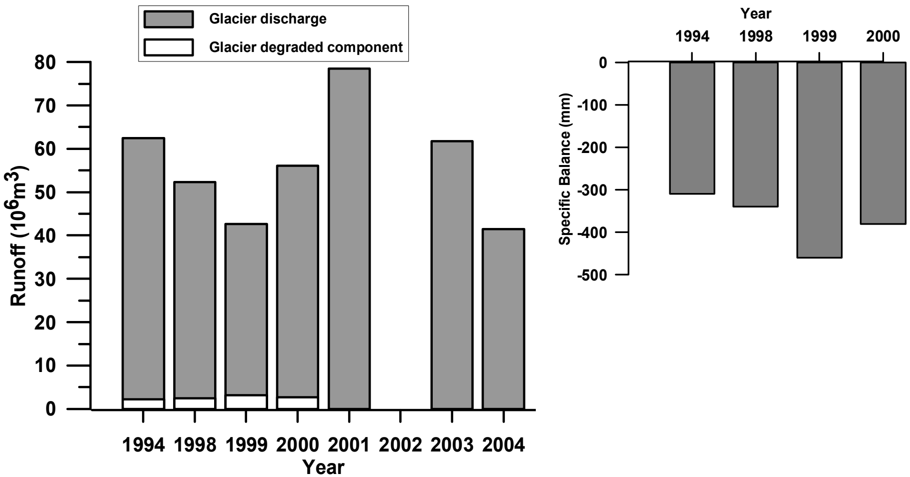

Fig. 9. **(A)** Ablation season discharges of Dokriani glacier and glacier degraded runoff component. **(B)** Enlarged graph of specific mass balance. Year 1994 and 1998 experienced high glacier discharge and low glacier degradation and year 1999 experienced one of the lowest summer runoff and highest negative glacier mass balance during the study period. This shows precipitation dominance of the "Himalayan catchment".

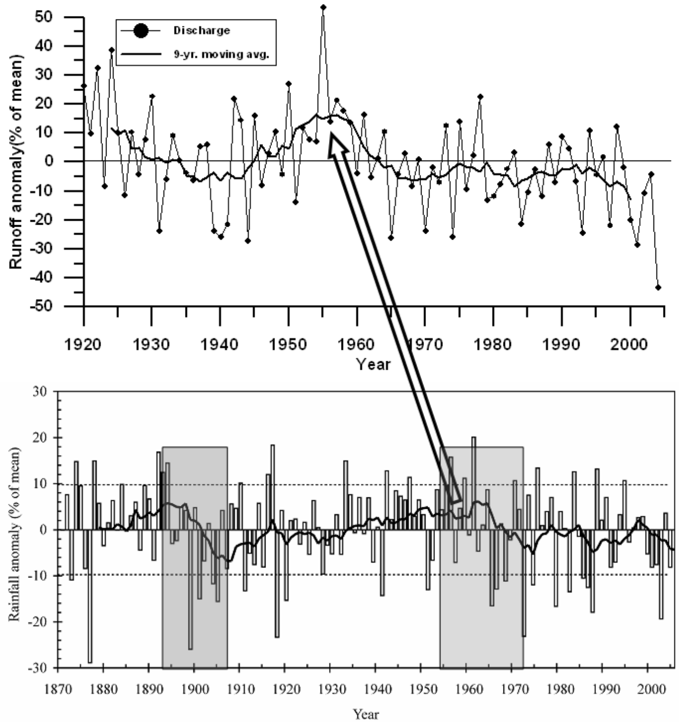

Fig. 10. (A) Discharge anomalies of River Satluj at Bhakra from 1920–2004 and **(B)** All-India summer monsoon rainfall anomalies from 1871–2004. Shaded bars show stationery/advancement periods of many glaciers in the Himalaya and Trans-Himalayan region. Period between 1945 to 1960 experienced high discharge associated with strong monsoon. Since 70's widespread recession of glaciers are reported from the region, but with reduced runoff as compared to 1950's. (Data source: Haryana Irrigation Department, 2001, Singh and Jain, 2002, www.bbmb.gov.in).

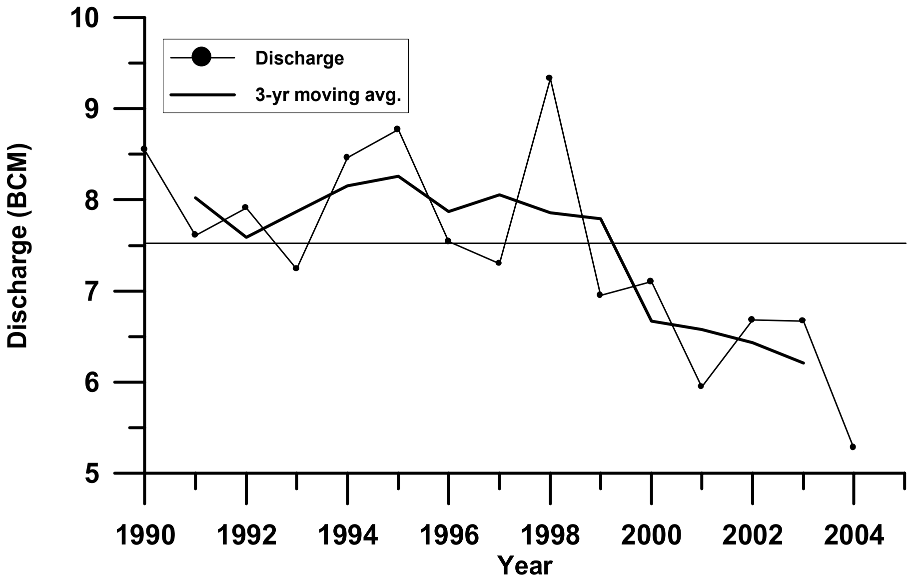

Fig. 11. Discharge variations of Beas river at Pandoh showing reduced runoff during 1998–2004 period. (Data source: Kumar et al., 2007).

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