Changing streamflow patterns in the rivers of northwestern Himalaya: Implications of global warming in the 20th century

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The results of trend analyses of the discharge data of four rivers in northwestern Himalaya, namely Beas, Chenab, Ravi and Satluj, are presented here and the impact of climate change in the last century is discussed. In the case of Satluj river, studies indicate an episodic variation in discharge in all three seasons on a longer timescale of about 82 years (1922–2004). Statistically significant decrease in the average annual and monsoon discharge and insignificant increase in winter and spring discharge, despite increasing temperatures during all the three seasons can also be seen. Decreasing discharge during winter and monsoon seasons in the post-1990 period, despite rising temperatures and average monsoon precipitation strongly indicates decreasing contribution of glaciers to the discharge and their gradual disappearance. On a shorter timescale of the last four decades of the 20th century, barring the Beas river, which shows a significantly decreasing trend, the other three rivers have shown a statistically insignificant change (at 95% confidence level) in their average annual discharge. Annual peak flood discharges show significant increasing trends in the Satluj and Chenab basins, significant decreasing trend in the Beas river and insignificant trend in the Ravi river. Notwithstanding these variations, the studies indicate an increase in the number of 'high-magnitude flood' events in the rivers in northwestern Himalaya in the last three decades.

Keywords: Annual peak flood discharge, climate change, glaciers, river discharge.

ATTEMPTS at the reconstruction of temperature and climate patterns on a global scale have established an overall increase in surface air temperature by about 0.5°C–1.1°C in the last century[1–5]. The rise is felt to be real in the last two decades[6–8] and ten warmest years after 1860 have all been experienced since 1980. While it is difficult to attribute this warming to the effects of solar variability and volcanism alone, the rapidity of the climate change, coinciding with the industrial revolution, has compelled many experts to believe with greater than 90% probability that anthropogenic (man-made) changes have been the major contributors[4,5,8–14].

On the regional scale, observations made in the Swiss Alps[15–18], French Alps[19], Rocky Mountains[20], Colorado, USA and across the United States[21], Europe[22] and Antarctica[23,24] have provided clear indications of a rise in temperature during the 20th century. Analysis of air-temperature data from the former Soviet Union (FSU) reveals a warming trend since early-1950s or mid-1960s, except in eastern Siberia, the Baltic Republics and some locations in Caucasus and at low elevations in Central Asia[25]. In China, dominant warming trends were detected at higher latitudes, with significant increase in the mean temperature[26,27]. Similarly, an increase of about 1.35°C in winter air temperature at Nagaoka, Japan in the last century has been reported[28]. In southern Andes (Argentina and Chile), mean annual temperature has been observed to be 0.53°C–0.86°C above the 1649–1899 means[29]. Studies[30–32] based on temperature data recorded at various stations located in the plains of India, have indicated a slight warming trend of about 0.4°C in the long-period data up to the late 1980s. For the country as a whole, a small warming trend of the order of 0.2°C–0.4°C was estimated, and the pattern over India conforms to the global trend[33]. Studies in Nepal Himalaya and hills of Uttarakhand have pointed towards a small positive trend in temperature[34–37]. Contrary to the global observations, pre-monsoon cooling (March–May) has also been reported in some portions of western Himalaya[38].

High mountain areas such as the Alps, Rockies, Himalayas, etc. considered as the 'hotspots' of biodiversity with climatic regimes that are similar to those of widely separated latitudinal belts and their ecosystems, are the most vulnerable regions of the world. Consequent to the general rise in air temperature, their river systems have shown impacts of shifts in climate regimes, which have resulted in the disruption of the existing socio-economic structures of population inhabiting their basins[15–17]. The Himalayas, which act as a mountain barrier on the earth, where polar, tropical and Mediterranean influences interact, play an important role in maintaining and controlling the monsoon system over the Asian continent[39]. For reasons of inaccessibility, ruggedness of the terrain and sparse net-

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Table 1. Discharge data availability (see Figure 1 for location)

River/discharge site	Data type/variable	Time-span	Data source
Satluj at Bhakra	Monthly discharge	1922–2004	BBMB[a] RR Yadav[b]
	Daily discharge	1961–2004	BBMB[c]
	Annual maximum flood discharge	1912–96	IT Commissioner[c]
Beas at Thalot	Daily discharge	1961–95	BBMB[a]
	Annual maximum flood discharge	1943–95	HPSEB[d]
Chenab at Akhnoor	Monthly discharge	1969–98	Bhagat and Zha[73]
	Annual maximum flood discharge	1961–95	IT Commissioner[c]
Ravi at Madhopur	Daily discharge	1962–95	BBMB[a]
	Annual maximum flood discharge	1962–95	IT Commissioner[c]

[a]Bhakra Beas Management Board, pers. commun.
[b]R. R. Yadav, pers. commun.
[c]Indus Treaty Commissioner, New Delhi; pers. commun.
[d]Himachal Pradesh Electricity Board (HPSEB); pers. commun.

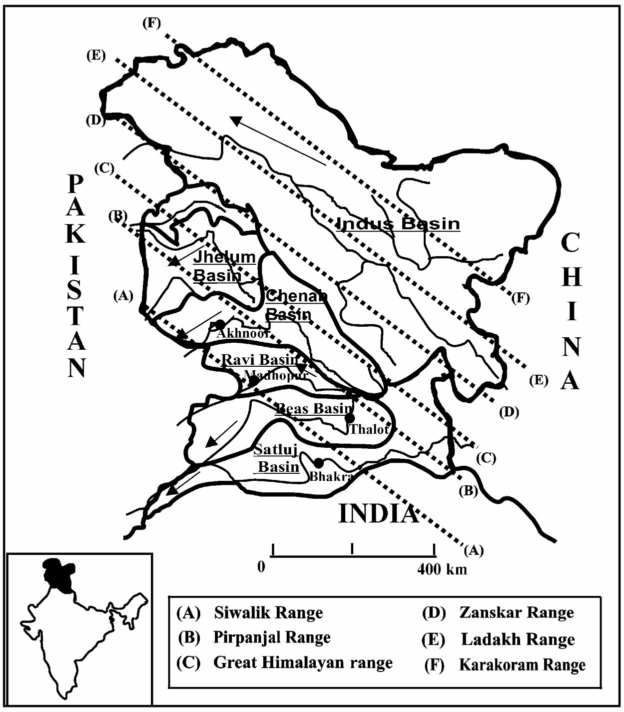

Figure 1. Location of various ranges and river basins in northwestern Himalaya. (Black arrow indicates direction of flow of rivers and black circles indicate locations of discharge gauging sites.)

work of gauging sites, the hydrology of the rivers and the nature of climate change in the region have not been studied adequately. The present article attempts to fill this vacuum by studying streamflow patterns in four river basins of northwestern Himalaya (NWH) with emphasis on the Satluj river, during different periods of the last century.

Study area and data

Bound by long. 72°–80°E and lat. 30°–37°N, the NWH mountains cover Jammu & Kashmir and Himachal Pradesh in India. The Great Himalayan and the Pirpanjal ranges surrounding the Kashmir Valley, the Zanskar, Ladakh and Karakoram ranges in the north and the Siwalik range in the south, confer the region with a unique physiographic setting of perennially snow-capped peaks interspersed with valleys and lakes. The Indus, Jhelum, Chandra-Bhaga (Chenab), Satluj, Ravi and Beas are the main river basins draining in the southwesterly direction in the area (Figure 1). Table 1 gives details about the availability of discharge data (daily discharge and annual maximum flood discharge) of four major rivers in the NWH for varying time-spans and their sources.

Because of limited data availability, instead of local variations, discharge variations are analysed on the regional scale in this article. Their relationship with precipitation and temperature variation on a longer timescale of about 82 years has also been examined. During the period of this study, the gauging stations were selected carefully to ensure that as far as possible, they had minimal upstream regulations and diversions, and the location or elevation of the river gauging site was not changed. With regard to the Satluj basin, it is worth mentioning here that it is a large basin (area 56,900 km^2 up to Bhakra) with varied climatological conditions in different parts. Almost half of the basin area falls in Tibet, with no meteorological and hydrological data available. There is an augmentation of discharge by way of Beas-Satluj Link Canal from Pandoh to Slapper. Contribution from the Beas river through this link has almost been constant over the years, with seasonal variation ranging from 33% during the winter months to about 18% during monsoon months.

The temporal and spatial consistencies of the discharge data of the four river basins in NWH were ascertained by double mass and bivariate linear regression analysis techniques[40] (M. R. Bhutiyani, unpublished). To bring uniformity and facilitate comparison between the hydrological responses of these rivers, yearly standardized discharge indices (SDI) were computed by subtracting the mean and dividing by the standard deviation of the discharge data series[41,42]. The SDI data series were subjected to trend analyses by two established statistical techniques[43]: standard parametric technique, such as linear regression analysis[39,44] and non-parametric test such as Kendall–Manny's test[43,45]. To remove inter-annual variability and assess episodic variation, all the above data were smoothed using cubic spline method with 50% variance reduction frequency and subjected to power spectrum analyses[30,46]. Data on 'high-magnitude flood' discharge events (defined as the maximum flood discharge that exceeds mean annual flood discharge by one standard deviation[47]) were also compiled and analysed.

Discussion

In comparison to a modest increase (0.5°C–1.1°C) in the global air temperature[1–5], the NWH region has warmed at a much higher rate (1.6°C/100 years) in the last century[44,48]. Increase in air temperature is significantly higher during the winter season (1.7°C/100 years) than the monsoon season (0.9°C/100 years). The winters in the last two decades have been unusually warm, with a total rise of about 4.4°C in average temperature[48]. Precipitation in the NWH has, in both the monsoon as well as winter seasons, more or less remained trendless in the last century and undergone epochal behaviour (M. R. Bhutiyani, unpublished). The variations in both temperature and precipitation are translated into changes in the hydrological regimes of the river basins of the NWH by way of variability in snow-melt run-off, glacier melting and monsoon run-off, and increase or decrease in average annual and annual peak flood discharges. In the context of the NWH, these variations are discussed here by analysing trends during discharge in different seasons.

Trend analysis of winter, spring, monsoon and annual discharge

There are three components of discharge in a glacierized basin; snow-melt run-off, glacier melt and run-off due to monsoon rainfall[49]. Because of sparse database and large-sized basins with varied physiographic settings, an accurate assessment of the contribution by each component of the discharge is impracticable. However, based on the yearly hydrographs (computed from average of daily discharge values from 1961 to 95 of four rivers, namely Beas, Satluj, Ravi and Chenab, the following periods can be identified to estimate the contributions by various components:

(a) Winter discharge (largely base flow from sub-glacial melting and groundwater storage): November–February.
(b) Spring discharge (base flow + seasonal snow-melt): March–May.
(c) Monsoon discharge (base flow + monsoon rainfall + glacier melt): June–October.

Although seasonal snow cover is an important parameter in the hydrological regime of a basin, its contribution is confined to the spring season when snow-melt and base-flow constitute two components of the discharge. Once the summer sets in, it is the exposed glacier ice in the ablation zone which is the main contributor to the melt along with monsoon rainfall. The contribution by snow cover above the equilibrium line to the discharge is insignificant in this period[50].

Figure 2 and Table 2 show the results of trend analyses of discharge in the winter, spring and monsoon seasons along with average annual discharge in the four rivers of NWH in a relatively shorter time-span of about 40 years (1961–2004) in the last century. These data indicate that in the last four decades, monsoon discharge in the Beas river has shown a statistically significant decrease and winter discharge in the Chenab river has shown a statistically significant increase. Barring these, statistically insignificant variation in discharge is observed in other basins during all the three seasons, indicating episodic fluctuations. These may have been caused because of the variations in the precipitation and temperature. Similar results have been obtained in different parts of the world (including the Himalayas) in the study of long-term trends in the mean streamflow of the rivers as possible indicators of climate change[49–60].

To further investigate the episodic variation in detail, Satluj discharge data of a reasonably longer time-span (1922–2004) are analysed. Results of the analyses of the discharge data of three seasons, namely winter, spring and monsoon, with reference to the temperature and precipitation variations in the respective seasons are given in Table 3 and Figures 3–5.

The data show a slightly increasing but statistically insignificant trend in the discharge during winter and spring months, despite rising temperatures. This indicates that the variation may have been in an episodic manner, with periods of above and below average discharge. A reasonably significant periodicity of 28 years obtained in the power spectrum analyses of winter, spring, monsoon and annual discharge, confirms episodic variation on a tri-decadal scale (Table 4). It is also interesting to note a statistically significant decreasing trend in discharge during monsoon months in the Satluj River. Similar trend is reflected in monsoon precipitation too (Figure 5). Monsoon is the period when rainfall and summer glacier melt are the major components of discharge, with glaciers playing a vital role as regulators[49,61].

Further analysis of temporal variation of discharge in the monsoon months during 1922–2004 (Figure 5) shows that five distinct periods of variation can be identified. The Satluj river had above normal discharge till 1932 (Period 'A'), below normal from 1933 to 1944 (Period

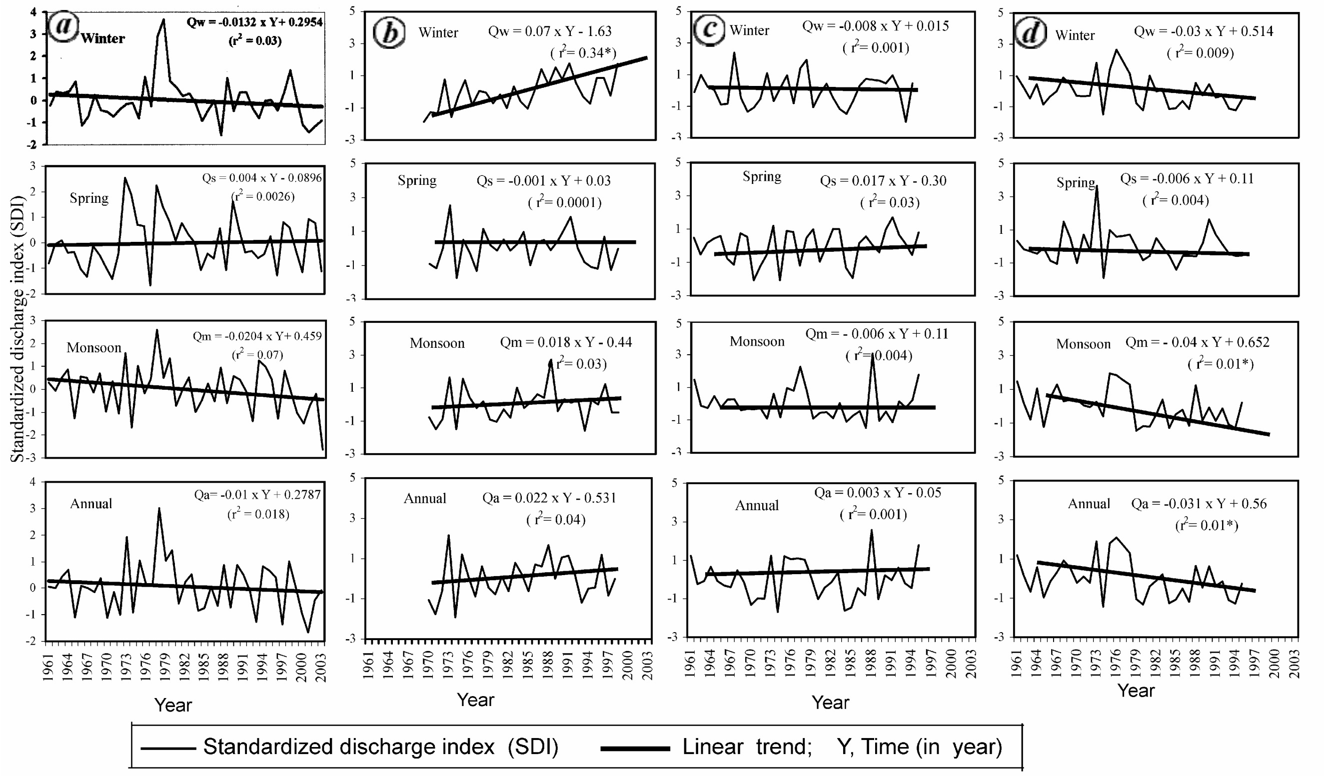

Figure 2. Temporal variation and linear trends in average discharge in winter (*Qw*), spring (*Qs*), monsoon (*Qm*) and annual (*Qa*) in the rivers of the NWH. ***a***, Satluj (1961–2004); ***b***, Chenab (1970–98); ***c***, Ravi (1961–95) and ***d***, Beas (1961–95). *Significant at 95% confidence level.

Table 2. Results of trend analyses of discharge in the northwestern Himalayan rivers

			Trend analysis	
Station (site)	Data availability	Season	Mann–Kendall's non-parametric test	Linear regression coefficient *b*
Beas (Thalot)	1961–95	Spring	(–)	(–)
		Monsoon	(–)*	(–)*
		Winter	(–)	(–)
		Average annual	(–)*	(–)*
Ravi (Madhopur)	1962–95	Spring	(+)	(+)
		Monsoon	(–)	(–)
		Winter	(–)	(–)
		Average annual	(+)	(+)
Chenab (Akhnoor)	1969–98	Spring	(–)	(–)
		Monsoon	(+)	(+)
		Winter	(+)*	(+)*
		Average annual	(+)	(+)
Satluj (Bhakra)	1961–2004	Spring	(+)	(+)
		Monsoon	(–)	(–)
		Winter	(–)	(–)
		Average annual	(–)	(–)

*Significant at 95% confidence level. (+), Increasing; (–), Decreasing.

'B'), above normal from 1945 to 1967 (Period 'C'), above normal from 1968 to 1990 (Period 'D') and below normal discharge thereafter till 2004 (Period 'E'). The most interesting aspect of this variation is that the increase in discharge from 1945 to 1967 coincides with increasing precipitation, with no significant change in temperature. The subsequent period from 1968 up to 1990 is marked by more or less average discharge, below average and decreasing monsoon precipitation and below average but increasing air temperature. This indicates that the glaciers act as natural regulators of discharge in these river basins, contributing more during the warm years (below average

Table 3. Results of trend analyses of discharge in the Satluj river

Station (site)	Data availability	Season	Trend analysis: Mann–Kendall's non-parametric test	Trend analysis: Linear regression coefficient *b*
Satluj (Bhakra)	1922–2004	Spring	(+)	(+)
		Monsoon	(–)*	(–)*
		Winter	(+)	(+)
		Average annual	(–)*	(–)*

*Significant at 95% confidence level. (+), Increasing; (–) Decreasing.

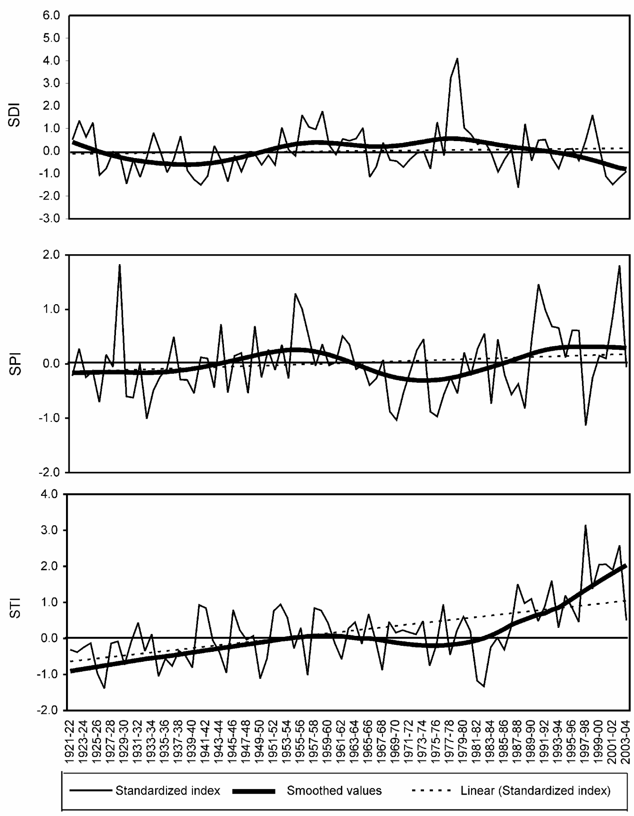

Figure 3. Temporal variation of winter SDI of the Satluj river at Bhakra and its relationship with winter standardized precipitation index (SPI) and standardized temperature index (STI) of the NWH during the period 1922–2004.

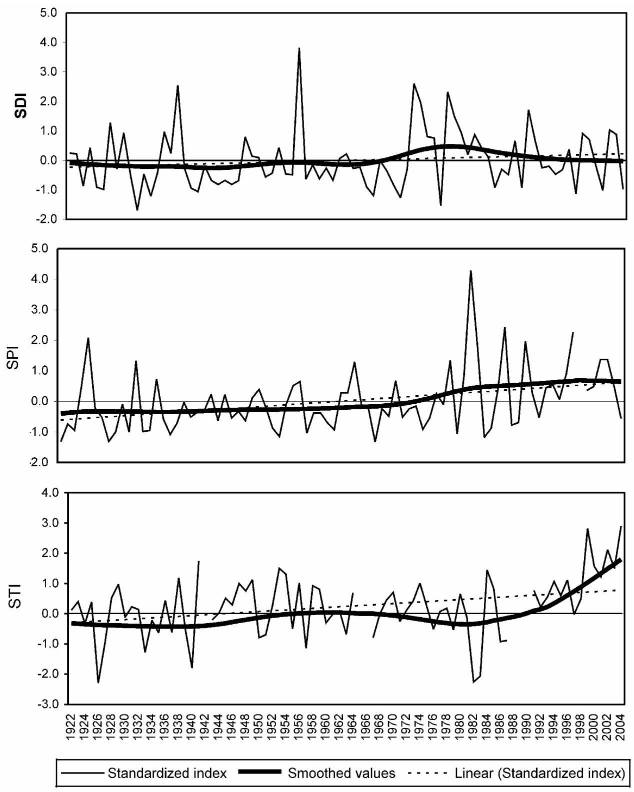

Figure 4. Temporal variation of spring SDI of the Satluj river at Bhakra and its relationship with spring SPI and STI of the NWH during the period 1922–2004.

monsoon) due to excessive melting and less during comparatively colder (above average monsoon) years, due to reduced melting. The period between 1991 and 2004, during which the Satluj river appears to have recorded decreasing discharge values, is also characterized by significant rise in air temperature and almost average precipitation. Ironically, average precipitation, coupled with increasing temperature should have caused further increase in the component of glacier-melt and enhanced discharge. On the contrary, discharge during this period has decreased, despite consistent augmentation through the Beas–Satluj Link Canal over a period of time. Although mass balance and length data of the glaciers in the NWH are not available for a reasonably long period, a limited number of studies in the last four decades has demonstrated negative mass balance, significant ice-loss and faster recession of the glaciers during this period[50,62–66]. The glacier-melt component of discharge in the Satluj Basin appears to have reached its maximum level around 1990. Because of excessive melting during the pre-1990 period, the glaciers appear to have thinned considerably. Decreasing discharge, even during winter, despite unusually rising air temperature and average precipitation during this period, corroborates the fact that thinning glaciers are the sole reason behind waning contribution of glacier-melt during this period. Table 5 gives the area and number of glaciers existing in these river basins. It is seen from these data that the Chenab Basin has the maximum glacierized area and number of glaciers in comparison with other river basins. The Beas and Ravi basins have comparatively fewer glaciers. Although they are next to the Chenab Basin in number, majority of the glaciers in the Satluj Basin are comparatively smaller in length than other basins (longest glacier being about 5.5 km[61]).

Below normal winter discharge in the Satluj river (primarily caused by sub-glacial melting and groundwater storage with less radiational melting on the surface) from 1991 to 2004, appears to be largely related to diminishing contribution from glaciers in the basin which are thinning considerably, as contribution by groundwater storage has more or less remained constant[49]. If the warming trend of similar magnitude continues in the future, with the smaller glaciers receding at a faster rate compared to the larger ones[7] (M. R. Bhutiyani, unpublished), their gradual disappearance may be the likely outcome. In contrast, winter discharge in the Chenab river has shown a statistically significant increase during the period 1969–98 (Figure 2), which may be attributed to a larger number of glaciers in the basin and the fact that they are relatively longer in comparison to the glaciers in the Satluj Basin. These observations conform to an overall global trend, wherein majority of the glaciers are in a general state of retreat, with smaller glaciers disappearing, larger ones in mid-latitude regions shrinking slowly and those in the Polar region warming considerably[67–70].

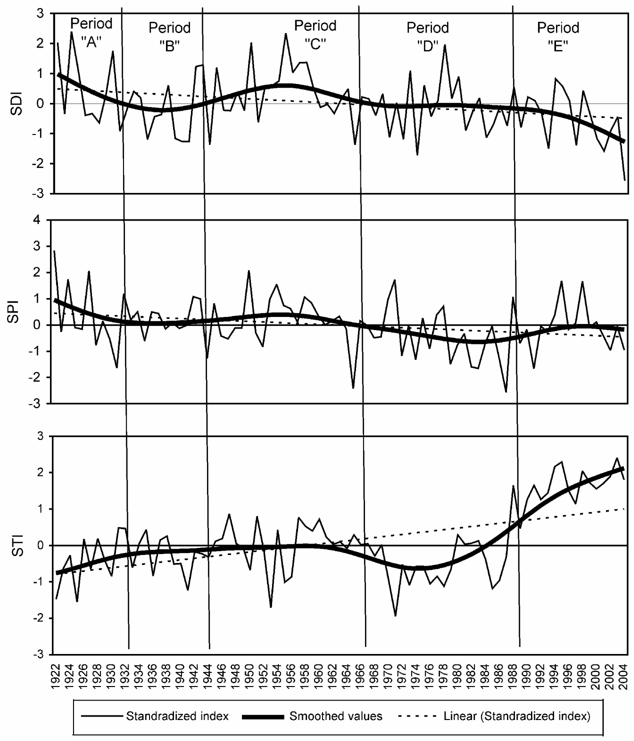

Figure 5. Temporal variation of monsoon SDI of the Satluj river at Bhakra and its relationship with monsoon SPI and STI of the NWH during the period 1922–2004.

Discharges in the Beas and Ravi rivers do not seem to be significantly affected, as the number of glaciers and the glacierized area in their basins in the NWH and contributions of glacier melt are much smaller compared to the Satluj Basin. Although spring discharge in the Beas Basin appears to have decreased during the period 1961–95, a slight increase has also been reported in the last decade or so, due to faster melting of seasonal snow[71]. The average annual discharge in these two rivers appears to be controlled to a large extent by the variation of monsoon precipitation during this period (M. R. Bhutiyani, unpublished). The overall decreasing trend in monsoon precipitation in the NWH during this period corroborates this observation (M. R. Bhutiyani, unpublished).

Trend analysis of annual peak flood discharge

Annual maximum series of annual peak flood discharge in the rivers of the NWH are shown in Figure 6. The results of the trend analyses of SDI of annual peak flood discharges of the four river basins are given in Figure 7 and Table 6.

The data show that while the Satluj and Chenab reveal significant increasing trends, Ravi and Beas show insignificant increasing and significant decreasing trend respectively, at 95% confidence level. Among the four NWH rivers under study, only the Satluj and Chenab appear to have a response matching with the variation in temperature. The years before the early-1940s, characterized by below average to average temperature and comparatively no change in monsoon as well as annual precipitation, are also marked by below average flood discharges during this period. This indicates that during this period, although

Table 4. Results of power spectrum analysis of discharge data of Satluj river

Season	Significant cycle in years
Winter	2.55*, 28**
Spring	28**
Monsoon	28**, 14*
Annual average	28*

*Significant at 95% confidence level.
**Significant at 90% confidence level.

Table 5. Details of glacierized areas and number of glaciers in four river basins in the NWH region

River basin	Total area in the NWH covered by the glaciers (km^2)	Total number of glaciers
Chenab	2280	989
Ravi	210	94
Beas	598	277
Satluj	1515	334

Data source: Dobhal and Kumar[61]; Geological Survey of India[74].

the rainfall regime did not show significant variation, due to below average temperatures, the reduced rate of melting of glaciers appears to have led to below average flood-discharge values. The period after the early-1940s has been marked by above average annual air temperatures. It seems to have given rise to above average flood discharge values, although the annual and monsoon precipitation shows below average values for majority of the years during this period. This, as discussed earlier, confirms the role played by glaciers in regulating the discharge. These variations are to a large extent in agreement with similar observations made in other parts of the world, where the inversion of temperature is also observed around 1940 and it corresponds to the world thermic maximum[72]. It can be seen from the plots of the Beas, Ravi and Chenab rivers that all these have shown above average maximum flood discharge values from 1984 till 1995, although both annual and monsoon rainfall has shown normal values for most of the years.

It is also seen from these plots (Figures 6 and 7) that there was a significant number of high-magnitude flood events (marked by ▲ in the figures) in the rivers of the NWH in the last century, and the frequency of such events has increased in the last 4–5 decades. On the Satluj river all ten events have occurred in this time-span. Similarly, on the Chenab river there were six, on the Beas there were four and on the Ravi there were five such high-magnitude flood events during this period. Majority of the years during this period have shown above average annual temperature index values, indicating a direct relationship between climate change (increasing temperatures) and annual flood discharges in the NWH in the last century.

Table 6. Results of trend analyses of annual peak discharge in the rivers of the NWH

River	Time-span	Trend analysis: Mann–Kendall's non-parametric	Trend analysis: Linear regression coefficient b
Beas at Thalot	1941–95	(–)*	(–)*
Ravi at Madhopur	1963–98	(+)	(+)
Satluj at Bhakra	1912–95	(+)*	(+)*
Chenab at Akhnoor	1962–98	(+)*	(+)*

*Significant at 95% confidence level.
(+) Increasing trend; (–) Decreasing trend.

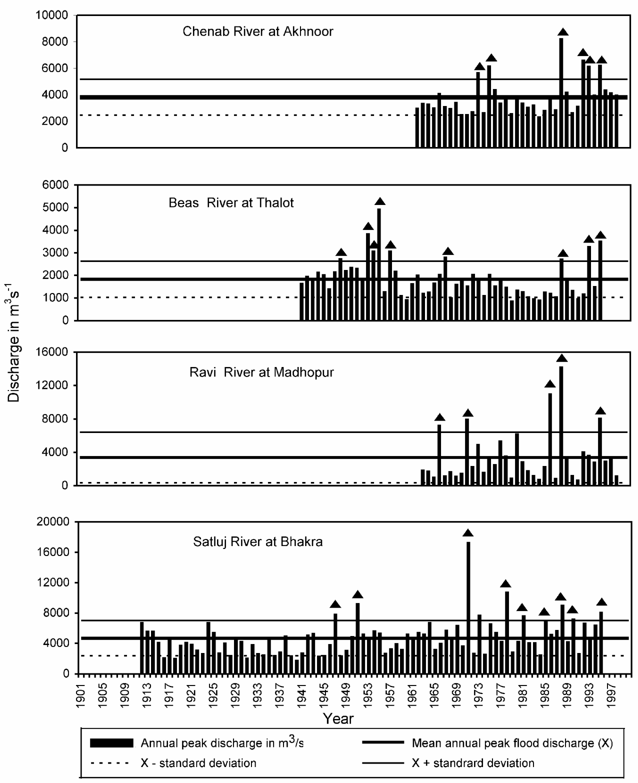

Figure 6. Annual maximum series of annual peak flood discharges in the rivers of the NWH. ▲ indicates the year with a 'high-magnitude' flood event.

Conclusion

The studies indicate a significantly decreasing average annual and monsoon discharge in the Beas river, and a

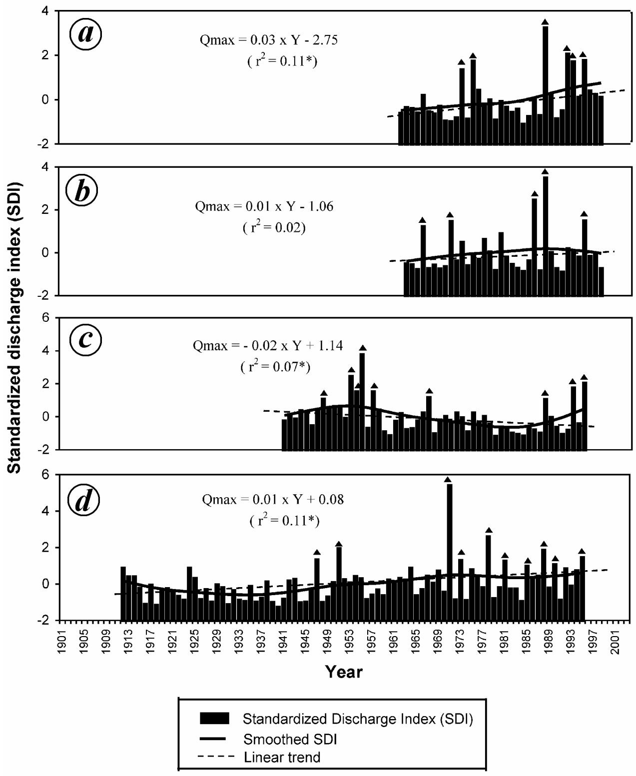

Figure 7. Temporal variation of annual maximum flood SDI of (***a***) the Chenab river at Akhnoor (1962–98), (***b***) Ravi river at Madhopur (1963–98), (***c***) Beas river at Thalot (1941–95) and (***d***) Satluj river at Bhakra (1912–1995). Q_{max} is the peak annual flood discharge and Y the time in years. *Significant at 95% confidence level; ▲ indicates the year with a 'high-magnitude' flood event.

decreasing but insignificant trend for the Ravi river in the last four decades of the last century. Both rivers have relatively fewer glaciers in their basins, yielding insignificant contribution from snow/glacier-melt and are mostly monsoon-fed. On the contrary, the Satluj and Chenab rivers have a large number of glaciers in their basins, which have played a regulatory role in controlling their discharge. Decrease in discharge from 1991 till 2004 in the Satluj river, may be on account of rapid recession of the glaciers and their waning contribution. As the smaller glaciers have receded at a relatively faster rate than the larger ones, this may ultimately lead to their disappearance in the near foreseeable future. The study also shows that there has been significant increase in the number of high-magnitude flood events in the rivers of the NWH in the last decades.

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